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Changes in Soil CO_2 Concentration Accompanying Infiltration and Evaporation at a Primary Forest and Grassland in Central Amazonia

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Abstract: Soil CO_2 concentration and microclimatic parameters were measured at a primary forest and grassland in dry season (August to September 2003) and rainy season (March 2004) in central Amazonia in order to investigate the effects of infiltration of rainfall and evaporation of soil water upon the changes in soil CO_2. The CO_2 temporarily increased with infiltration, and decreased after soil water descended downward. Then, the increase and decrease moved to deeper soil. This phenomenon was found at both a primary forest and a grassland in the rainy season, and was found in the dry season as well at primary forest. At the grassland in dry season, the soil moisture change was positive during daytime, while the CO_2 concentration change was negative. During nighttime, in contrast, the soil moisture change was negative and the concentration change was positive. It was estimated that the fluctuation of radiation between day and night reversed the relative position of soil water and CO_2 in the soil. In the rainy season, there was not a large difference in the surface soil concentration (10–30 cm: 20,000–25,000 ppm) between the sites, while in dry season the concentration at the grassland was quite low (2,500–2,600 ppm). From these findings, it was estimated that the soil CO_2 was emitted or the root respiration was quitted due to the withering of herbs on the grassland in the dry season. In either case, it is thought that the decrease in soil CO_2 was brought about by the exposure of naked land due to the disappearance of forest canopy.

Key words: central Amazonia, soil CO_2, infiltration, evaporation, primary forest, grassland

Introduction

Amazonian tropical forests started disappearing in the 1960s under the goal of developing the Amazonia (Nishizawa and Koike 1992). Exploitation of mineral and lumber resources, construction of interstate roads, inflows of immigrants from northeastern and southern parts of Brazil, and preferential treatment in tax payments promoted the settlement of capitalists and enterprises from the south (Horisaka 1997). However, mining development and lumber cutting have actually been little more than the devastation of natural environments (EMBRAPA 2005; INPE 2005). Even if large pastures were created, they were subject to speculative hoarding and selling. Thus, the developments came to be criticized by domestic and overseas environmental organizations (Fearnside 1991). In response to the fact that more than 15% of forests in Amazonia have disappeared (Laurance and Fearnside 2002), researchers started to investigate the CO_2 uptake by forests. Through the ABRACOS from 1990 to1994, MACOE in 1995, and LBA projects from 1999 to 2003 (Fisch et al. 1998; Nobre et al. 2001), the CO_2 flux was measured at primary forests and pastures (grasslands) in the whole Amazonia (Culf et al. 1999; Grace et al. 1999; Malhi and Grace 2000), and the effects of enlargement of degraded lands and forest fires derived from El Nino upon global warming have been simulated (Phillips et al. 1998; Houghton et al. 2000). These papers show that primary forests are a sink of CO_2 at present, but will change to a source of CO_2 if the forest disappearance continues.

Soil CO_2, whose concentration amounts to several hundreds times more than that of the atmosphere, has not been extensively investigated. Since the infrared CO_2 analyzer (IRGA) was developed, CO_2 efflux has been measured at the soil surface as soil respiration (Davidson and Trumbore 1995; Camargo et al. 1999; Davidson et al. 2000; McGroddy and Silver 2000; Hashimoto et al. 2004). But when it rains, raindrops do not come into a chamber at which the concentration is measured, and even on sunny days the air condition within the chamber changes from the ambient atmosphere when the measurement extends over a long period. The vertical profile of soil CO_2 is investigated by passing the air absorbed by injection through the IRGA (Davidson and Trumbore 1995), or by chemical reaction (Hashimoto et al. 2004), but neither of the results is from automatic measurements. Soil carbon is also a few times as much as that of aboveground biomass (Davidson and Ackerman 1993). For example, Moraes et al. (1995) estimated that the carbon stock in the top 1 m of soil in the whole Amazonia totally amounts to 47 Gt, and Nepstad et al. (1994) estimated that the soil carbon is averaged to be 20 kgC/m^2 at a depth of 1 m. Therefore, the soil C pool at plantation forests, secondary forests, and abandoned pastures has been compared to that at primary forests, and the results indicate that the soil C stock changes with the species composition at plantations (Smith et al. 1998a, 1998b; Silver et al. 2000; Smith et al. 2002), the stock at secondary forests composed of pioneer species is not so different from that at primary forests (Uhl and Jordan 1984; Buschbacher et al. 1988; Fearnside and Guimarães 1996; Johnson et al. 2001), the stock changes with the management of pastures and the number of years that have passed since the pastures were opened (Martins et al. 1991; Nepstad et al. 1994; Davidson et al. 1995; Trumbore et al. 1995; Neill et al. 1997; Camargo et al. 1999), and the stock is influenced by the physical properties of the soil (McGrath et al. 2001).

Recently, a new CO_2 sensor (NDIR), which is based on the single-beam dual-wavelength principle, has been developed, and a report dealing with serial soil CO_2 data has been presented (Nakamoto et al. 2001); soil CO_2 temporarily increased when rainfall infiltrated into a sand dune, and it decreased when the water moved into deeper places. Such phenomena have not been detected by previous manually-operated methods. Therefore, the present study proposes to compare the CO_2 concentration between a shrinking primary forest and increasingly-degraded grassland. Sunny days continue in dry season but squalls suddenly happen. Temperature and humidity largely fluctuate at grassland but they hardly change within a forest. In the rainy season, a large number of rainy days keep temperatures lower and humidity higher. The shielding effect of soil respiration by rainfall and the relationship to the aboveground CO_2, and changes in soil CO_2 in response to infiltration and evaporation, are compared between sites and seasons with different fluctuation of microclimatic parameters.

Methods

Fieldwork was carried out in the vicinity of Novo Aripuana City in the Brazilian State of Amazonas during August to September 2003 (dry season) and March 2004 (rainy season) as shown in Figure 1. A 200 km^2 primary forest is conserved about 40 km east of Novo Aripuana, locally called Cascaleira (5° 18′S, 60° 04′W). The vegetation type is categorized as forest canopy emerging lowland dense forest, whose average height is about 30 m (Ferreira et al. 2001). Tanaka (1998) identified 2,986 individual trees, over 43 botanical families, and 163 species in a 25 ha primary forest, and noted that not only the late succession species at primary forests but also species peculiar to numerous treefall gaps increased the biodiversity. A part of the forest, whose area is 2 km^2, has been left untouched as grassland after clear cutting and burning in 1997. Thorny herbs, 40–50 cm high, grow sparsely there. They wither in the dry season. The Oxisols (Latossolo amarelo) reaches to a depth of 5–6 m in soil. People use the silt-like soil when making bricks and tiles. A reddish pebble layer (Cascalho) with a diameter of 1–2 cm lies below (Souza 1991). The shallowest ground water level is about 18 m below ground. The humus layer is about 10 cm

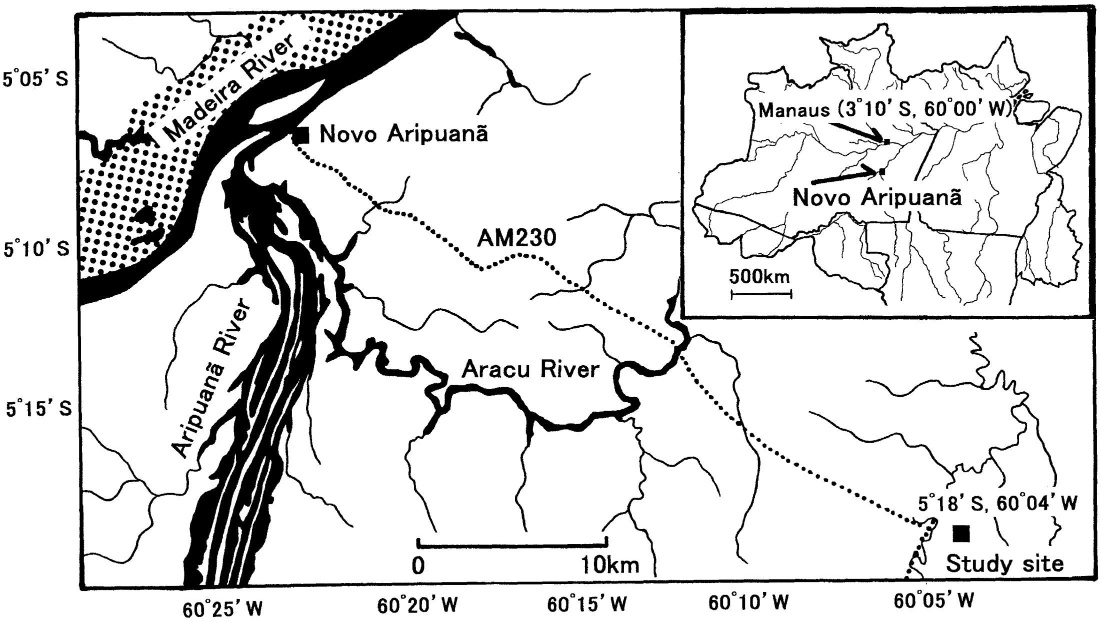

Figure 1. Location of study site in the Novo Aripuanã area
The dots pertain to the inundated area in the high-water-level season. AM230 is the state road.

at both sites. The climate is classified as tropical monsoon (Am), but there is a weak dry season during June to October in which the monthly rainfall is less than 100 mm. It is the season when people set fire to the forest to plant cassava. The annual temperature is 26℃, humidity is 85%, and the rainfall is 2,750 mm (SUDAM/PHCA 1984).

The same parameters were measured both at the forest and grassland. A soil pit 50 cm long by 100 cm wide by 120 cm deep was made at each site, and a dielectric aquameter sensor (Decagon, ECHO10), a platinum resistant thermometer (TandD, TR81), and NDIR-CO_2 sensor (Visala, GMT221) were buried to the vertical section at depths of 10, 30, 50, and 100 cm. Then, the pit was filled in with soil. The data loggers were stocked in sealed containers for waterproofing. The range of the CO_2 sensor was 0–2% in dry season, but because the actual data exceeded 2% at 50 and 100 cm in the forest, it was 0–5% in the middle of measurements in rainy season. To avoid the sensor touching the soil directly, the sensor and the cable were inserted into a 30 cm arc-like PVC pipe (id: 2 cm), and it was put into the soil. The other side was sealed with putty. Above the ground, the same sensor (GMT222: 0–2,000 ppm) was set at heights of 10 and 150 cm, and was sheltered by a two-liter plastic bottle wrapped with aluminum foil. The CO_2 data were stored in voltage data loggers (TandD, VR 71). Two 12V car batteries (Moura, 63A) were connected in series to supply 24 V to operate the sensor. Considering the electricity for measurement and waiting, and the safety factor, the batteries were withdrawn once a week to charge at a power plant in Novo Aripuanã. Air temperature and humidity were measured at heights of 10 and 150 cm using a thermo-hygrometer (Hioki, No.3641). The sensor was sheltered like the CO_2 sensor. Atmospheric pressure was measured using a barocap sensor (Visala, PTB210) at a height of 150 cm. The data were stored in the VR71. A 12V car battery (Moura, 40A) was used as a power source. Heat balance-related parameters (upward/downward short- and long-wave radiations, soil heat flux) were measured using a four-components radiometer (Eko, MR40) at a height of 150 cm, and two soil heat plates (Eko, MF81) were buried in the soil surface. The data were stored in micro-voltage data loggers (Eko, MP 75D). Only soil moisture was sampled every 30 minutes, and all the other parameters were sampled every 10 minutes. Because there was only one set of equipment, they were shifted from the forest (August 13–19 and 21–27) to the grassland (August 29–September 4 and 6–12) in the dry season of 2003, and from the forest (March 2–7 and 9–14) to the grassland (March 16–21) in the rainy season of 2004. Soil temperatures at depths of 50 and 100 cm were not measured in 2004 because no diurnal fluctuation was found in the measurement in 2003. In addition, a rain gauge (Ota, No.34T) was set in the two sites to monitor the hourly rainfall to a pulse logger (TandD, RF3). Soil samples of four depths were obtained using stainless steel cans (Daiki, 100 cc), and were dried in an oven to calculate the volumetric water content (%) from the ratio between fresh and dry weights. Then, the water content was regressed to the dielectric constant to introduce an equation between them. Aerial photos were taken using a fish-eye lens (Sigma, EX8 mmF4), and the positives were input into a computer via a macrolens (Fujinon, A13-10BMD-D8) to estimate the sky-view factor using image analysis software (Mitani, MacScope2.5).

Results

Microclimates near the soil surface

It rained 10 times during the month from August 13 to September 12 (Figure 2). All cases were squalls or showers, which stopped in a few

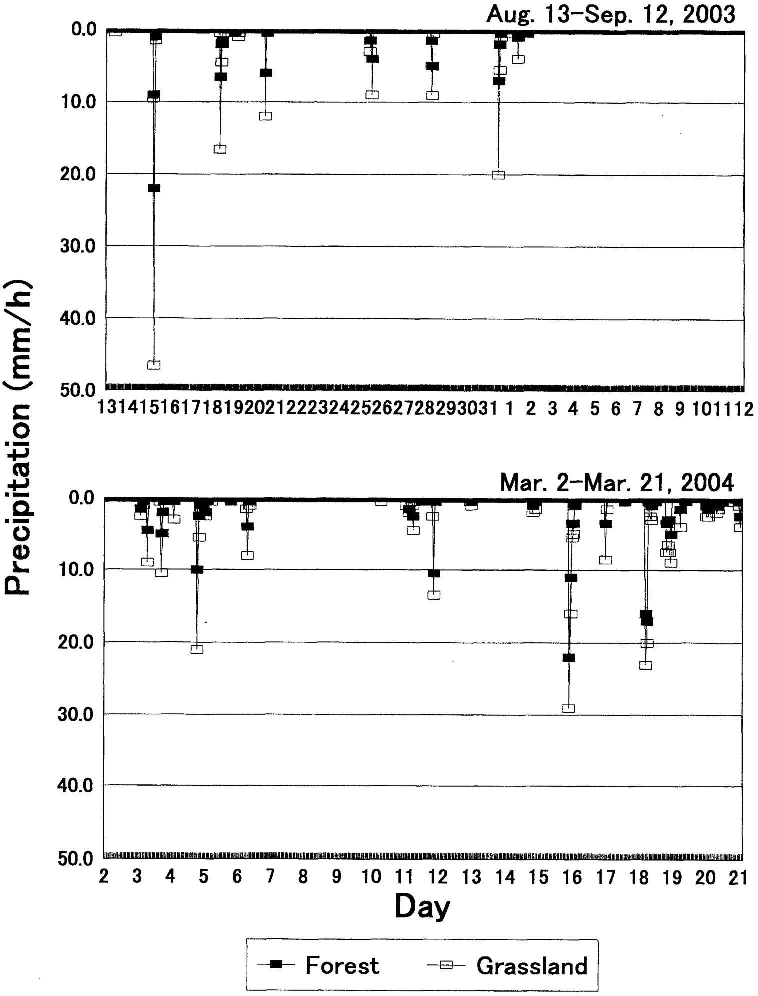

Figure 2. Precipitation (mm/h) in the forest (■) and grassland (□) during August to September 2003 (dry season) and March 2004 (rainy season).

hours. But the hourly rainfall recorded at 18 : 00 on August 15 was 46.5 mm at the grassland and 22.0 mm at the forest. In all cases, the amount of rainfall at the forest was about half that at the grassland because the rainfall was trapped by the canopy. During March 2 to 21 (rainy season), the number of rainy days (15 days) was much larger than that in dry season. There were four cases at the grassland and one case at the forest in which the hourly rainfall exceeded 20.0 mm, but they did not surpass 30.0 mm. However, the duration of rainfall was longer than during dry season (4–5 hours).

On the forest floor in the dry season, the downward short-wave radiation (SWd) was affected by forest canopy; SWd was limited to about two hours in each the morning and evening, reaching as merely sun flecks (100–400 W/m^2). The upward short-wave radiation (SWu) appeared only at those times (dozens of W/m^2). Both the upward and downward long-wave radiations (LWu, LWd) ranged from 500 (daytime) to 420 W/m^2 (nighttime). SWd at the grassland showed a symmetrical normal distribution. It peaked at 800–1,000 W/m^2, and SWu also reached 100–200 W/m^2. LWu was about 150 W/m^2 larger than LWd in daytime, and the relationship was the same at night as well, keeping a difference of 20–30 W/m^2. In the rainy season in the forest, the peak of SWd was about 50 W/m^2. SWu was much smaller. The diurnal fluctuations of LWd and LWu were mostly constant at 450 W/m^2 throughout the days. On the grassland, radiations changed with the weather; on sunny days, SWd and SWu peaked at 800–1,000 W/m^2 and 100–200 W/m^2, respectively, but on rainy days they were about half that in the dry season. It was common in dry season that $|LWu|$ was larger than LWd in both daytime and nighttime.

The minimum temperature at 10 and 150 cm above the soil surface changed from 22–23℃, and the maximum temperature changed from 27–28℃ at the forest in dry season. Th (temperature at 150 cm) was slightly higher than Tl (temperature at 10 cm) in daytime, and the relationship reversed in the nighttime ($|Tl-Th| \leqq 0.5$℃). On the grassland, they largely fluctuated from 20 to 43℃. On sunny days, the height difference was $Th \leqq Tl$ both during day and night. When it rained, the temperature decrease was weak at night, and the increase was also dull the next morning. The dew-point temperatures at both heights (Tdph, Tdpl) overlapped at nighttime in the forest. On the day following rainfall, Tdp showed the same value as T even in the daytime. On the grassland during afternoons without rainfall, the difference between Th and Tdph reached 15℃ (Th > Tdph), and the difference between Tl and Tdpl reached about 20℃ (Tl > Tdpl). In the rainy season, the temperatures varied from 23 to 28℃ in the forest. Throughout most days, T was equal to Tdp. On the grassland, temperatures as high as in the dry season were observed on sunny days but were lower than 30℃ on rainy days. Due to high vapor pressure, the daytime Tdp increased to as high as 27–28℃, keeping the height difference of Tdpl > Tdph.

In the dry season, relative humidity was 100% throughout two weeks at 10 cm above the soil surface (Hl) in the forest. The Hh at 150 cm decreased to 85% in the daytime, but became 100% in the evening. On the grassland, both of those measured factors decreased to 40% in the daytime. In the rainy season, Hl at the forest was 100% throughout the days, and Hh was also 100% on rainy days. On the grassland, there was a day when the humidity dropped to the 50% level (a sunny day), and there was a day when it remained at the 80% level (a rainy day). The amount of condensation, which is the decrease in absolute humidity (Y: g/m^3) in nighttime in which T overlapped Tdp, was relatively large on clear nights (4–5 g/m^3) at the forest in dry season, but was as small as 1 g/m^3 on rainy nights. On the grassland, Y itself was smaller, but the decrease in Y was as large as in the forest. In the rainy season, Y was about 27 g/m^3 on clear days, but was about 25 g/m^3 on rainy days in the forest. The amount of condensation (1–2 g/m^3) was smaller than that in the dry season. The decrease in Y was small on the grassland as well. The saturation deficit (Ed: hPa) was smaller than 10 hPa at both 10 cm (Edl) and 150 cm (Edh) at the forest in the dry season (Edl > Edh). But on the grassland, Es was 20 hPa at the minimum and reached about 60 hPa at the maximum. In the rainy season, Ed was smaller than 5 hPa at the forest. During most days, Ed was zero, meaning evaporation did not occur. At the grassland, Ed varied from 7 to 30 hPa or even more.

On the grassland where enough fetch was secured, the distribution of net radiation (Rn) to soil heat (G), sensible heat (S), and latent heat (lE) fluxes was estimated, using the bowen ratio. On sunny days in the dry season, Rn reached 600–700 W/m^2. The lE peaked before noon (150–300 W/m^2), and S and G peaked in the afternoon (S: 200–400 W/m^2, G: 200–300 W/m^2). G became negative in nighttime. The heat release was the largest at sunset (50 W/m^2). Then, it became smaller until sunrise. Rn was also negative until midnight, but went close to zero at dawn. On the following day of rainfall, lE had the largest share, and G was the next. S was smaller than half of G. Even in the rainy season, the peak of Rn sometimes showed similar values to those in the dry season, but the time was temporary. There was a day when lE surpassed 500 W/m^2. When it rained, G was negative even in the daytime. Rn in the forest was dependent on sun flecks; it temporarily reached 400 W/m^2 in the dry season, but was smaller than a few dozens of W/m^2 in the rainy season. G was also a few to a few dozens of W/m^2.

The average and standard deviation (SD) of Tl, Hl, Yl, Edl, SWd, SWu, LWd, LWu, Rn, and G are shown in Table 1. Data for the initial and final days of each measurement were excluded to obtain 24-hour statistics. Tl was the largest (29.5℃) from September 7–11 (grassland, dry season), and the lowest (24.5℃) from March 3–6 (forest, rainy season). In both seasons, the diurnal fluctuation was large on the grassland, but it was as small as 1℃ in the forest. Hl was the largest (100%) in the forest in both seasons, the next largest was on the grassland in the rainy season (91.6±13.7%), but it was small in dry season (85.4±20.1 and 76.8±24.3%). No large difference was found in Yl among the sites and the periods. Edl was the largest on the grassland in the dry season (14.5 and 7.8 hPa), and the next largest was on the grassland in the rainy season (4.4 hPa). In the forest it was almost zero in both seasons. There was a large difference in SWd. In the dry season, it was 186 and 242 W/m^2 on the grassland, while it was 11 and 24 W/m^2 in the forest. A large difference was found in the rainy season, too (173 W/m^2: grassland, 6 W/m^2: forest). The |SWu| was larger on the grassland than in the forest. LWd was larger in the forest than on the grassland, while the relationship of |LWu| was in reverse. The LWd−|LWu| was negative in all cases. The heat release was large on the grassland in the dry season (−39 and −51 W/m^2), but was reduced to −21 W/m^2 in the rainy season. In the forest it was −2 and −11 W/m^2 for the dry season, and −1 W/m^2 for the rainy season. Rn and G were larger on the grassland than in the forest. The SD of Rn and G characterized the difference between the forest floor and open space. The sky-view factor was 19.7±2.4% at the forest, while it was 100% at the grassland.

The CO_2 concentration above the soil surface (AC) decreased in the daytime due to photosynthesis, and increased at night due to respiration of plants, including soil respiration, however, the increase dulled when it rained at night because the emission from the soil surface was disrupted. Figure 3 shows the normalized atmospheric CO_2 anomaly calculated from (AC-average)/SD. At dawn of August 26 on which a shower was observed, the normalized anomaly was smaller than zero, and both ACl (10 cm) and ACh (150 cm) remained around the 400 ppm level. At the grassland, they reached 700–800 ppm on sunny days. However, they were suppressed to about 500 ppm, and the anomaly was around zero on the mornings following showers on August 31 and September 1. Even during the rainy season, showers at night and dawn maintained the concentration at the 300 ppm level. The concentration was higher in the dry season than in the rainy season both at day and night, and the difference was clear on the grassland. The height difference was ACl<ACh in the daytime and ACl>ACh at night, which was clear at the grassland in the dry season (÷20 ppm), but was smaller in the rainy season, and no difference was observed on rainy days.

Soil moisture, soil temperature, and soil CO_2 in shallow soil

In the forest in the dry season, layers with a high and low soil moisture (SM) appeared by

Table 1. Daily averages and standard deviations of microclimatic parameters

Tl, Hl, Yl, and Edl are the values at 10 cm above the soil surface. Negative values mean that radiations were emitted upward.

	Forest		Forest		Grassland		Grassland		Forest		Forest		Grassland	
	Dry season Aug. 15–18, 2003		Dry season Aug. 22–26, 2003		Dry season Aug. 30–Sep. 3, 2003		Dry season Sep. 7–11, 2003		Rainy season Mar. 3–6, 2004		Rainy season Mar. 10–13, 2004		Rainy season Mar. 17–20, 2004	
	Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD
Tl (℃)	24.8	1.7	25.4	1.9	26.8	5.3	29.5	6.8	24.5	1.3	25.2	1.2	26.8	4.1
Hl (%)	100.0	0.0	100.0	0.0	85.4	20.1	76.8	24.3	100.0	0.0	100.0	0.0	91.6	13.7
Yl (g/m^3)	22.9	2.3	23.7	2.6	21.0	2.0	21.3	2.0	22.3	1.7	23.1	1.6	23.0	1.9
Edl (hPa)	0.0	0.0	0.0	0.0	7.8	11.6	14.5	17.8	0.3	0.1	0.3	0.0	4.4	8.1
SWd (W/m^2)	10.8	20.4	24.4	63.9	186.0	256.7	241.7	317.2	5.7	9.1	6.7	10.2	173.3	264.8
SWu (W/m^2)	−3.1	5.2	−3.8	7.3	−17.2	40.1	−22.9	52.0	−0.7	2.3	−1.3	2.7	−26.3	38.4
LWd (W/m^2)	443.2	15.9	439.3	18.0	425.1	16.2	429.9	20.3	438.7	9.5	442.7	10.2	435.8	14.3
LWu (W/m^2)	−445.1	12.7	−450.4	13.9	−463.9	36.2	−480.7	48.5	−440.2	7.8	−443.7	7.7	−456.9	25.1
Rn (W/m^2)	5.7	19.1	9.5	62.2	130.0	197.1	168.0	243.2	3.6	8.5	4.4	10.0	125.9	214.4
G (W/m^2)	−1.3	10.4	0.9	11.9	29.6	90.0	28.9	87.3	−3.6	11.9	−2.4	10.0	19.7	81.7

Tl: air temperature, Hl: relative humidity, Yl: absolute humidity, Edl: saturation deficit (up to here, 10 cm above the soil surface), SWd: downward shortwave radiation, SWu: upward shortwave radiation, LWd: downward longwave radiation, LWu: upward longwave radiation, Rn: net radiation, G: soil heat flux.

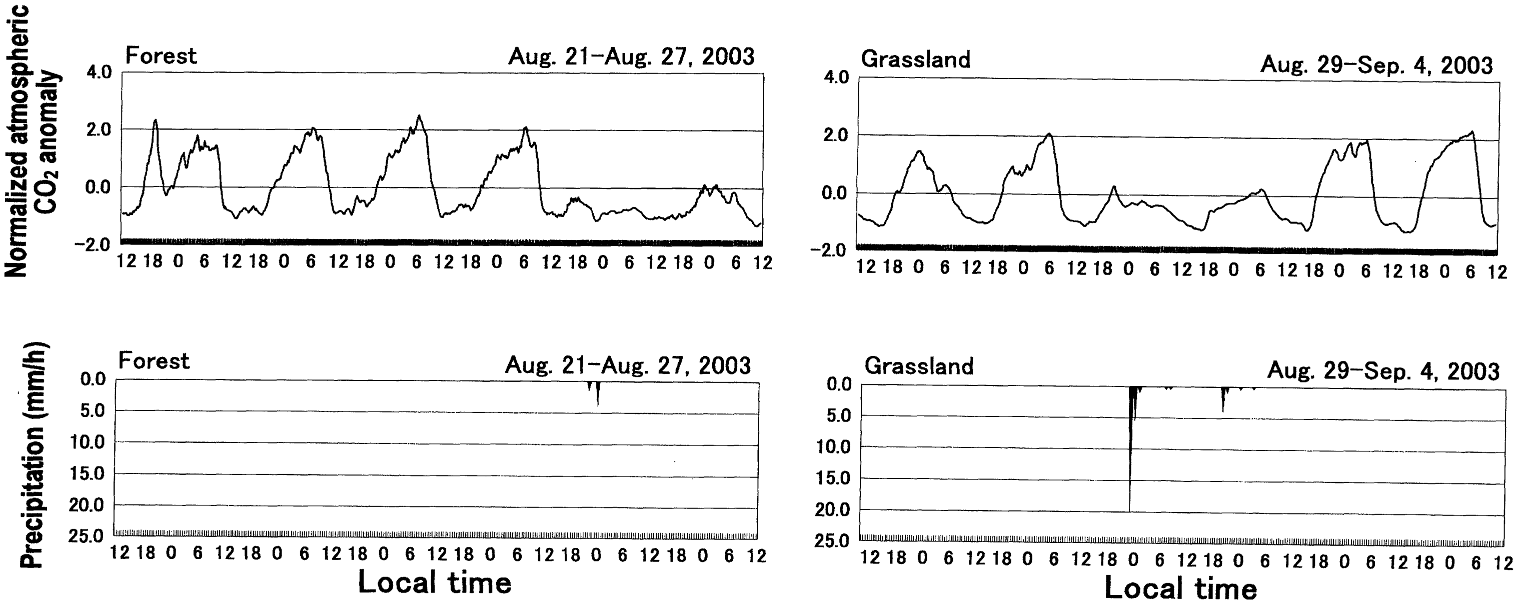

Figure 3. An example of normalized atmospheric CO_2 anomaly and hourly precipitation in the forest and grassland.

Table 2. Daily averages and standard deviations of soil moisture (SM), soil temperature (ST), and soil CO_2 concentration (SC) at 10 cm, 30 cm, 50 cm, and 100 cm below the soil surface

	Forest		Forest		Grassland		Grassland		Forest		Forest		Grassland	
	Dry season Aug. 15–18, 2003		Dry season Aug. 22–26, 2003		Dry season Aug. 30–Sep. 3, 2003		Dry season Sep. 7–11, 2003		Rainy season Mar. 3–6, 2004		Rainy season Mar. 10–13, 2004		Rainy season Mar. 17–20, 2004	
	Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD
SM10 (m^3/m^3)	0.30	0.01	0.29	0.00	0.36	0.01	0.31	0.00	0.32	0.01	0.31	0.01	0.40	0.02
SM30 (m^3/m^3)	0.23	0.01	0.23	0.00	0.33	0.00	0.32	0.00	0.36	0.01	0.36	0.00	0.31	0.00
SM50 (m^3/m^3)	0.28	0.01	0.28	0.00	0.32	0.00	0.32	0.00	0.35	0.01	0.35	0.00	0.37	0.00
SM100 (m^3/m^3)	0.19	0.00	0.19	0.00	0.22	0.00	0.22	0.00	0.30	0.04	0.29	0.01	0.25	0.01
ST10 (℃)	25.1	0.5	25.9	0.4	28.2	1.7	31.1	2.0	25.1	0.5	25.5	0.2	27.6	1.0
ST30 (℃)	25.2	0.1	25.7	0.2	28.2	0.5	30.2	0.4	25.4	0.1	25.7	0.1	27.7	0.6
ST50 (℃)	25.1	0.0	25.4	0.1	28.4	0.3	29.3	0.2	–	–	–	–	–	–
ST100 (℃)	25.3	0.1	25.4	0.0	28.7	0.1	28.7	0.1	–	–	–	–	–	–
SC10 (ppm)	7,587	1,292	12,106	1,327	2,398	982	1,499	281	10,534	4,668	23,914	1,370	22,766	1,671
SC30 (ppm)	7,871	3,431	17,663	492	3,372	1,281	3,023	924	18,947	3,844	26,473	1,629	28,687	2,355
SC50 (ppm)	10,720	2,520	–	–	6,262	2,496	7,227	1,416	–	–	35,590	2,501	30,771	880
SC100 (ppm)	21,015	1,611	–	–	18,777	685	19,647	466	–	–	49,884	2,496	–	–

SM: soil moisture, ST: soil temperature, SC: soil CO_2 concentration. The number (10, 30, 50, and 100) indicates the depth (cm) below the soil surface.

turns among four depths from 10 to 100 cm (Table 2): the profile was SM10 (0.28–0.30 m^3/m^3) > SM50 (0.26–0.29 m^3/m^3) > SM30 (0.21–0.23 m^3/m^3) > SM100 (0.18 m^3/m^3). SM10 increased about 0.10 m^3/m^3 soon after a heavy rain (32.0 mm) in the evening on August 15, then it stabilized at a higher level than before the rain. One to two hours' time difference was found in the peak between SM10 and SM100. When it rained less, such as 10.5 mm during the night of August 18, and 5.5 mm from August 25–26, SM10 and SM30 rose a little; then SM50 reacted later, but SM100 did not increase. SM on the grassland was higher than in the forest, and the profile from August 29 to September 4 was SM10 (0.35–0.36) > SM30 (0.33–0.34) > SM 50 (0.32–0.33) > SM100 (≒0.22). As for the showers during the nights of August 31 (26.5 mm) and September 1 (6.0 mm), SM jumped up at shallow depths, but the reaction of SM100 was negligible. Because sunny days continued thereafter, the difference between SM30 and SM50 reduced, and SM10 also decreased to the same value (0.31 m^3/m^3) in the next week. SM 100 was a further 0.10 m^3/m^3 lower than at the other three depths. SM greatly changed with rainfall at both sites in the rainy season. In the forest, increases occurred on March 3, 4, 5, and 6. Remarkable increases and decreases were observed at all depths on March 5 when the rainfall amounted to 18.5 mm. Similar changes were observed on March 12 with a rainfall of 11.5 mm. The vertical profile was SM30 ≒ SM 50 (0.35–0.39) > SM 10 (0.30–0.38) > SM 100 (0.28–0.31), which was high in medium layers. On the grassland, it rained everyday, and SM10 sensitively reacted. It was common to the former cases that the reaction became dull and had a time lag in deep soils. The vertical profile was SM10 (0.35–0.42) > SM50 (0.36–0.40) > SM30 (0.30–0.32) > SM100 (≒0.25). Between the seasons, SM was higher in the rainy season, and between the sites, it was higher at the grassland than in the forest.

Soil temperatures (ST) at four depths changed from 24 to 27℃ in the forest in the dry season. ST10 had a diurnal fluctuation (<2℃); it reached the maximums between 18 : 00 and 21 : 00, and reached the minimums at around 9 : 00. No diurnal fluctuation was found in ST 30, ST50, and ST100. ST10 rapidly decreased when it rained, such as on August 15 and August 25–26. The diurnal fluctuation was found to a depth of 30 cm on the grassland, and was larger than in the forest. ST10 reached 30–35℃ at around 17 : 00, and decreased to 25.5–28.5℃ at around 8 : 00, while the peak of ST30 reached 28–31℃ at midnight, and the bottom was 27.5–30℃ at noon. ST10, ST30, and ST50 decreased when it rained at night on August 31, and the decrease was larger in shallow soil. ST 100 kept a constant value (28.7±0.1℃). In the rainy season, data were collected at 10 and 30 cm only. The average was around the 25℃ level in the forest, which was similar to that in the dry season. A diurnal fluctuation was found only in ST10. The range was less than 1℃. The diurnal fluctuation appeared in both ST10 and ST30 on the grassland. The range was smaller than during dry season (ST10: 1–4℃, ST30: 1–2℃) but was more noticeable than in the forest. The range greatly fluctuated depending on whether there were showers or not.

Soil CO_2 concentration at a depth of 10 cm (SC10) was about 5,000 ppm in the forest when measurements started on August 14, but it increased to the 9,000 ppm level after a squall the next evening (Figure 4). In contrast, SC30 and SC50 decreased at that time. Even though the squall stopped, SC50 kept decreasing gradually, and SC100 repeatedly edged upward and downward. Before the squall, the vertical profile was SC 10 < SC 30 < SC 50 < SC 100, but it turned to SC10 ≒ SC30 ≒ SC50 (9,000 ppm) < SC 100 (20,000 ppm) a day after the squall. In a squall on August 18, SC10 increased 2,000 ppm, and at the other three depths there were increases of about 4,000 ppm. With a shower on August 25–26, SC10 increased about 4,000 ppm, and SC30 also increased a little. SC50 and SC100 could not be measured because the concentrations exceeded the range of the sensors, meaning that they were higher than 30,000 ppm. The vertical profile on the grassland was similar to that of the forest, but in shallow soil the concentration was lower than that in the forest: SC10 fluctuated from 1,000 to 2,000 ppm, and SC30 did so from 2,000 to 4,500 ppm. The peak appeared in nighttime, and the bottom appeared in daytime. However, SC50 had a reverse pat-

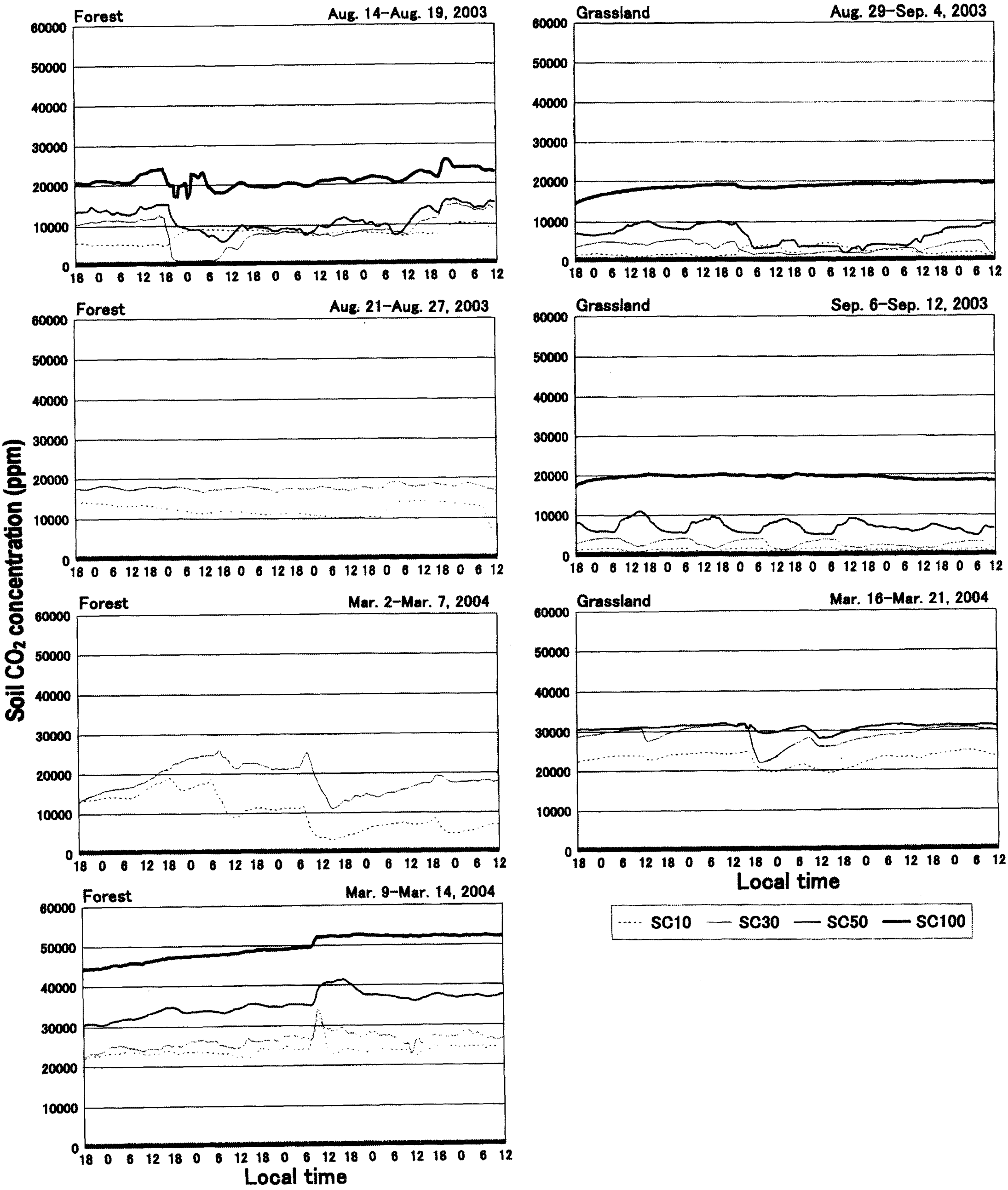

Figure 4. Diurnal changes in soil CO_2 concentration (SC) at the depths of 10, 30, 50, and 100 cm.

tern: it increased in the daytime (9,000–10,000), and decreased at nigh (5,000–8,000), and SC100 did not have a diurnal change (19,000–20,000). As SC10 and SC30 increased at night, SC50 decreased: both of the variations seemed to wipe each other out. But this pattern was not found during rainy nights. In the forest in the rainy season (March 2–7), both SC10 and SC30 reacted in the same phase to a long spell of rain, which increased together with rains, then decreased, and gradually increased. SC50 and SC 100 were over the range of the sensors (>30,000 ppm). With rain on March 12 in the next week as well, the increase and decrease synchronized between SC10 (increase from 24,000 to 33,000 and decrease to 23,000 ppm) and SC30 (increase from 26,000 to 35,000 and decrease to 29,000 ppm). However, it took half a day for SC50 to increase from 35,000 to 41,000 and to decrease to 38,000 ppm, and SC 100 did not decrease from 52,000 ppm after it increased from 50,000 ppm. It rained everyday on the grassland during the next week. SC10 and SC30 repeated its increasing and decreasing with the rainfall events. SC100 was estimated to be higher than 75,000 ppm because the concentration exceeded the range of the sensor.

Discussion

Soil pores are composed of water and air masses, which are in contact with soil particles, and the masses compete with each other for space when they move upward and downward in the processes of infiltration and evaporation. Changes in physical properties within soil pores in infiltration, and the existence of zero flux plane in the process of evaporation, have been investigated so far, and the kinetic equations to show the simultaneous flow of water, gas, solute, and heat have been already established (Kayane 1980; Kitaya and Yabuki 1987; Collin and Rasmuson 1988; Nakano 1991; Rolston et al. 1991; Zak et al. 1999). Gas flux is calculated from a product between the gas diffusivity and the vertical difference of concentration by means of Fick's Law. Davidson and Trumbore (1995) measured the bulk density (BD) and particle density (PD) of soil as well as the soil CO_2 concentration at each depth, and calculated the flux, using the effective diffusivity estimated from the air-filled porosity (ε–w); the difference between the porosity ($\varepsilon = 1-\mathrm{BD}/\mathrm{PD}$) and water-filled porosity (w = soil moisture). However, the parameters were measured once in the dry and rainy seasons. In our study, the CO_2 flux could not be calculated because the bulk and particle densities concerned in the porosity were not measured, but the sequential data of soil moisture and soil CO_2 concentration of a few weeks were gathered. Figure 5 shows the 10-minute soil CO_2 concentration changes (SCC) and 30-minute soil moisture changes (SMC) before and after rainfall measured in the forest. In the case of March 5, as rainfall infiltrated into the soil, SMC at a depth of 10 cm changed to positive, then the change shifted in deep layers from SMC30 to SMC100. After the infiltration, SMC became negative. SCC was almost synchronized with SMC: in shallow soil it became positive with infiltration, then the positive zone seemed to shift in deep places although SCC50 and SCC100 were not available. A series of these changes imply that water infiltrated from soil surface, pressed the CO_2 gas in the pores and made the concentration increase temporarily, but the shielding was cancelled as the water moved down, and the concentration returned to the value at which it used to be. The peak of rainfall was 10 mm at 7 : 00, and the infiltration seems to have reached 1 m deep at 10 : 00. SCC became negative at 8 : 00, and the change stopped at 15 : 00. Changes in SMC and SCC showed a similar pattern on March 12, too. When the rainfall started at 8 : 00, SMC changed into positive from SMC10 to SMC100 in turn, and then changed into negative after 10 : 00. SCC also became positive with infiltration, and then changed into negative. It gradually stabilized around zero by 13 : 00. As explained above, when the percentage of liquid content increases at the arrival of infiltration, the CO_2 concentration just below the layer temporarily increases but it returns to the former state after the infiltration passes through the layer. This shielding effect was found at both sites, during all seasons, and whenever it rained. Davidson et al. (2000), who measured soil respiration before and after rainfall by means of the closed chamber method, reported that the flux increased when it rained. This is contrary to Figure 5. The reason is that the CO_2 gas, which was shielded by infiltrated water out of the chamber, horizontally moved to the chamber where raindrops did not enter inside, and was emitted to the space. Figure 5 suggests that soil respiration is suppressed when raindrops cover the soil surface. The atmospheric CO_2 just above the soil surface did not rise at dawn when it rained in nighttime as shown in Figure 3. It was before the photosynthesis started. Accordingly, the cause should be the suppression of soil CO_2 release by infiltration.

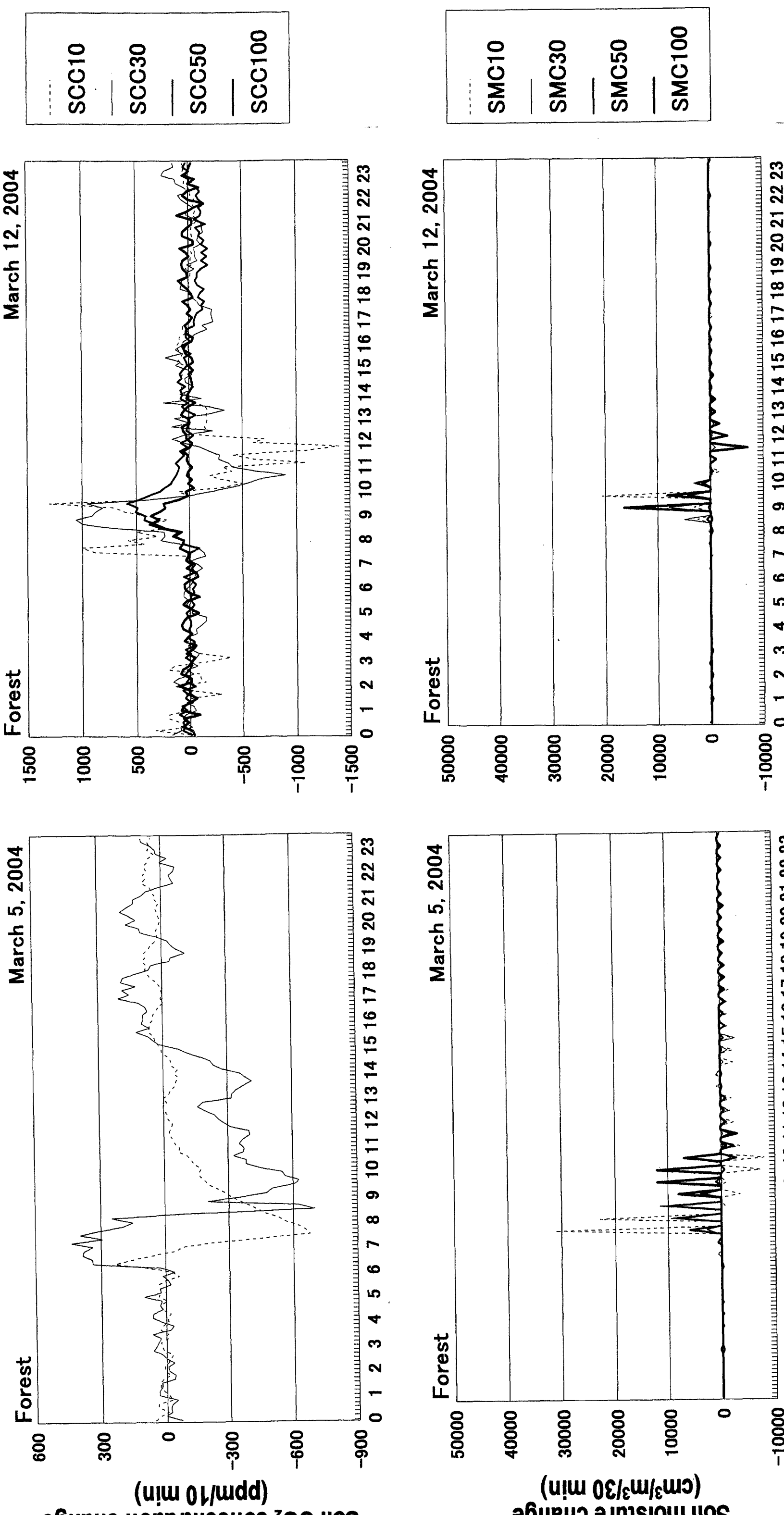

Figure 5. The 10-minute soil CO$_2$ concentration changes (SCC: ppm/10 min) and 30-minute soil moisture changes (SMC: cm^3/m^3/30 min) before and after rainfall.

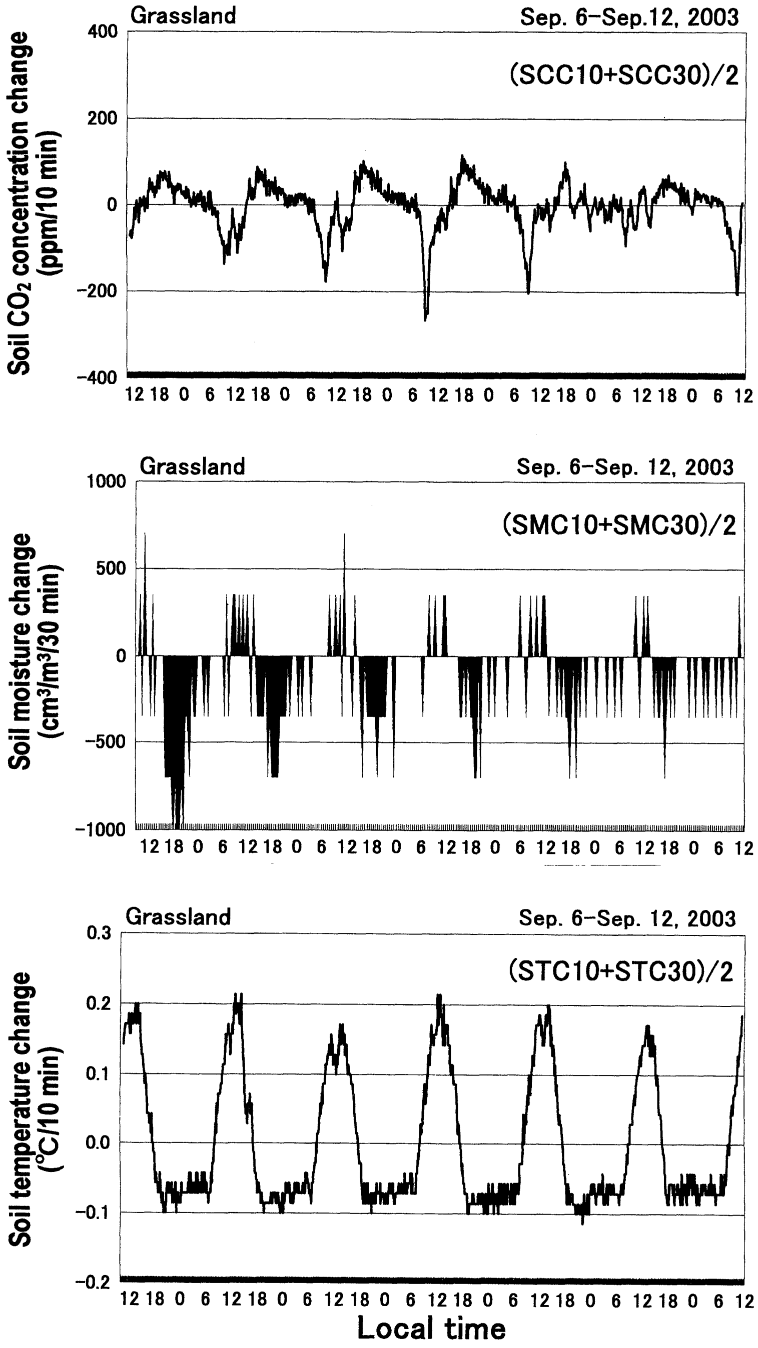

Figure 6. The 10-minute changes in SCC, SMC, and soil temperature (STC) calculated from the average between 10 and 30 cm of depth at the grassland without rainfall.

The 10-minute changes in SCC, SMC, and soil temperature (STC) calculated from the average between 10 and 30 cm deep at the grassland during September 6–12 are shown in Figure 6. No rainfall was observed in this period. SCC was negative from 9 : 00 to 15 : 00, then changed into positive by the next morning. SMC was opposite: it was positive from 9 : 00 to 15 : 00, then changed into negative. STC also repeated the same fluctuation as SMC. This relationship was not found at the depths of 50 cm and 1 m. Also, this relationship was not found on rainy days. Further, the relationship was not found in the forest in either dry or rainy seasons. From these circumstances, it is thought that in the daytime when the soil temperature of shallow soil increased and soil moisture moved toward the soil surface by evaporation, the position of CO_2 gas moved relatively downward, and when the soil temperature started decreasing in the evening, evaporation stopped and CO_2 gas moved upward. The driving force of soil temperature change is solar radiation. The radiation is stocked in soil in the daytime as soil heat flux, and it is released at night as radiative cooling. This input and output of energy generates the diurnal fluctuation of soil temperature, and it changes the relative position of soil moisture and CO_2 gas between day and night. Consequently, the concentration in shallow soil is high at night following sunny days, meaning that the gas is quickly discharged into the atmosphere. A definitive difference between the grassland and forest is this diurnal fluctuation of microclimatic parameters (Table 1). The fluctuation is not formed at the forest depending on sun flecks only. Hashimoto et al. (2004) did not refer to the diurnal fluctuation because they used a manually-operated chemical reaction in measuring the concentration. The method of Davidson and Trumbore (1995) is also not based on an automatic measurement. In this meaning, the new sensor used in our study was successful in comparing the soil CO_2 concentration to other parameters with respect to infiltration and evaporation in the same interval.

Some researchers point out the role of soil invertebrates and microbial organisms (decomposition); Tapia et al. (1999) described the invertebrates in the litter layers of an abandoned pasture, and Chambers et al. (2000) investigated the role upon fallen trees. Other researchers estimated the number of individuals, such as collembola, acari, and formica, to be 20,000 to 60,000/m^2 to the 5 cm depth from the soil surface (Adis 1988; Bandeira and Torres 1985; 1988; Macambira 1997), under the assumption that the role of invertebrates is larger than that of micro-organisms in the Amazonia. However, there is no report about the activities and biomass in the oxisols below the humus layers. There is no doubt that such organisms play an important role in the production of CO_2 in soil. Biological aspects will have to be researched more, as will physical phenomena which have been addressed up to the present.

The average CO_2 concentration at between 10 and 30 cm, measured in the present study, was 11,307±1,63ppm in the forest in the dry season, and 19,967±2,878ppm in the rainy season; that on the grassland in the dry season was 2,573±867ppm, and that in the rainy season was 25,727±2,013ppm. These are the values of only one or two weeks, but the high average in the rainy season agrees with the results from Hashimoto et al. (2004) and Davidson and Trumbore (1995). The seasonal difference is 10 times greater on the grassland, while it is about 1.8 times higher at the forest. The cause of the large difference on the grassland is thought to be that the soil CO_2 was released into the atmosphere as a result of physical or biological processes: for example, perhaps the root respiration stopped due to withering in dry season, or the gas moved to even deeper places. It is understandable that a high concentration is accumulated in deep soils due to a spell of rain. In fact, the concentration was over 30,000ppm at 50 cm of depth on the grassland in the rainy season, and it was over 75,000ppm at 1 m of depth as it exceeded the range of the sensor. But in the dry season it was stable around 20,000ppm at a depth of 1 m. Further, an inverse phase was found between 10–30 cm and 50 cm during day and night. Therefore, it is hard to imagine that the decrease occurred as the CO_2 moved downward. The result from Davidson and Trumbore (1995) also showed that the seasonal difference became smaller at a few meters of depth both in a primary forest and on pasture. In our study, the concentration at 10–30 cm under the surface at the grassland is 23% of that in the forest in the dry season. If this difference occurred with the emission into the atmosphere and the withering of plants, it might have been caused by the disappearance of forest canopy and the accompanying changes in microclimatic parameters.

Conclusions

In the present study, soil CO_2 concentration and microclimatic parameters were compared in a primary forest and grassland in the dry season and the rainy season in central Amazonia. Soil CO_2 temporarily increased with infiltration, and decreased after soil water descended downward. Then, the increase and decrease moved to deeper soil. On the grassland in the dry season, the soil moisture change was positive during the daytime, while the soil CO_2 concentration change was negative. During the nighttime, in contrast, the soil moisture change was negative and the concentration change was positive. It was estimated that the fluctuation of radiation between day and night reversed the relative position of soil water and CO_2 in soil. In the rainy season, there was not a large difference in the surface soil concentration between the sites, while in the dry season the concentration on the grassland was quite small. These findings suggest that the decrease in soil CO_2 was brought about by the disappearance of forest canopy, although there are still uncertainties concerning the activities of invertebrates and microbial organisms.

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