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# Effect of land use change from paddy rice cultivation to upland crop cultivation on soil carbon budget of a cropland in Japan

(Running title: Carbon Budget in a Cropland with Paddy-Upland Crop Rotation)

Authors:

Seiichi Nishimura, Seiichiro Yonemura, Takuji Sawamoto*, Yasuhito Shirato, Hiroko Akiyama, Shigeto Sudo, and Kazuyuki Yagi

Affiliations:

National Institute for Agro-Environmental Sciences, 3-1-3 Kannondai, Tsukuba, Ibaraki 305-8604, Japan

*Present Address: Rakuno Gakuen University, 582 Midori-cho, Bunkyodai, Ebetsu, Hokkaido 069-8501, Japan

Correspondence:

S. Nishimura: National Institute for Agro-Environmental Sciences, 3-1-3 Kannondai, Tsukuba, Ibaraki 305-8604, Japan.

Phone: +81-29-838-8231, Fax: +81-29-838-8199

E-mail: ssnn@niaes.affrc.go.jp

**Abstract**

Effect of land use change from paddy rice cultivation to upland crop cultivation on soil carbon budget (SCB) was studied by comparing three types of cropping system (single cropping of paddy rice (PR), single cropping of upland rice (UR) and double cropping of soybean and wheat (SW)) in an experimental field having the same history as consecutively cultivated paddy rice fields. The carbon dioxide ($CO_2$) and methane ($CH_4$) fluxes from the fields were measured continuously over two and a half years with an automated flux monitoring system. Atmospheric $CO_2$ was significantly absorbed during the growth periods of different crops, including all the summer crops and winter wheat. The amounts of absorbed $CO_2$ during the summer crop growth period were highest in the PR plots and lowest in the UR plots. On the other hand, $CO_2$ emission was observed during the fallow period. In addition, a significantly high peak and the subsequent gradual decrease in $CO_2$ emission were observed after plowing the fields in autumn. Significant $CH_4$ emission was found in only the PR plots during the submerged period. With consideration of gas flux data and the amount of carbon supplied and removed by agricultural management practices such as straw incorporation and crop harvest, the SCB in the croplands was estimated. The soil carbon budgets of the PR plots were positive (79 to 137 g C $m^{-2}$ $y^{-1}$), which indicates the accumulation of carbon in the soil. On the other hand, those of the UR and SW plots were negative (-343 to -275 g C $m^{-2}$ $y^{-1}$ and -361 to -256 g C $m^{-2}$ $season^{-1}$, respectively), which indicates significant carbon loss from the soil. The contribution of $CH_4$ emission to SCB was small compared with that of $CO_2$ dynamics. Significant differences in the carbon content of the top soil between the plots were also found after the experiment, consistent with the above SCB result. The results indicate that land use change from paddy rice cultivation to upland crop cultivation causes significant loss of carbon from cropland soil.

Key words:
Net ecosystem exchange; Paddy-upland crop rotation; Soil carbon budget

## 1. Introduction

Soil in croplands acts as a large reservoir of atmospheric carbon dioxide ($CO_2$) and methane ($CH_4$) which are major greenhouse gases (e.g., Eswaran et al., 1993). Carbon in soil organic matter also helps maintaining soil fertility for sustainable crop production. Therefore, studies on soil carbon budget (SCB) in croplands are required from the viewpoints of emissions of greenhouse gases ($CO_2$ and $CH_4$) and soil fertility. In croplands, carbon is supplied to the soil as root exudates, dead roots and stubble of the crops. Some other additional carbon is also supplied by organic matter incorporation. At the same time, carbon in the soil is lost such as by gaseous emissions of $CO_2$ and $CH_4$ and by leaching to the underground as dissolved organic and inorganic carbon in the leachate. Soil carbon budget can be estimated by integrating the amounts of these net carbon supply and removal. It can also be estimated by investigating change of carbon content in the top soil, although it is difficult to take possible carbon accumulation or loss in the deeper soil layer into account by this method.

Soil carbon budget has been estimated by these methods in many previous studies in fields of various upland crop and vegetable cultivation systems. The estimated SCBs in the previous studies were highly variable. Some studies have shown significant carbon loss from soil with upland crop cultivation in Japan (Koizumi et al., 1993, Koizumi, 2001, Hu et al., 2004). On the other hand, other studies have shown that the SCB was near zero, which indicates that the carbon content of the soil was kept stable (Robertson et al., 2000), or that there was significant carbon accumulation (Hollinger et al., 2005, Nouchi and Yonemura, 2005). The reasons for such wide range of the estimated SCB have been remained uncertain.

The dynamics of carbon in paddy fields significantly differs from that in fields with upland crop cultivation in which aerobic decomposition process is dominant.

During the submerged period of paddy rice cultivation, $CO_2$ production in the soil is severely restricted under anaerobic condition. Instead, $CH_4$ is actively produced in the soil and emitted to the atmosphere mainly through the rice plants. The processes of carbon dynamics in submerged paddy soil have been investigated in the previous studies. For example, Kimura et al. (2004) recently summarized a review paper in which individual anaerobic decomposition processes of plant residue and soil organic matter, and the fates of photosynthesized carbon of rice in the soil were described. Studies on the $CH_4$ emission have also been intensively conducted including many field experiments (e.g., Sass et al., 1992, Yagi et al., 1996, Corton et al., 2000, Wang et al., 2000, Wassmann et al., 2000, Yu et al., 2004) and regional-scale estimations with mathematical models (e.g., Mitra et al., 2002, Park and Yun, 2002, Liu and Wu, 2004). However, studies on comprehensive carbon dynamics are limited in paddy fields. In particular, studies on the $CO_2$ flux on the flood water surface are limited (Kimura et al., 2004), with only a few reported (e.g., Koizumi, 2001, Usui et al., 2003). Therefore, SCB in paddy fields has not been sufficiently clarified to date.

In Japan and other Asian countries, consecutive paddy rice cultivation has been conducted for long years. In addition, nowadays, the crop rotation of paddy rice and upland crop cultivation is also widely conducted, and various upland crops, particularly cereal crops, are cultivated in drained paddy fields (The Ministry of Agriculture, Forestry and Fisheries of Japan, 2003). Since drainage of paddy fields for upland crop cultivation may cause significant loss of soil carbon according to the enhancement of aerobic soil organic matter decomposition (Mitsuchi, 1974), studies comparing SCBs in fields with consecutive paddy rice cultivation and those with paddy-upland crop rotation are required. However, there have been little or no studies, to the best of our knowledge, of the comparison of SCB between in fields with consecutive paddy rice cultivation and those with paddy-upland crop rotation in the fields with the same cultivation history.

The objectives of this study are, 1) quantitative estimation of SCBs, and 2) comparison of SCBs in the fields with consecutive paddy rice cultivation and in those with paddy-upland crop rotation. We conducted three different crop cultivations, i.e., single cropping of paddy rice, single cropping of upland rice and double cropping of soybean and wheat, in an experimental field that had the same cultivation history as consecutively cultivated paddy rice fields. Both $CO_2$ and $CH_4$ fluxes from the fields were measured simultaneously 6 times per day with an automated closed chamber system (Nishimura et al., 2005). The amounts of carbon removed as the harvested crop and supplied as the straw incorporation were also investigated. Based on the integration of these data, we estimated SCB, compared it among the three cropping systems, and discussed the effect of land use change from paddy rice cultivation to upland crop cultivation on SCB.

## 2. Materials and methods

### *2.1. Outline of the experimental field and crop cultivation*

The experiment was conducted for two and a half years from 2002 to 2004 in field at the National Institute for Agro-Environmental Sciences (NIAES) (36˚01'N, 140˚07'E), Japan. The field had six lysimeters, each of 9 $m^2$ (3 m × 3 m) cross-sectional area and 1.0 m depth. The soil type of the field was Gray lowland soil (Fluvisols). The top soil had the texture of clay loam with clay content of 36%. From the soil core sampling carried out on Apr. 19, 2002, the bulk densities of the soil samples from 0 - 5 and 8 - 13 cm depths were 0.837 and 1.014 g $cm^{-3}$, the soil pH in $H_2O$ was 5.7, and the carbon and nitrogen contents of the top soil were 18.8 mg C g $soil^{-1}$ and 1.6 mg N g $soil^{-1}$, respectively.

Before the experiment, paddy rice had been cultivated in all the plots for approximately consecutive 10 years. Three cropping systems, namely, single cropping of paddy rice (*Oryza sativa* L. cv. Nipponbare), single cropping of upland rice (*Oryza sativa* L. cv. Toyohatamochi), and double cropping of soybean (*Glycine max* (L.) Merrill cv. Enrei) and wheat (*Triticum aestivum* L. cv. Norin-61), were carried out each in two of the lysimeter plots. Urea, fused phosphate and potassium chloride were applied as nitrogen, phosphate and potassium fertilizers, respectively, in all the treatments. The planting densities, fertilization rates, harvested aboveground biomass and the amounts of straw incorporation are summarized in Table 1.

The leaves and stems of the harvested paddy rice, upland rice and wheat plants were dried and incorporated into the soil except for the wheat plants harvested in the spring of 2004. The leaves and stems of the harvested soybean plants were removed (not incorporated).

The outline of the water management of the PR plots during the rice cultivation period was based on Japanese conventional practices of continuous flood irrigation before summer, drainage and subsequent intermittent flood irrigations in summer, and final drainage about 20 days before the rice harvest in autumn.

The water percolation rate of the PR plots was regulated to be about 1 cm day$^{-1}$ using a tubing pump system (Model No. 7553-80, Cole-Parmer, USA) installed at the bottom of the soil layer of the lysimeters. In 2003, the underground drain pipe in one of the PR plots suffered from unexpected choking. Owing to this problem, water percolation rate could not be controlled sufficiently and the first summer drainage was delayed by approximately one month compared with that in 2002.

### *2.2. Measurement of $CO_2$ and $CH_4$ fluxes*

A chamber made with transparent polycarbonate and acrylic plates was placed at the center of each lysimeter plot. The cross-sectional area of a chamber was 0.81 $m^2$ (0.9 m × 0.9 m). The height of the chamber was 0.6 m during the fallow period or when the plants were shorter than 0.6 m. It was changed to 1.2 m with the connection of additional sidewalls when the plants grew taller. During the crop cultivation period, 18 paddy rice, approximately 50 upland rice, 6 soybean and approximately 170 wheat plants were placed in the chamber. The planting densities in the chamber were equal to those outside the chamber. Every ~ 40 minutes, the lids of one of the chamber were closed with pneumatic cylinders, kept closed for about 30 minutes, and then opened again. The chambers were closed for flux measurement separately; therefore, each chamber was closed every 4 hours (6 times per day).

During the closed period, the inside air of the chamber was circulated with a pump at flow rates of 5 - 7 L $min^{-1}$. Part of the circulated air was led to an infrared gas analyzer (LI-6262, LI-COR, USA) at a flow rate of 0.3 L $min^{-1}$ for the measurement of $CO_2$ concentration. $CO_2$ flux was calculated based on the increase/decrease rate of $CO_2$ concentration during the 1 - 3 minute period after the chamber closure. Another part of the circulated air was injected in a gas chromatograph (GC-14B, Shimadzu, Japan) equipped with a flame ionization detector and several switching valves 4 times at 8.5 minute intervals for the measurement of $CH_4$ concentration. $CH_4$ flux was calculated based on the increase/decrease rate of the 4 measured $CH_4$ concentrations. Other details of the flux measurement system are shown in our previous report (Nishimura et al., 2005).

The cumulative $CO_2$ and $CH_4$ fluxes between the flux measurement intervals (= 4 h) were respectively calculated using

$$F_{CO2} = \frac{dC_{CO2}}{dt} \times \frac{1}{A} \times \frac{M_{CO2}PV}{R(T+273)} \times t_i \quad (1)$$

$$F_{CH4} = \frac{dC_{CH4}}{dt} \times \frac{1}{A} \times \frac{M_{CH4}PV}{R(T+273)} \times t_i \quad (2)$$

where $F_{CO2}$ and $F_{CH4}$ are respectively the cumulative $CO_2$ and $CH_4$ fluxes between the flux measurement intervals (g $CO_2$ $m^{-2}$, g $CH_4$ $m^{-2}$), $dC_{CO2}/dt$ and $dC_{CH4}/dt$ are the increase/decrease rates of $CO_2$ and $CH_4$ concentrations (mol $mol^{-1}$ $h^{-1}$), $A$ is the area of the chamber (= 0.81 $m^2$), $M_{CO2}$ and $M_{CH4}$ are the mass numbers of $CO_2$ (= 44) and $CH_4$ (= 16), $P$ is the atmospheric pressure (which was fixed to $1.013 \times 10^5$ N $m^{-2}$), $V$ is the chamber volume ($m^3$), $R$ is the gas constant (= 8.31 J $mol^{-1}$ $K^{-1}$), $T$ is the air temperature (°C) inside the chamber measured with platinum resistance thermometers placed approximately 30 cm above the soil surface, and $t_i$ (= 4 h) is the interval between each flux measurement.

The long-term cumulative $CO_2$ flux may be slightly underestimated if it is calculated by simply integrating the values using equation (1) because of the following reason. When large plants inside the chamber assimilate a high amount of $CO_2$ via photosynthesis under high-solar-radiation condition, $CO_2$ concentration may decrease to the compensation level during the chamber closure period so that photosynthetic $CO_2$ absorption becomes restricted until the chamber opens again. The $CO_2$ compensation level of $C_3$ plants is generally within 30 to 80 μmol $mol^{-1}$ (Jones, 1992). In this experiment, we assumed the following two things. One is that the $CO_2$ concentration inside the chamber changes at constant rate during the chamber closure periods unless it decreases to the $CO_2$ compensation level. The other is that, if the $CO_2$ concentration in the chamber decreases to the $CO_2$ compensation level, no $CO_2$ absorption or emission occurs until the chamber opens again. Based on these assumptions, in the cases that $\frac{dC_{CO2}}{dt} \times t_c < C_{CO2c} - C_{CO2a}$, we applied equation (3) instead of equation (1) to calculate the cumulative $CO_2$ flux between the measurement intervals.

$$F_{CO2} = \frac{dC_{CO2}}{dt} \times \frac{1}{A} \times \frac{M_{CO2}PV}{R(T+273)} \times t_o + (C_{CO2c} - C_{CO2a}) \times \frac{1}{A} \times \frac{M_{CO2}PV}{R(T+273)} \quad (3)$$

Where, $t_c$ (= 0.5 h) and $t_o$ (= 3.5 h) are the durations in which the chamber lids are closed and open, and $C_{CO2c}$ and $C_{CO2a}$ are the $CO_2$ compensation level and atmospheric $CO_2$ concentration, respectively. For this calculation, $C_{CO2c}$ and $C_{CO2a}$ were fixed to $50\times10^{-6}$ and $370\times10^{-6}$ mol mol$^{-1}$, respectively.

There were 44 to 47 days for $CO_2$ and 36 to 41 days for $CH_4$ (different among the plots) with flux data deficit (wholly or partly) during the whole experimental period, due to malfunctions or system maintenances. The $CO_2$ and $CH_4$ flux data of the dates with data deficits were not used for the calculation of cumulative fluxes. Instead, daily cumulative $CO_2$ and $CH_4$ fluxes with data deficits were estimated by linear interpolation using the daily cumulative flux data of the adjacent two dates (i.e., the dates immediately before and after the period with flux data deficits) without flux data deficits.

### *2.3. Estimation of soil carbon budget*

Figure 1 shows the outline of carbon dynamics in cropland ecosystems. In this experiment, net $CO_2$ flux data include both photosynthetic $CO_2$ assimilation and respiratory $CO_2$ emission by plants (crops and weeds) and soil $CO_2$ flux together.

Therefore, SCB was calculated using

$$SCB = -NEE - Me - Yh - Yo + Is + Io \quad (4)$$

where net ecosystem exchange (*NEE*, which corresponds to the cumulative $CO_2$ flux data) is the net amount of carbon emitted to the atmosphere in the form of $CO_2$, *Me* is the carbon emitted to the atmosphere in the form of $CH_4$, *Yh* and *Yo* are the carbon removed by crop harvest and that removed by weeding and thinning, *Is* and *Io* are the carbon supplied to the soil by straw incorporation and that supplied by seed/seedling and chemical fertilizer (urea). For this calculation, values of *Yh* and *Yo* inside the chambers were applied. In this article, carbon accumulation into the soil is designated positive, and carbon loss from the soil negative.

*2.5. Soil analysis*

Soil core samples from 0 - 5 and 8 - 13 cm depths were collected using a 100 $cm^3$ core sampler on Apr. 19, 2002 and Apr. 26, 2004 for the PR and UR plots, and on Apr. 19, 2002 and Jun. 4, 2004 for the SW plots, respectively, with five replicates per one plot. The collected soil samples were air-dried and then passed through a 2 mm sieve. Part of the soil samples was oven-dried for the calculation of soil bulk density. The carbon contents of the soils were analyzed with a nitrogen and carbon analyzer (NC-900, Sumika Chemical Analysis Service, Japan).

The amount of carbon in the plowed soil layer (ca 0 - 15 cm depth) was estimated according to the following procedure. Since the soil bulk density is highly variable spatio-temporally, it should be better to calculate the amount of soil carbon on "identical soil mass" basis rather than that in the fixed soil thickness. In this study, we calculated the amount of soil carbon on identical soil mass basis, as indicated by Ellert and Bettany (1995). For this calculation, we assumed that the carbon contents of the plowed soil layer of 0 - 5 and below 5 cm depths are identical to the measured values of 0 - 5 and 8 - 13 cm depths, respectively, of each soil sample. As the identical soil mass, we used the mean soil mass in the plowed layer calculated by the bulk densities of the soil samples in the spring of 2002, as shown in the following equation (5). Then, the modified soil thickness of which the identical soil mass is included was calculated for each soil sample, as shown in the following equation (6). Based on these data, the amount of carbon on identical soil mass basis was calculated, as shown in the following equation (7).

$$M_{soil,equiv} = 10 \times (5 \times B_{S0-5} + 10 \times B_{S8-13}) = 143.2 = 10 \times \{5 \times B_{0-5} + (D_{mod} - 5) \times B_{8-13}\} \quad (5)$$

$$D_{mod} = 5 + \frac{5 \times B_{S0-5} + 10 \times B_{S8-13} - 5 \times B_{0-5}}{B_{8-13}} = 5 + \frac{14.32 - 5 \times B_{0-5}}{B_{8-13}} \quad (6)$$

$$TC = 10 \times \{5 \times B_{0-5} \times C_{0-5} + (D_{mod} - 5) \times B_{8-13} \times C_{8-13}\} \quad (7)$$

Where, $M_{soil,equiv}$ is the designated identical soil mass (= 143.2 kg soil $m^{-2}$), $B_{0-5}$ and $B_{8-13}$ are the soil bulk densities of 0 - 5 and 8 - 13 cm depths, respectively, of each soil sample (g $cm^{-3}$), $B_{S0-5}$ (= 0.837) and $B_{S8-13}$ (= 1.014) are the mean soil bulk densities of 0 - 5 and 8 - 13 cm depths, respectively, in the spring of 2002 (g $cm^{-3}$), $D_{mod}$ is the modified soil thickness (cm) of which soil mass is identical to $M_{soil,equiv}$, $TC$ is the amount of carbon (g C $m^{-2}$) on the $M_{soil,equiv}$ basis, $C_{0-5}$ and $C_{8-13}$ are the carbon contents of each soil sample of 0 - 5 and 8 - 13 cm depths (mg C g $soil^{-1}$), respectively.

### 2.5. Other soil and plant measurement

Soil temperature was measured with platinum resistance thermometers placed in the soil at 5 cm depth and recorded on a data logger (HR2400, Yokogawa, Japan). Ambient air temperature and precipitation data were obtained hourly from the climate data acquisition station in the NIAES.

The harvested plants were dried for 3 days in an oven at 80 ºC and then their dry weights were measured. The dry weights of the plants removed by thinning and weeding were also measured. The carbon contents of the plants were analyzed with a nitrogen and carbon analyzer (NC-900, Sumika Chemical Analysis Service, Japan).

## 3. Results

### 3.1. Seasonal course of $CO_2$ flux

Figure 2 shows the seasonal courses of $CO_2$ and $CH_4$ fluxes, and climatic data from Jan. 1, 2002 to Jun. 10, 2004. In the UR and SW plots, $CO_2$ fluxes remained positive during the initial one month duration or longer of the crop cultivation period when the cultivated upland plants were still short, which shows that the amount of $CO_2$ assimilated by the plants were still lower than those released through respiration of the plants and soil microorganisms. In the UR plots in the spring of 2003, in particular, a positive $CO_2$ flux remained for more than two months after the sowing of upland rice seeds. In the PR plots, in contrast, $CO_2$ flux became near zero immediately after flooding the fields, which was due to the restriction of soil $CO_2$ emission under submerged condition. Due to the predominance of photosynthetic $CO_2$ assimilation by the cultivated plants, significantly high negative $CO_2$ fluxes were observed in all the plots when the plants grew taller. The amount of absorbed $CO_2$ during the summer crop cultivation period was highest in the PR plots and lowest in the UR plots. In the PR plots, the maximum $CO_2$ absorption rate during the rice cultivation period was 48 g $CO_2$ $m^{-2}$ $d^{-1}$. In the SW plots, the maximum $CO_2$ absorption rate during the wheat cultivation period was 49 g $CO_2$ $m^{-2}$ $d^{-1}$, which was comparable to that in the PR plots in summer. During the late crop cultivation period, i.e., ripening stage, the amount of $CO_2$ absorption gradually decreased and the $CO_2$ fluxes sometimes became positive.

During the fallow period, on the other hand, positive $CO_2$ fluxes were observed in all the plots due to soil $CO_2$ emission. However, during part of the fallow period, (e.g., from March to April, 2004 in the PR and UR plots), a small amount of $CO_2$ absorption was observed. This was probably due to the predominance of photosynthetic $CO_2$ assimilation by arable weeds.

Temporal enhancements and the subsequent gradual decreases in $CO_2$ emission were observed immediately after the crop harvest. Temporal enhancements of $CO_2$ emission were also observed after plowing the fields in autumn. On the other hand, temporal enhancements of $CO_2$ emission were not significant after the plowing in spring.

In the PR and UR plots, significant correlations between $CO_2$ flux and soil temperature were found during the fallow period from autumn to the next spring when no or small weeds/ratoons were growing in the plots (Fig. 3). The relationships apparently changed with plowing with straw incorporation in autumn, but not with plowing without straw incorporation in spring.

### *3.2. Seasonal course of $CH_4$ flux*

In the PR plots, $CH_4$ flux gradually increased during the period with continuous flood irrigation during spring and summer in both 2002 and 2003 (Fig. 2a). Thereafter, $CH_4$ flux decreased rapidly to almost zero within a few days after the first summer drainage of the field. In 2002, the $CH_4$ flux remained to be low after the first summer drainage. In 2003, a significant temporal increase in $CH_4$ flux was observed even after the first summer drainage, around the end of August. The cumulative $CH_4$ emission in the PR plots in 2003 was 5.8 times higher than that in 2002.

In the UR and SW plots, small amounts of $CH_4$ uptake were observed throughout the year, although the values were extremely small.

### *3.3. Crop biomass, cumulative $CO_2$ and $CH_4$ fluxes and soil carbon budget*

The dry weights of the harvested aboveground parts of the plants placed in the chambers ranged between 75% and 120% that placed outside the chambers (Table 1). The differences were possibly due to the changes in environmental factors such as increase in air temperature or decrease in light intensity inside the chambers during the crop growth period, which are generally referred to as "chamber effect".

The cumulative $CO_2$ and $CH_4$ fluxes, the amounts of carbon removed by crop harvest, weeding and thinning, the amounts of carbon supplied by straw incorporation and others, and the estimated SCBs are summarized in Table 2. Cumulative $CO_2$ fluxes were negative in the PR and SW plots, which indicates dominance of photosynthetic carbon absorption. In contrast, they were positive in the UR plots, which indicates dominance of respiratory carbon release by the soil microorganisms.

The cumulative $CH_4$ fluxes were positive in only the PR plots, namely, 2 and 14 g C $m^{-2}$ $y^{-1}$ in 2002 and 2003, respectively. The cumulative $CH_4$ fluxes were negative in the UR and SW plots, although the amounts of carbon as the $CH_4$ uptake were less than 0.1 g C $m^{-2}$ $y^{-1}$ or 0.1 g C $m^{-2}$ $y^{-1}$ $season^{-1}$ in all the cases.

The estimated SCBs in the PR plots were positive, namely, 79 and 137 g C $m^{-2}$ $y^{-1}$ in 2002 and 2003, respectively, which indicates carbon accumulation into the soil. In contrast, the SCBs in the UR plots were negative, namely, -343 and -275 g C $m^{-2}$ $y^{-1}$ in 2002 and 2003, respectively, which indicates carbon loss from the soil. The SCBs in the SW plots were also negative, namely, -361 and -256 g C $m^{-2}$ $season^{-1}$ in the 1st and 2nd cropping cycles, respectively.

### *3.4. Soil carbon content*

The carbon contents of the soil samples from 0 - 5 and 8 - 13 cm depths and the estimated amounts of carbon in the soil of about 0 - 15 cm depth are shown in Table 3. The soil carbon content and the estimated amount of carbon in the soil did not significantly differ between the treatments in the spring of 2002. After the field experiment with two cropping cycles, the difference in the soil carbon content of the top soil (0 - 5 cm depth) became significant among the three cropping systems, with the highest in the PR plots and the lowest in the UR plots. The soil carbon content beneath the top soil (8 - 13 cm depth) also differed, with the highest in the PR plots and the lowest in the SW plots. The amount of carbon in the soil of about 0 - 15 cm depth in the PR plots became higher by 148 and 177 g C $m^{-2}$ than those in the UR and SW plots, respectively.

## 4. Discussion

### *4.1. Seasonal course of $CO_2$ flux*

For the three summer crops, the amount of net $CO_2$ absorption was highest in the PR plots as shown by the largest negative values of NEE (Table 2). This was mainly due to the highest dry matter production by paddy rice (Table 1). In addition, $CO_2$ emission from the soil surface was considered to have been kept in low level during the submerged period due to the restriction of $CO_2$ production under anaerobic soil condition.

During the fallow periods (in the PR and UR plots), positive $CO_2$ flux according to the dominance of soil $CO_2$ emission was observed. Among the various environmental factors, soil temperature was the most major factor which determines soil $CO_2$ flux, as indicated in many previous studies (e.g., Nakadai et al., 1996, Lee et al., 2002). In addition, temporal enhancements of soil $CO_2$ flux immediately after plowing with straw incorporation in autumn were found so that the relationships between soil temperature and $CO_2$ fluxes were significantly changed before and after the plowing practices (Figs 2, 3). Not only the enhancement of the decomposition of dead roots, stubbles and incorporated straw by the soil microorganisms, but also the temporal release of gaseous $CO_2$ in the soil which is referred to as "degassing" from plowed soil, may have significant contribution to the temporal enhancements of soil $CO_2$ emission. In particular, some previous studies mentioned a significant amount of $CO_2$ emission during and immediately after plowing and indicated its close association with degassing (Calderón & Jackson, 2002, Wuest et al., 2003), although its contribution to the cumulative $CO_2$ emission has not been clarified quantitatively. On the other hand, no such significant enhancement of soil $CO_2$ emission was observed after plowing in spring. This indicates the little amount of easily decomposable organic matter remaining and less pronounced accumulation of gaseous $CO_2$ in the soil.

### *4.2. Seasonal course of $CH_4$ flux*

The seasonal course of $CH_4$ flux in the PR plots during the rice cultivation period, i.e., gradual and consecutive increase during the continuously flooded period, and a rapid decrease according to the subsequent drainages, follows those reported in many previous studies (e.g., Sass et al., 1992, Yagi et al., 1996, Corton et al., 2000, Wang et al., 2000, Wassmann et al., 2000). The magnitude of $CH_4$ flux during the continuously flooded period was significantly higher in 2003 than in 2002. This was mainly due to the prolonged continuously flooded period brought about by the delay of the first summer drainage in 2003. In 2003, a temporal increase in $CH_4$ flux was observed even during the summer with intermittent flood irrigations, around late August. In 2002, such increase in $CH_4$ flux was much less distinct during the summer with intermittent flood irrigations. The temporal increase in $CH_4$ flux during the intermittent flood irrigations has been attributed to the flush of gaseous $CH_4$ previously trapped in the soil (e.g., Yagi et al., 1996). In addition to the amount of emitted $CH_4$, the amount of gaseous $CH_4$ trapped in the soil during the continuously flooded period may have also been much higher in 2003 than in 2002, which caused the temporal increase in $CH_4$ emission even after the summer drainage.

In the UR and SW plots, low negative $CH_4$ fluxes were observed throughout the year, which shows $CH_4$ uptake into the soil. The amounts of cumulative $CH_4$ uptake were less than 0.1 g C $m^{-2}$ $y^{-1}$ or 0.1 g C $m^{-2}$ $season^{-1}$ in all the cases. These values were lower than many of those reported in previous studies (Kessavalou et al., 1998, Ball et al., 1999, Yonemura et al., 2000), and than the global mean value suggested by Mosier et al. (1998).

### *4.3. Cumulative $CO_2$ and $CH_4$ fluxes and soil carbon budget*

The annual rates of NEE in the UR plots were positive in both 2002 and 2003. This indicates that the amount of $CO_2$ emission by the decomposition of soil microorganisms was higher than the amount of net $CO_2$ absorption by the upland rice plants. Furthermore, carbon was also removed by the harvest and the loss could not be compensated by only rice straw incorporation. The annual rates of NEE in the SW plots were negative, which indicates net carbon absorption into the ecosystem. However, this did not result in the accumulation of carbon into the soil. The amount of carbon removed by the crop harvest was higher than the absorbed $CO_2$ and therefore the estimated SCB became negative and could not also be compensated by only wheat straw incorporation (Table 2). The amount of carbon supply required for maintaining soil carbon content may be quite high. Huggins et al. (1998) estimated in a cropland with corn cultivation that the value was 560 g C $m^{-2}$ $season^{-1}$. In the report by Nouchi and Yonemura (2005) in which significant carbon accumulation (133 g C $m^{-2}$ $season^{-1}$) into the soil was reported in a field with double cropping of soybean and barley and with no-tillage management, the amount of supplied crop residue was quite high, 744 g C $m^{-2}$ $season^{-1}$.

In Japanese upland croplands, Koizumi (2001) reported that the amount of carbon loss from the soil was within 158 to 314 g C $m^{-2}$ $y^{-1}$ in fields under upland crop cultivation. Another field experiments in upland crop fields under wheat, onion and soybean cultivations in the northern part of Japan also showed significant carbon loss of 147 - 410 g C $m^{-2}$ $y^{-1}$ from the soil (Hu et al., 2004, Mu et al., 2006). Generally, the range of estimated SCBs shown in this study is similar to those in the literature. However, other previous studies showed quite different results, with the SCBs near zero (Robertson et al., 2000) or with significant carbon accumulation into the soil (Hollinger et al., 2005, Nouchi and Yonemura, 2005).

The annual rates of NEE were negative in the PR plots. In contrast to the UR and SW plots, the amount of carbon supplied by the $CO_2$ absorption and rice straw incorporation was higher than that removed by the harvest, therefore the estimated SCB became positive (Table 2), which indicates carbon accumulation into the soil. In the case of paddy fields, Koizumi (2001) reported that the amount of carbon loss from the soil was 21 g C $m^{-2}$, which was not significantly different from zero. According to Koizumi et al. (2001), the amount of $CO_2$ emission from a paddy water surface was much lower than those from the soil surface in upland crop fields due to the submerged anaerobic condition and photosynthetic $CO_2$ absorption by aquatic weeds and algae, which largely contribute in lessening carbon loss from submerged paddy soils. With consideration of results in the literature, the restriction of soil $CO_2$ emission during the periods under submerged conditions may have also played an important role in lessening cumulative $CO_2$ emission from the soil in this study. Another previous field experiment by Minamikawa et al. (2005) showed that the SCB in a Japanese paddy field was a loss of 65 - 106 g C $m^{-2}$ $season^{-1}$. Witt et al. (2000) found an increased amount of soil carbon induced by rice-rice double cropping for two years in a paddy field in the Philippines. Although the SCBs reported in these previous and the present studies vary, the results of these studies suggest that the amount of carbon loss from fields with paddy rice cultivation is relatively low compared with that with upland crop cultivation. However, it may be quite difficult to compare the estimated SCBs in various previous literatures directly because not only the climatic and soil conditions of the experimental fields but also the method for estimating SCB differed among the literatures. In this study, climatic condition, soil origin, crop cultivation history and the method for estimating SCB were the same among the treatments (PR, UR and SW) so that change in the SCB according to the land use change from paddy rice cultivation to upland crop cultivation was explicitly shown to be significant.

As shown in Table 2, the ecosystem exchange of $CO_2$ and supply and removal of carbon by agricultural practices predominantly affected SCB in the PR plots. The contribution of $CH_4$ emissions to SCB in the PR plots was minor. However, from the viewpoint of global warming, the contribution of $CH_4$ emissions becomes much higher since the global warming potential (GWP) of $CH_4$ is 23 times higher than that of $CO_2$ in a time horizon of 100 years (Intergovernmental Panel on Climate Change, 2001).

In addition to the aboveground dynamics of $CO_2$ and $CH_4$, the amount of carbon supplied in inlet water and that released to underground water may also become significant in fields under paddy rice cultivation. According to Koizumi (2001), the amounts were reported to be 33 and 26 g C $m^{-2}$, respectively. Katoh et al. (2004) showed by a soil column experiment that the amount of percolated inorganic carbon was within 75 to 150 g C $m^{-2}$, of which 88% was retained in the subsoil layer. Taking the results of these previous studies into account, the estimated SCB in the PR plots may change by up to approximately 20 g C $m^{-2}$, although this is not too significant to alter the entire discussion of this study. The amount of carbon supply in rainfall is thought to be small, i.e., less than 2 g C $m^{-2}$ $y^{-1}$ (Koizumi, 2001).

In this study, the dry weights of aboveground parts of the crops inside the chambers at the time of harvest ranged from 75% to 120% those recorded from crops outside the chambers, possibly due to the chamber effect (Table 1). These differences may have been a cause of errors in the estimated SCBs, although they seem to be much lower than the differences among the cropping systems (Table 2) and therefore not so significant to alter the entire discussion of this study.

### *4.4. Soil carbon content*

A significant change in the SCB by land use change was also indicated by the analysis of soil carbon content. The amounts of soil carbon of 0 - 15 cm depth in the UR and SW plots became significantly lower than that in the PR plots in the spring of 2004 (Table 3). This also indicates the possible significant carbon loss from the soil according to the land use change from paddy rice cultivation to upland crop cultivation. The differences in soil carbon content between the treatments shown in Table 3 are much lower than those expected by the estimation based on the integration of carbon dynamics shown in Table 2. The carbon content of the soil below 15 cm depth may have also changed with the land use change. VandenBygaart and Kay (2004) reported that the soil carbon of 300 g C $m^{-2}$ was decreased after 18 months by the intensive tillage of the formerly nontilled field and that most of the decrease in the carbon was attributed to the soil layer of 15 - 30 cm depth.

### *4.5. Prospect for the advanced studies*

Although this study revealed significant soil carbon loss by the land use change from paddy rice to upland crop cultivation, it is not certain whether such changes in the soil carbon continue for years. The data on the SCB shown in this study should be recognized in the dynamics of soil carbon with long-term crop cultivation history. Further study such as long-term field experiments are required to clarify the dynamics of soil carbon in a long-term duration.

As mentioned above, the estimated SCBs based on the integration of net carbon input/output (Table 2) were not consistent to the change in soil carbon content (Table 3) quantitatively. Duiker and Lal (2000) also reported similar inconsistency between the estimated SCB and change in soil carbon content. Although there are various methods of estimating SCB in croplands such as by the integration of carbon input/output, soil carbon content investigation or mathematical models, it may be still difficult to conclude which is the best method. Therefore, a comparison with the estimation of SCB by different methods may be quite effective in the future studies for the advanced quantitative estimation of SCB.

## 5. Conclusion

Effect of land use change from paddy rice cultivation to upland crop cultivation on soil carbon budget (SCB) was studied by comparing three types of cropping system (single cropping of paddy rice (PR), single cropping of upland rice (UR) and double cropping of soybean and wheat (SW)) in an experimental field having the same history as consecutively cultivated paddy rice fields.

The SCBs of the PR plots were positive (79 to 137 g C $m^{-2}$ $y^{-1}$), which indicates the accumulation of carbon in the soil. On the other hand, those of the UR and SW plots were negative (-343 to -275 g C $m^{-2}$ $y^{-1}$ and -361 to -256 g C $m^{-2}$ $season^{-1}$, respectively), which indicates significant carbon loss from the soil.

The amounts of carbon in the soil of about 0 - 15 cm depth in the UR and SW plots became lower by 148 and 177 g C $m^{-2}$ than that in the PR plots, respectively, after the field experiment with two cropping cycles.

These results indicated that the drainage of paddy fields for upland crop cultivation causes significant carbon loss from the soil, although the management may be effective for the reduction in net GWP by the $CH_4$ emission.

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Table 1. Planting densities, fertilizer application rates, cultivation periods and dry weights of harvested aboveground parts of cultivated crops from 2002 to 2004[a].

[a] This table is also shown in Nishimura et al. (2005).

[b] The values in parentheses show the amount of fertilizer as supplemental application.

[c] Cultivation period is represented by dates from transplanting to harvest for paddy rice, and by those from seed sowing to harvest for upland crops.

[d] The values in parentheses show the dry weight of harvested aboveground parts outside the chambers and the ratio of dry weight inside the chambers to that outside the chambers.

[e] Soybean and wheat were cultivated in the same plots as double cropping.

| Planting density | Rate of fertilizer application[b] | Cultivation period[c] | Dry weight of aboveground parts[d] |
|---|---|---|---|
| (hills / plants m$^{-2}$) | (g N m$^{-2}$, g $P_2O_5$ m$^{-2}$, g $K_2O$ m$^{-2}$) | | (g m$^{-2}$) |
| | Paddy rice | | |
| 22.2 | 5 + (4), 8, 8 + (3) | 2002/05/15 – 2002/09/24 | 1705 ± 75 (1476 ± 0) (115%) |
| | | 2003/05/15 – 2003/09/29 | 1277 ± 99 (1178 ± 13) (108%) |
| | Upland rice | | |
| ca 60 | 3 + (3), 10, 10 | 2002/04/24 – 2002/09/09 | 549 ± 84 (736 ± 61) (75%) |
| | | 2003/04/25 – 2003/09/16 | 428 ± 173 (397 ± 200) (108%) |
| | Soybean[e] | | |
| 7.4 | 2, 6, 6 | 2002/05/29 – 2002/10/25 | 524 ± 11 (474 ± 44) (111%) |
| | | 2003/06/24 – 2003/10/19 | 336 ± 3 (404 ± 18) (83%) |
| | Wheat[e] | | |
| ca 210 | 8 + (2), 10, 10 | 2002/11/13 – 2003/06/10 | 1237 ± 64 (1035 ± 21) (120%) |
| | | 2003/11/04 – 2004/06/03 | 1203 ± 104 (1056 ± 26) (114%) |

Table 2. Cumulative $CO_2$ and $CH_4$ fluxes (NEE and Me), amounts of carbon removed by crop harvest (Yh) and weeding and thinning (Yo), amounts of carbon supplied by straw incorporation (Is) and seed/seedling and chemical fertilizer (Io), and the estimated soil carbon budgets (SCB) in experimental plots with single cropping of paddy rice cultivation (PR), single cropping of upland rice cultivation (UR) and double cropping of soybean and wheat cultivations (SW).

[a] Note that the periods for calculating the cumulative fluxes and SCBs of the SW plots and those of the PR and SW plots are different.

[b] The values are shown as mean ± standard deviation.

[c] Values in parentheses show the amounts of carbon removed outside the chambers.

[d] SCB was calculated using $SCB = -NEE - Me - Yh - Yo + Is + Io$.

[e] Different alphabets show significant differences between the cropping systems within each cropping cycle ($P < 0.05$) by Tukey's multiple comparison analysis.

1st cropping cycle[a]

| | NEE[b] | Me[b] | Yh[b,c] | Yo[b] | Is[b] | Io[b] | SCB[b,d,e] |
|---|---|---|---|---|---|---|---|
| | ($g\ C\ m^{-2}$) | ($g\ C\ m^{-2}$) | ($g\ C\ m^{-2}$) | ($g\ C\ m^{-2}$) | ($g\ C\ m^{-2}$) | ($g\ C\ m^{-2}$) | ($g\ C\ m^{-2}$) |
| PR | | | | | | | |
| 2002/01/01 - 2002/12/31 (Annual total in 2002) | -437±27 | 2±1 | 601±19 (517±5) | 0 | 236±5 | 8±0 | 79±52[a] |
| UR | | | | | | | |
| 2002/01/01 - 2002/12/31 (Annual total in 2002) | 238±43 | -0.07±0.00 | 203±33 (266±24) | 16±4 | 111±11 | 3±0 | -343±4[b] |
| SW | | | | | | | |
| 2002/05/24 - 2002/11/05 (Soybean) | -86±47 | -0.02±0.01 | 240±8 (204±21) | 10±2 | 0 | 4±0 | -159±38 |
| 2002/11/06 - 2003/06/19 (Wheat) | -267±14 | -0.04±0.00 | 476±27 (404±9) | 0 | 0 | 8±0 | -202±41 |
| 2002/05/24 - 2003/06/19 (Double cropping total) | -354±34 | -0.06±0.01 | 716±35 (608±12) | 10±2 | 0 | 12±0 | -361±3[b] |

2nd cropping cycle[a]

| | NEE[b] | Me[b] | Yh[b,c] | Yo[b] | Is[b] | Io[b] | SCB[b,d,e] |
|---|---|---|---|---|---|---|---|
| | ($g\ C\ m^{-2}$) | ($g\ C\ m^{-2}$) | ($g\ C\ m^{-2}$) | ($g\ C\ m^{-2}$) | ($g\ C\ m^{-2}$) | ($g\ C\ m^{-2}$) | ($g\ C\ m^{-2}$) |
| PR | | | | | | | |
| 2003/01/01 - 2003/12/31 (Annual total in 2003) | -394±125 | 14±5 | 469±36 (445±7) | 0 | 217±7 | 8±0 | 137±87[a] |
| UR | | | | | | | |
| 2003/01/01 - 2003/12/31 (Annual total in 2003) | 161±35 | -0.05±0.01 | 162±64 (154±74) | 19±11 | 63±30 | 3±0 | -275±10[b] |
| SW | | | | | | | |
| 2003/06/20 - 2003/10/30 (Soybean) | 76±2 | -0.02±0.00 | 160±1 (184±11) | 1±0 | 161±2 | 4±0 | -72±1 |
| 2003/10/31 - 2004/06/10 (Wheat) | -278±8 | -0.04±0.00 | 469±40 (413±12) | 0 | 0 | 8±0 | -184±48 |
| 2003/06/20 - 2004/06/10 (Double cropping total) | -201±10 | -0.06±0.01 | 629±39 (597±1) | 1±0 | 161±2 | 12±0 | -256±47[b] |

Table 3. Carbon contents of soil samples from 0 - 5 cm and 8 - 13 cm depths and the amounts of soil carbon on equivalent soil mass basis in experimental plots with single cropping of paddy rice cultivation (PR), single cropping of upland rice cultivation (UR) and double cropping of soybean and wheat cultivations (SW) in 2002 (upper) and 2004 (lower).

[a] Soil core samples were collected using a 100 $cm^3$ core sampler on Apr. 19, 2002 and Apr. 26, 2004 for the PR and UR plots, and on Apr. 19, 2002 and Jun. 4, 2004 for the SW plots, respectively.

[b] The values are shown as mean ± standard deviation.

[c] Different alphabets show significant differences between the cropping systems within each year ($P < 0.05$) by Tukey's multiple comparison analysis, and 'n.s.' shows no significant differences between the cropping systems within each year by one-way ANOVA.

[d] Description on the calculation of soil carbon on equivalent soil mass is shown in the text.

2002[a]

| | carbon content of 0 - 5-cm depth[b,c] | carbon content of 8 - 13-cm depth[b,c] | carbon in equivalent soil mass[d] soil thickness[b] | soil mass | carbon mass[b,c] |
|---|---|---|---|---|---|
| | (mg C g soil$^{-1}$) | (mg C g soil$^{-1}$) | (cm) | (kg soil m$^{-2}$) | (g C m$^{-2}$) |
| PR | 18.92 ± 0.55[n.s.] | 17.93 ± 0.73[n.s.] | 15.5 ± 1.3 | 143.2 | 2610 ± 89[n.s.] |
| UR | 18.91 ± 0.74[n.s.] | 17.30 ± 1.03[n.s.] | 14.6 ± 0.6 | 143.2 | 2547 ± 123[n.s.] |
| SW | 18.56 ± 0.24[n.s.] | 17.16 ± 0.96[n.s.] | 15.2 ± 1.2 | 143.2 | 2516 ± 106[n.s.] |

2004[a]

| | carbon content of 0 - 5-cm depth[b,c] | carbon content of 8 - 13-cm depth[b,c] | carbon in equivalent soil mass[d] soil thickness[b] | soil mass | carbon mass[b,c] |
|---|---|---|---|---|---|
| | (mg C g soil$^{-1}$) | (mg C g soil$^{-1}$) | (cm) | (kg soil m$^{-2}$) | (g C m$^{-2}$) |
| PR | 20.20 ± 2.32[a] | 17.97 ± 1.75[a] | 13.8 ± 0.9 | 143.2 | 2676 ± 153[a] |
| UR | 18.46 ± 0.97[b] | 17.17 ± 1.23[ab] | 14.1 ± 1.7 | 143.2 | 2528 ± 92[b] |
| SW | 19.17 ± 0.49[ab] | 16.45 ± 0.69[b] | 13.2 ± 0.4 | 143.2 | 2499 ± 77[b] |

Figure Captions

Figure 1

Schematic diagram of carbon dynamics in cropland ecosystems.

The amounts of carbon in compartments with * were measured in this study for the estimation of increase/decrease in the amount of soil carbon (**). Compartments with *** were not considered in this study.

Figure 2

Seasonal courses of $CO_2$ and $CH_4$ fluxes in experimental plots with single cropping of paddy rice cultivation (PR) (a), single cropping of upland rice cultivation (UR) (b), double cropping of soybean and wheat cultivations (SW) (c), air temperature, solar radiation and precipitation (d) from Jan. 1, 2002 to Jun. 10, 2004.

$CO_2$ and $CH_4$ flux data are averages of two plots, which are daily cumulative values. Air temperature data are the daily means. Solar radiation and precipitation data are daily cumulative values.

Horizontal arrows in (a), (b) and (c) show crop cultivation periods. Solid and broken vertical arrows in (a), (b) and (c) show plowing with and without straw incorporation, respectively. Solid and broken horizontal bars at the bottom of (a) show continuously and intermittently flooded periods in the PR plots, respectively.

Note that the vertical scale of $CH_4$ flux in the PR plots (a) is different from those in the UR and SW plots (b, c).

Part of the data shown in this figure ($CH_4$ flux in the PR plots in 2002) is also shown in Nishimura et al. (2004).

Figure 3

Relationships between $CO_2$ flux and soil temperature in the PR (a) and UR (b) plots during fallow period from autumn of 2002 to spring of 2003, with no or small weeds/ratoons growing.

$CO_2$ flux and soil temperature data are daily cumulative values and means of each lysimeter plot, respectively.

Closed circle: data from crop harvest to autumn plowing with straw incorporation (from Sept. 25 to Oct. 16, 2002 for (a), and from Sept. 10 to Oct. 16, 2002 for (b)).

Open triangle: data from autumn plowing with straw incorporation to next early spring (from Oct. 18, 2002 to Feb. 28, 2003).

Open square: data immediately after spring plowing without straw incorporation (from Apr. 2, to Apr. 10, 2003).

Data shown in open triangle and open square were applied together for calculating regression curves.

Figure 1

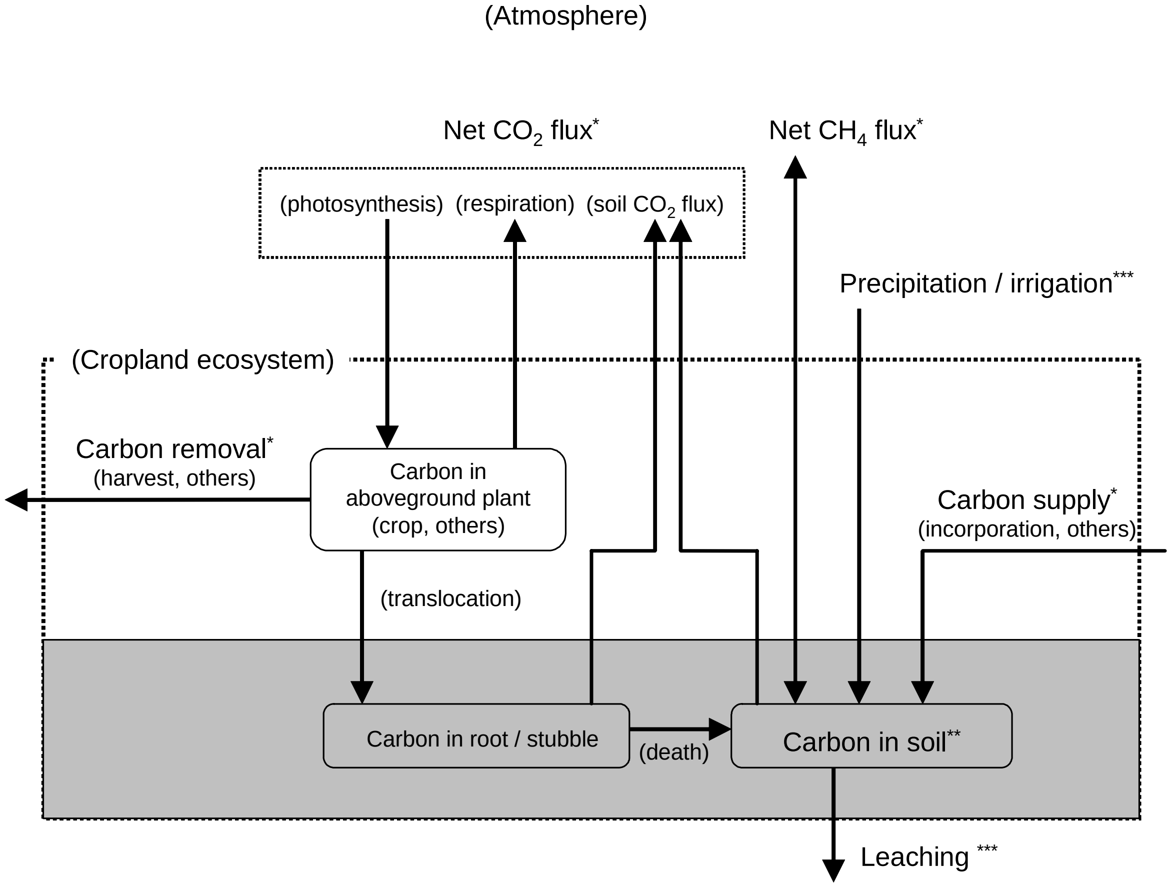

(Atmosphere)
Net $CO_2$ flux*
Net $CH_4$ flux*
(photosynthesis) (respiration) (soil $CO_2$ flux)
Precipitation / irrigation***
(Cropland ecosystem)
Carbon removal*
(harvest, others)
Carbon in aboveground plant (crop, others)
Carbon supply*
(incorporation, others)
(translocation)
Carbon in root / stubble
(death)
Carbon in soil**
Leaching ***

Figure 2

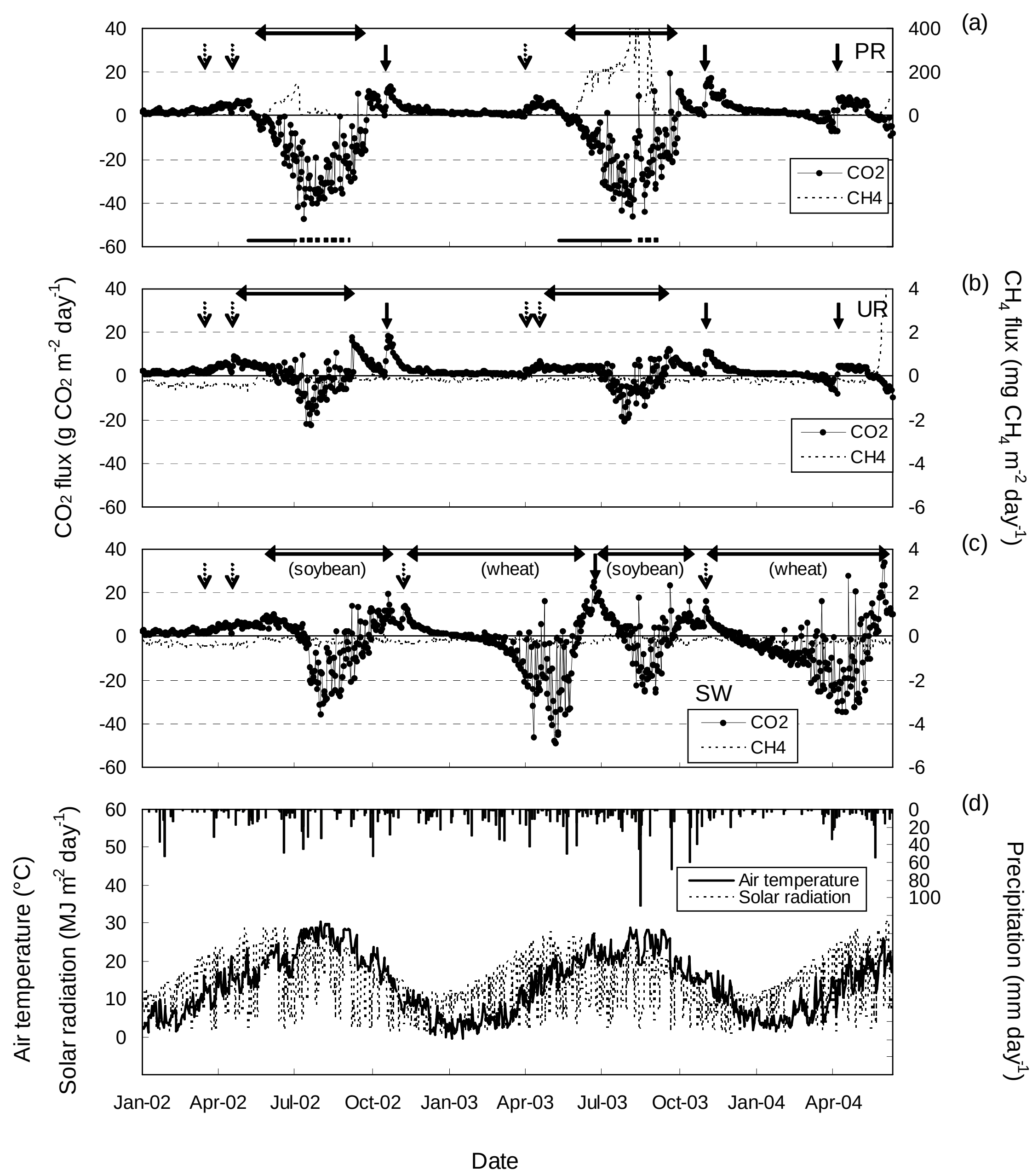
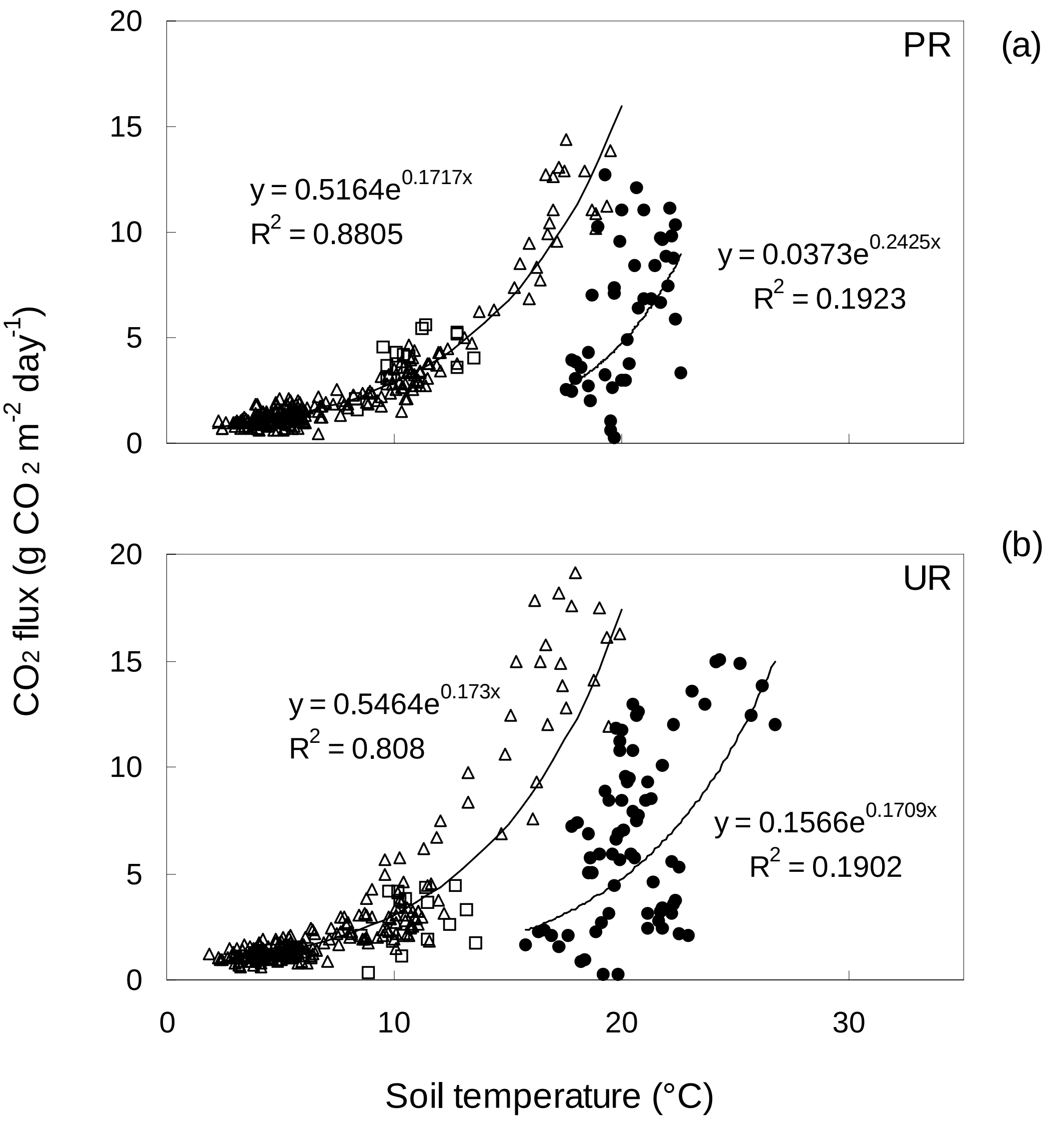

(a)
PR
CO2
CH4
(b)
UR
CO2
CH4
(c)
(soybean)
(wheat)
(soybean)
(wheat)
SW
CO2
CH4
(d)
Air temperature
Solar radiation
CO2 flux (g CO2 m-2 day-1)
CH4 flux (mg CH4 m-2 day-1)
Air temperature (°C)
Solar radiation (MJ m-2 day-1)
Precipitation (mm day-1)
Jan-02
Apr-02
Jul-02
Oct-02
Jan-03
Apr-03
Jul-03
Oct-03
Jan-04
Apr-04
Date

Figure 3



PR
(a)
y = 0.5164e^0.1717x
R^2 = 0.8805
y = 0.0373e^0.2425x
R^2 = 0.1923
(b)
UR
y = 0.5464e^0.173x
R^2 = 0.808
y = 0.1566e^0.1709x
R^2 = 0.1902
CO2 flux (g CO2 m-2 day-1)
Soil temperature (°C)
0
5
10
15
20
0
10
20
30