Measuring the rhizodeposition of carbon by rice: an approach based on carbon flux observations

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ABSTRACT
Rhizodeposition is an important component of carbon cycling in terrestrial ecosystems. However, there remains tremendous uncertainty in its quantification due to the methodological limitations. In the present study, we propose a method to evaluate the rhizodeposition by plants by observing carbon flux. We investigated the ecosystem CO₂ flux variability and calculated the rhizodeposition of carbon by the rice rhizosphere, by using the carbon flux, meteorological data, and biomass observation from 2003 to 2011 at the Taoyuan Agro-ecological Experimental Station, a representative subtropical paddy ecosystem. Our data indicated that the process of rhizodeposition is the major reason for the discrepancy between the biomass and net primary productivity of the paddy ecosystem under intensive human interference. Both the amount and ratio of rhizodeposition of carbon in this paddy ecosystem were assessed; this provides important theoretical and methodological support for further investigating rhizodeposition by rice under field conditions. The rhizodeposition amount in the growing season of early rice, late rice, and for the entire planting period was 0.52–2.56, 0.74–3.75, and 1.61–5.24 t ha⁻¹, respectively, with the corresponding mean (±SD) rhizodeposition ratios of 23.16 ± 8.87%, 28.16 ± 12.94%, and 27.00 ± 9.3%. This method enabled us to calculate rhizodeposition under in situ conditions, and the results showed that the growing season of late rice was the primary period for rhizodeposition in rice ecosystem.

1. Introduction

Soil is a core component of terrestrial ecosystems, as it forms the largest carbon pool with the slowest turnover time (Schlesinger 1982). Soil carbon pool is largely composed of an organic carbon pool, whereas the proportion contributed by the inorganic carbon pool is relatively small. The combined total storage of organic and inorganic carbon in 0–100 cm soil depth is about 2400 Pg worldwide, which is c. three to fourfold that stored in the atmospheric carbon pool and c. three to fivefold that held by vegetation systems (Post et al. 1990). Based on their investigation of 2696 soil profiles from around the world, Post and colleagues estimated that the total amount of organic carbon in the soil is 1395 Pg (Post et al. 1982). Clearly, the soil organic carbon (SOC) pool plays an important role in the process of carbon cycling in many terrestrial ecosystems.

The special position of the rhizosphere in the plant–soil system determines its unique contributing role. The rhizosphere is the center of the interactions between organisms and their immediate environments, where the most intensive ecological exchange of matter and energy occurs. Rhizodeposition of carbon contributes the most to the rhizosphere carbon consumption, and it is the key driver maintaining root respiration. In addition, rhizosphere deposits are important substances for signal transduction in the plant–soil system, and they also serve as vital sources of nutrients and energy for rhizosphere microorganisms (Cheng et al. 1993). Thus, as an important material flow, information flow, and energy flow in the plant–soil system, rhizodeposition is crucial for plant nutrition and physiology and for the soil biological activity in the system. By affecting or restricting the carbon balance in plants in this way, rhizodeposition can further influence the process of carbon cycling at the ecosystem level.

Cropland ecosystems are an important subset of the global terrestrial ecosystem, because they are extremely dynamic and the ecosystem most heavily affected by human activity. The health of cropland soil is directly related to human sustenance and survival via its influence on the yield and quality of food crops. Therefore, cropland soil is an increasingly important focus of research in the study of terrestrial ecosystems. Because rice is a staple commodity in the cropland ecosystem, the health of the rice paddy soil is of great importance in agricultural land use and for global carbon sequestration.

Many studies have investigated the effects of human activities (e.g., soil cultivation, management, and fertilization) and environmental factors (e.g., climate and soil fertility) on the carbon cycling dynamics in the rice paddy ecosystem (Lal 2003; Liu et al. 2007; Zhang et al. 2009). As the key location where plants interact with environmental factors, the roots of rice should play an important role in the carbon cycling process of paddy ecosystem. Hence, studying the material exchange between the rice roots and soil, especially the rhizodeposition of carbon and the amount of carbon exchanged...
during this process, it is critical to better understand how rice roots influence the carbon biogeochemistry in paddy ecosystems.

Nevertheless, rhizodeposition remains poorly understood, due to the complexity of root-derived carbon composition, the high degree of spatial heterogeneity in the rhizosphere, and a lack of available methods for the collection of rhizodeposits (Kuzyakov and Jones 2006; Walker et al. 2003). Quantification of rhizodeposition includes the $^{14}$C tracer method (Kissel et al. 1999; Pausch et al. 2013) or the carbon-allocation coefficient method (Bolinder et al. 2007). However, these methods are either applicable only to laboratory conditions—which may not be representative of results under in situ field conditions—and hard to perform when requiring radioactive labeling, or they result in large uncertainty because they are indirect estimations. The objective of the present study was to propose and test a more rational and robust method to estimate the rhizodeposition of carbon by rice under in situ conditions.

2. Materials and methods

2.1. Conception of rhizodeposition

The rhizodeposition includes organic carbon released by living roots into the soil (i.e., exudations, secretions, sloughed off cells, carbon released by root turnover) (Kuzyakov 2002). This leads to a decrease in the root biomass. Based on the above premises and this explanation, we estimated the rhizodeposition of carbon under the in situ conditions by using the observation data of carbon flux with the following equations:

1. Gross primary production, which represents the total amount of carbon fixation by photosynthesis in a single ‘closed’ ecosystem.
2. Net primary production (NPP), which is defined as
   \[ NPP = GPP - R_A \]  
   where $R_A$ indicates the assimilation product as consumed by the respiration of the autotrophic organisms. $R_A$ is usually composed of three parts: $R_{\text{root}}$, $R_{\text{wood}}$, and $R_{\text{leaf}}$, which are the autotrophic respirations of root, stem, and leaf, respectively.
3. Net ecosystem production (NEP), which is defined as
   \[ \text{NEP} = \text{NPP} - R_h = \text{GPP} - R_A - R_h \]  
   where $R_h$ is the respiratory flux of the heterotrophic organisms. The NEP, the plant biomass, is the major fate of the organic carbon produced during plant growth (NPP); the alternative fate is storage in the soil as organic matter via microbial decomposition and then a return to the atmosphere after entering the soil surface as litter. For the plant-centered terrestrial ecosystem, the respiration flux of heterotrophic organisms is usually characterized by the respiration flux of soil microorganisms ($R_{\text{microbe}}$), which is the soil respiration flux, $R_s$.
4. Net ecosystem exchange (NEE), which is the net carbon flux between the terrestrial ecosystem and the atmosphere, is described by the following equation:
   \[ \text{NEE} = R_A + R_s - \text{GPP} = R_{\text{eco}} - \text{GPP} = -\text{NEP} \]  
   where $R_{\text{eco}}$ indicates the ecosystem respiration, and therefore,
   \[ \text{NPP} = \text{NEP} + R_h = R_h - \text{NEE} \]  
5. Rhizodeposition of carbon. Because of the rhizosphere deposition, there is a discrepancy between NPP and the biomass of ecosystems, which is designated as $\Delta C$:
   \[ \Delta C = \text{NPP} - \text{Biomass} \]  
   where $\Delta C$ represents the rhizodeposition of carbon. Based on this equation, the rhizodeposition of carbon in the ecosystem could be estimated for a certain time period.
6. Deposition rate of rhizosphere carbon. The rhizodeposition ratio, $\delta$, is defined as the proportion of the rhizodeposition of carbon directed to NPP, which was calculated as follows:
   \[ \sigma = \frac{\Delta C}{\text{NPP}} \times 100\%. \]

2.2. Observation of carbon fluxes and related parameters

The NEE and the other related parameters were observed from 1 January 2003 to 31 December 2011 at the Taoyuan agro-ecological experimental station (28°55′N, 111°27′E), which is affiliated with Chinese Academy of Sciences. The station is in a typical red soil hilly region, which lies in a transition monsoon humid climate zone from the mid-subtropics to northern subtropics, with annual averages in temperature of 16.5°C, in precipitation of 1437 mm, in evaporation of 1157 mm, in sunshine duration of 1531 h, and in total radiation of 4226 MJ m$^{-2}$. The soil in the region is paddy soil developed from quaternary red earth, on which the dominant local cropping rotation of ‘rice-rice-fallow’ has been adopted.

The device for the carbon flux measurements was an automatic eddy covariance system. It had a three-dimensional ultrasonic wind thermometer (CKJ-540, Kajo Denki Co. Ltd., Tokyo, Japan), a non-dispersive infrared analyzer (C-CS7500, Campbell Scientific, Inc., Logan, UT, USA), a specific data logger (CR23X, Campbell Scientific, Inc.), and a radiotelephone (Siemens, Munich, Germany). The sensor was positioned at 2 m above the ground. The flux system data were collected using a frequency of 10 Hz, stored in the specific data logger, and downloaded regularly using a PC and radiotelephone (Siemens).

The soil temperature at the station was measured at depths of 0, 5, 10, and 20 cm using an impedance thermometer (CPT-10, Campbell Scientific, Inc.).
2.3. Data process and calculation of flux data

Under field conditions, there are always uncertainties in any automatic observational data, typically caused by various factors, such as the failure and maintenance of instruments and high environmental variability, which sometimes results in missing data and invalid records (i.e., irrelevant data from a random record and setting threshold). Therefore, pre-data processing was carried out for the original records to delete any such invalid and anomalous entries.

Data after pre-processing were considered as valid data. To replace the missing data in the time series, the flux data gap-filling and flux-partitioning tool (GF & PF), developed by Max Planck Institute for Biogeochemistry (MPIB), was used to perform data interpolations.

2.4. Calculation of soil respiration ($R_s$)

The $R_s$ lacked a direct measurement, so it is estimated. In the same site, Ren et al. (2007) continuously monitored carbon flux and meteorological data during 2003–2005. They found that the carbon flux monitored by eddy covariance system in the nighttime of fallow period, which was supposed to be $R_s$, corresponded well with soil temperature at 5 cm depth, and the all-day $R_s$ of the paddy ecosystem could be inverted using this relationship and the all-day soil temperature (Ren et al. 2007). This method was adopted in the present study.

Rice fields during the growing season are often under flooded conditions, so eliminating the effect of flooding on the paddy soil respiration is necessary when inverting the paddy soil respiration at this time (Zou et al. 2003). Here, we adopted the relationship between the submerged depth ($x$) and the CO$_2$ emission of soil ($y$) as established by Zou et al. (2003) to calibrate the inversion of soil respiration during the paddy growing season.

$$ y = 135.23 - 6.1088x $$

2.5. The estimation of annual biomass in the ecosystem

During the period of rice crop growth, the plant height, seedling number, root length, root weight, root density, and biomass (above- and below-ground) were measured every 7–8 days. The biomass was determined as follows: the tiller numbers were recorded every 7–8 days from the 7th day after transplanting until the harvesting period. Each time, 20 plots were investigated (10 at the east and 10 at the west of the field), and rice plants from five hills were collected, based on the average tiller numbers, to measure the fresh weight of above- and below-ground tissues. The plant materials were killed at 105°C for 15 min, followed by drying at 80°C until a constant weight to measure their above and below-ground biomass components.

At harvest, the root-shoot ratio (R/S) and the harvest index (HI) were first calculated. Next, the biomass of the rice plants in each unit area of the paddy field was determined based on the actual yield, then the planting density was used to estimate plant biomass on a per hectare basis of the paddy field (expressed as C t ha$^{-1}$).

3. Results

3.1. Annual variation characteristics of the carbon flux in a paddy ecosystem

The variability in the CO$_2$ flux in paddy ecosystems has been studied (Zhu et al. 2005, 2008), but the period for that data collection is relatively short. In the present study, 9 years of flux data were obtained, which should capture the variation pattern of the CO$_2$ flux in a paddy ecosystem in a more accurate way.

Fig. 1 shows the variation in the daily average NEE from 01/01/2003 to 31/12/2011. From the beginning of a year, as the temperature rose, the daily average of NEE was also gradually increased. Two peaks occurred in each studied year: at the maturation period of early rice (June–July) and again at that of

![Figure 1. Variation of daily NEE paddy ecosystem over 2003–2011.](image)
late rice (September–October). Because of the active photosynthesis and respiration at the rice maturation stage, the carbon fixed by photosynthesis was largely stored in the rice plant as material and energy for grain formation.

Generally, the paddy ecosystem serves as a source of atmospheric CO$_2$ (positive NEE) at night and as a sink (negative NEE) during the day. The 9-year flux data showed that the effect of the nocturnal source was much weaker than that of the diurnal sink (Fig. 2). Although during certain periods the nocturnal source was stronger than the diurnal sink under unstable external conditions, overall this paddy ecosystem functioned as a notable sink of atmospheric CO$_2$ during the 9-year study period.

The NEE of early rice, late rice, and the whole planting period, along with the all-year NEE in each year, was all calculated separately. Their respective average and standard deviation among years were also determined, as shown in Table 1. Unfortunately, because of recurring problems with the instruments, a lot of data were missed in 2004 (especially during the rice growing period) and the gap-filling exercise generated massive errors; hence, the data from 2004 were eliminated from Table 1. The paddy ecosystem behaved as a carbon sink during all seasonal stages, and the formation of the carbon sink usually occurred in the planting period, suggesting that rice planting plays an important role in strengthening the carbon sink of this ecosystem. Eight years of data, from 2003 to 2011, showed that the carbon sink in the paddy ecosystem of the early rice season was 2.08–6.99 t ha$^{-1}$, with an average of 3.35 ± 1.53 t ha$^{-1}$, whereas in the late rice season, these corresponding values were higher, at 2.93–6.81 and 4.70 ± 1.61 t ha$^{-1}$. For the whole planting period, the carbon sink of the paddy ecosystem was 5.02–13.34 t ha$^{-1}$, with an average of 7.29 ± 1.65 t ha$^{-1}$, which accounted for 73.60–93.94% of the total carbon sink in a whole year. This result clearly indicates that the carbon sink in this paddy ecosystem during the planting period is c. 85% of that for the whole year. In the fallow period, due to the relatively low temperature and limited precipitation, the residual weeds still played a role as a small carbon sink in the paddy ecosystem (15% of the whole year), which allowed the paddy ecosystem to function as a respectable carbon sink over the years.

3.2. The variation characteristics of the R$_s$ in paddy ecosystem

Fig. 3 shows the annual variation of soil respiration in the paddy ecosystem during the 9 years. R$_s$ increased as the soil temperature rose as the season changed. Maximum R$_s$ occurred in July each year, and this could be attributed to the local climate. The Taoyuan station has a subtropical monsoon climate in which the temperature attains its maximum in July, so R$_s$ also reached its maximal value in this month. Later, due to the temperature dropping, R$_s$ was also reduced. Elevation in temperature induces the activity of proteases required for heterotrophic respiration, which accelerates the plant respiration rates. As a result of the seasonal temperature differences, average R$_s$ in late rice season was 24% higher than in early rice season (Table 1).

3.3. The carbon deposition of the rice rhizosphere

Based on the above methods, the R$_s$, biomass, ΔC, and δ were calculated for the early rice and late rice seasons in

![Figure 2. Variation of diurnal and nocturnal NEE paddy ecosystem over 2003–2011.](image)

| Period             | 2003   | 2005   | 2006   | 2007   | 2008   | 2009   | 2010   | 2011   | Average | Standard deviation |
|--------------------|--------|--------|--------|--------|--------|--------|--------|--------|---------|-------------------|
| Early rice season  | –2.62  | –3.19  | –6.99  | –2.08  | –2.81  | –3.01  | –2.62  | –3.44  | –3.35   | 1.53              |
| Late rice season   | –3.76  | –4.73  | –6.35  | –2.93  | –6.41  | –3.05  | –6.81  | –3.56  | –4.70   | 1.61              |
| Planting period    | –6.38  | –7.92  | –13.34 | –5.02  | –9.22  | –6.06  | –9.43  | –6.99  | –7.29   | 1.65              |
| Whole year         | –7.10  | –9.34  | –17.09 | –6.81  | –10.83 | –7.44  | –10.04 | –8.58  | –8.59   | 1.55              |

Data for 2004 were removed because of too many missing data points in this year due to equipment failure.
the paddy ecosystem, as shown in Table 2. As mentioned earlier, 2004 had much data missing, so it was also excluded from Table 2. The 8-year data revealed that the $R_s$ during the growing season of early rice and its total biomass at harvesting was $2.34–3.40$ and $4.01–5.01$ t ha$^{-1}$, respectively. By contrast, the corresponding values were much higher during the growing season of late rice, with an $R_s$ of $2.63–4.33$ t ha$^{-1}$ and a total biomass of $5.28–5.95$ t ha$^{-1}$, suggesting a more intensive carbon exchange in the ecosystem occurred in the growing season of late rice; it also exhibited a stronger capability and higher level of carbon sequestration. Comparing the planting periods over the whole year, the $R_s$ of the planting stage represented >80% of that for the whole year, indicating that the vegetation coverage status of the whole ecosystem also substantially affects the intensity of heterotrophic respiration (soil respiration). Thus, the change from the rice plants in the planting period to just a few weeds during the fallow period alters the carbon exchange status of the whole ecosystem.

The rhizodeposition plays an important role in the carbon cycling of the whole paddy ecosystem. As shown in Table 2, the rhizodeposition $\Delta C$ was $1.0$ t ha$^{-1}$ during the growing season of early rice, with a minimum of $0.52$ t ha$^{-1}$ in 2007 and a maximum of $4.49$ t ha$^{-1}$ in 2006. The reasons for these two extremes remain unclear. Apart from these two extremes, the rhizodeposition ratio $\delta$ of $13.23–24.97\%$ in the other years should objectively reflect the amount of rhizodeposition in the growing season of early rice (Table 3). During the growing season of late rice, the $\Delta C$ ranged from $0.15$ to $4.49$ t ha$^{-1}$ with a corresponding $\delta$ of $2.56–43.64\%$, thus indicating that more carbon was deposited by late rice and that this season is the primary stage for the rhizodeposition of carbon.

To obtain an overall average and standard deviation of the rhizodeposition ratio, all the data from 2004 were removed (because of missing entries), as were the minimal and maximal values of the carbon deposition rate from the 8-year valid records (see Table 3). Then, the overall average rhizodeposition ratio was $23.16 \pm 8.87\%$, $28.16 \pm 12.94\%$, and $27.00 \pm 9.3\%$ for the growing season of early rice, late rice, and for the whole planting stage, respectively. The results demonstrate that $12.32–41.31\%$ of photosynthetic carbon entered the soil via rhizodeposition during the growing season in the paddy ecosystem with rice as the primary crop.

Table 2. The amount of rhizodeposition and other relevant parameters during the early and late rice growing season (unit: t ha$^{-1}$).

| Year | NEE | $R_s$ | NPP | Biomass | $\Delta C$ | NEE | $R_s$ | NPP | Biomass | $\Delta C$ |
|------|-----|------|-----|--------|----------|-----|------|-----|--------|----------|
| 2003 | $-2.62$ | 2.72 | 5.34 | 4.01 | 1.33 | $-3.76$ | 4.33 | 8.09 | 5.55 | 2.54 |
| 2005 | $-3.19$ | 3.4 | 6.59 | 4.03 | 2.56 | $-4.73$ | 3.9 | 8.63 | 5.95 | 2.68 |
| 2006 | $-6.99$ | 2.51 | 9.5 | 5.01 | 4.49 | $-6.35$ | 2.87 | 9.22 | 5.47 | 3.75 |
| 2007 | $-2.08$ | 2.61 | 4.69 | 4.17 | 0.52 | $-2.93$ | 2.81 | 5.75 | 5.6 | 0.15 |
| 2008 | $-2.81$ | 2.35 | 5.16 | 4.19 | 0.97 | $-6.41$ | 2.63 | 9.04 | 5.33 | 3.71 |
| 2009 | $-3.01$ | 2.34 | 5.35 | 4.02 | 1.33 | $-3.05$ | 2.97 | 6.02 | 5.28 | 0.74 |
| 2010 | $-2.62$ | 2.89 | 5.51 | 4.5 | 1.01 | $-6.81$ | 3.48 | 10.29 | 5.8 | 4.49 |
| 2011 | $-3.44$ | 2.34 | 5.77 | 5.01 | 0.76 | $-3.56$ | 3.22 | 6.78 | 5.93 | 0.85 |

$^a$Data for 2004 were removed because of too many missing data points in this year due to equipment failure.
Table 3. Rhizodeposition ratio of the rice paddy ecosystem in the different years ($\delta$, %).

| Year  | Early rice | Late rice | Planting period |
|-------|------------|-----------|-----------------|
| 2003  | 24.97      | 31.41     | 28.81           |
| 2005  | 38.85      | 31.05     | 34.42           |
| 2006  | 47.28*     | 40.66     | 44.02           |
| 2007  | 11.08      | 2.61      | 6.42            |
| 2008  | 18.80      | 41.02     | 32.95           |
| 2009  | 24.86      | 12.32     | 18.20           |
| 2010  | 18.33      | 43.64     | 34.81           |
| 2011  | 13.17      | 12.29     | 12.83           |
| Average | 23.16  | 28.16     | 27.00           |
| Standard deviation | 8.87 | 12.94 | 9.30 |

*Data for 2004 were removed because of too many missing data points in this year due to equipment failure.

Italicized values were maximum or minimum of a column and were excluded from the calculation of average and standard deviation.

4. Discussion

From the point view of climate change mitigation and soil quality management, we need to characterize, predict, and manage soil carbon stock in agroecosystems; therefore accurate estimation of carbon input to soil is essential. Quantifying below ground carbon inputs, notably from exudates and other ephemeral root-derived materials, is difficult and remains a research topic (Gill et al. 2002; Grogan and Matthews 2002; Kuzyakov and Domanski, 2000). Bolinder et al. (2007) proposed an allocation coefficient approach to apportion crop plant carbon into crop product, residue, root tissue, and rhizodeposition, and thus to estimated rhizodeposition from agricultural yields, using published or assumed values from HI and shoot:root ratios. This method is straightforward and easy to use. However, this is an indirect method and there is large uncertainty as a result of the large uncertainties in HI and shoot:root ratios.

A direct method to quantify rhizodeposition is to label plants with $^{14}$CO$_2$, leading to distinct isotopic differences of root- and soil-derived carbon and thus, the portion of root-released carbon remaining in soil can be quantified (Werth and Kuzyakov 2008). However, these approaches largely underestimate rhizodeposition since they did not account for the amount of rhizodeposits rapidly decomposed by microorganisms (Werth and Kuzyakov 2008). Pausch et al. (2013) improved the method by separating soil $^{14}$CO$_2$ efflux into root and rhizomicrobial respiration and thus accounted for not only the fraction of rhizodeposits remaining in soil but also for that decomposed by microorganisms and released from soil as CO$_2$. This labeling method yields accurate measurement of rhizodeposition, yet it works only under controlled condition and does not account for the spatial variability at field scale.

Compared with previous method, the proposed approach in the present study is based on field observation of carbon fluxes; therefore, it works at in-situ condition, accounts for the spatial and temporal variability. Moreover, no labeling or distinguishing between soil respiration and root respiration is needed. Therefore, it provides a good alternative to quantify rhizodeposition. With this new method, we could determine that the rhizodeposition of carbon was 0.52–2.56, 0.74–3.75, and 1.61–5.24 t ha$^{-1}$ (excluding minimal and maximal) for the growing season of early rice, late rice, and the planting stage, respectively, while the corresponding rhizodeposition ratios were 23.16 ± 8.87%, 28.16 ± 12.94%, and 27.00 ± 9.3%, respectively. The growing season of late rice was the primary stage of rhizodeposition.

Plant photosynthesis is an important driving force of carbon exchange between the land and atmosphere, and it is also an important source of SOC: each year, 10% of atmospheric CO$_2$ flows from vegetation to the soil (Dannenberg and Conrad 1999). Approximately 28–59% of photosynthetic products are transferred to the underground during the growing period of plants, and 4–70% of them enter the soil through root exudation (Gong et al. 2012; Lynch and Whipps 1990). It has been reported that rhizodeposition accounts for 40% of the net carbon assimilation (Vaneen et al. 1991), but it can be very variable. For example, 12–54% of the photosynthetic carbon flows into the soil during the growth period of wheat (Whipps 1990), but only 0.5–10% occurs in maize crop (Kuzyakov and Domanski 2000); this difference is attributed to the fact that wheat is a C3 plant, while maize is a C4 plant. In the present study, the results for rice, also a C3 plant, agreed well with previous studies.

The proportion of photosynthetic carbon that flows into soil likely varies with the different developmental stages of plants. For rice, the proportion of photosynthetic carbon allocated underground decreases from 28% to 2% from tillering to maturity, and this is related to the growth rate of root system (Lu et al. 2002). In a single growing season, the total photosynthetic carbon transferred to underground by cereal crops and forage grass could reach 1500 kg km$^{-2}$ (Gregory and Atwell 1991). Therefore, our result that rice exhibited a relatively large rhizosphere carbon deposition ratio during the whole growing season is consistent with these previous studies.

By continuously supplying C$^{14}$O$_2$ to rice plant for 80 days in a pot incubation, Ge et al. (2012) found that the new carbon in SOC pools was about 5.1% of the rice biomass carbon, with some additional carbon in dissolved organic carbon pool and microbial biomass carbon pool. Given that 64–86% of the photosynthetic carbon input to soil is rapidly respired by soil microorganisms (Hutsch et al. 2002; Lynch and Whipps 1990), we estimate that the total rhizodeposition ratio in the rice pot experiment of (Ge et al. 2012) would also reach around 20%, close to results in the present study.

Nevertheless, the amount of rhizodeposition is influenced by many other biotic and abiotic factors in the plant–soil system (Amos and Walters 2006; Jones et al. 2004; Nguyen 2003). The soil environment can affect rhizodeposition through physical aspects (e.g., water availability, temperature, soil texture) and chemical conditions (e.g., pH, availability of nutrient ions), as well as through the activity and diversity of microbial populations (Lynch et al. 2001). In agricultural system, human activities such as water and fertilizer management practices also strongly influence rhizodeposition. The root system of rice is very sensitive to soil water condition, as the water status controls root development, and partitioning in soil profile (Cruz et al. 1986). Temperature and sunlight may affect root system root biomass as well as rhizodeposition, mainly through root growth dynamics and photosynthesis and the allocation of carbon (Arai-Sanoh et al. 2010; Jones et al. 2004).
Although the paddy ecosystem served as a good carbon sink in the present study, its role in carbon sequestration still has a relatively large uncertainty. This is because the paddy ecosystem has been affected by intensive human interference and other external environmental factors, which points to the value of cropland management.

5. Conclusions

By measuring local carbon flux, we applied a new method and idea to quantitatively analyze the rhizodeposition of carbon. This enabled us to calculate the carbon exchange flux in atmosphere-plant(rice)-soil system for a certain time period, so as to obtain the approximate value of the rhizodeposition of carbon from a macroscopic perspective. As such, this work provides an important methodological basis for further study of rhizodeposition under in situ conditions. Compared with conventional methods relying on laboratory or highly controlled conditions for accuracy, the present study effectively solves the problem of measuring in situ rhizodeposition by obtaining results closer to reality. Additionally, our new method shows good adaptability: it is easy to implement and less affected by environmental factors than is the traditional isotope method.

Acknowledgments

This study was financially supported by the Science and Technology Agency of Hunan Province, China [Grant Number: 2017CT5010, 2017NK2380]. We gratefully acknowledge the technical assistance provided by the Taoyuan Agroecological Experimental Station of the Chinese Academy of Sciences, and the assistance by Prof. Chengli Tong.

Funding

This study was financially supported by the Science and Technology Agency of Hunan Province, China [Grant Number: 2017CT5010, 2017NK2380].

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