Agriculture, Ecosystems and Environment 210 (2015) 15–24

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Carbon release from rice roots under paddy rice and maize–paddy rice cropping

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ARTICLE INFO

Article history:
Received 10 December 2014
Received in revised form 24 April 2015
Accepted 27 April 2015
Available online 15 May 2015

Keywords:
Rhizodeposition
Root exudates
Paddy rice
Dissolved organic carbon
Dissolved inorganic carbon
^{13}C pulse labeling

ABSTRACT

Crop rotations encompassing flooded rice and an upland crop are commonly found in large parts of South and East Asia. However, also rice farmers in Southeast Asia increasingly switch from double-cropping paddy rice to one non-flooded crop–such as maize–in the dry season. We hypothesized that introducing maize (maize–paddy rice, M-MIX) into a double paddy rice (R-WET) cropping system will increase carbon (C) release from rice roots into the rhizosphere and the dissolved soil C pool. To test this hypothesis we assessed the kinetics of C release by the rice plants in a hydroponic greenhouse experiment, and used these data for interpreting their C release in field experiments using ^{13}C pulse labeling of rice plants. In the greenhouse we observed that rice roots released ^{13}C labeled dissolved organic carbon (DOC) for 21 days with a mean residence time (MRT) of 19 days after exposure to a $^{13}CO_2$ pulse. The MRT of labeled dissolved inorganic carbon (DIC) released from rice roots was only 2 days. In the field $^{13}CO_2$ pulse labeling increased the ^{13}C excess of rhizosphere soil up to 0.7 ± 0.2 mg $^{13}C\,kg^{-1}$ in R-WET and 0.9 ± 0.3 mg kg^{-1} in M-MIX. The ^{13}C signature of bulk soil remained unaffected. DOC concentrations in R-WET were significantly higher than in M-MIX during the mature grain stage of the rice plants. Nevertheless, the ^{13}C excess in DOC transiently increased by only 0.5 $\mu g\,L^{-1}$ after labeling in 13 cm depth in one of three lysimeters previously cropped with maize (M-MIX), while no labeled DOC was detected in 13 cm depth of the R-WET lysimeters and in 60 cm depth of both treatments. In contrast, the ^{13}C excess of DIC increased by 42.4–93.1 $\mu g\,L^{-1}$ a few days after labeling with a MRT of 53–66 days in both treatments. Considering the results of the greenhouse experiment, this suggests a rapid mineralization of labeled rhizodeposits in the field and an effective transient storage of CO_2 produced by respiration in soil water.

1. Introduction

Intensive paddy rice cropping is one of the most important food production systems in the world (Dobermann and Witt, 2000), covering a total area of 163 Mha worldwide (FAO, 2012). Organic carbon (C) stocks of paddy soils are often elevated in comparison to other soils (Cai, 1997; Pan et al., 2003, 2009), particularly in topsoils (Kalbitz et al., 2013). However, many paddy rice systems are currently under change. Water shortages, high energy costs for irrigation, volatile rice prices, and also an increasing need of livestock feed like maize, motivate farmers to switch from continuous rice cropping to mixed maize–paddy rice cropping (Witt et al., 2000; Timsina et al., 2010). In Asia the area under rice–maize rotation systems has thus increased to more than 3 Mha (Timsina et al., 2010). However the conversion from continuous rice cultivation to a maize–rice rotation with drying and tillage of aerated soil during land preparation for maize can have pronounced implications for C cycling (Timsina et al., 2010) and greenhouse gas emissions (Kraus et al., 2015; Weller et al., 2015).

More than 1 Mg atmospheric carbon per hectare can be transferred to paddy soil during a rice growing season by roots (Lu et al., 2002a; Li and Yagi, 2004), of which up to 300 kg C per hectare is released in the form of exudates, secretions, lysates, mucilages, and sloughed-off root cells (Kimura et al., 2004). This C input strongly affects biogeochemical soil processes. Root-derived C is an important source of CH_4 emitted from flooded rice fields. However, the actual percentage of CH_4 originating from root exudation varies in a wide range from 4 to 100% as found in pot

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http://dx.doi.org/10.1016/j.agee.2015.04.029
0167-8809/

experiments by Minoda and Kimura (1994) and Minoda et al. (1996). The average contribution of C assimilated by photosynthesis and released by roots to CH_4 emissions were 22% for systems with rice straw addition to soils and 29% for systems without rice straw addition (Minoda et al., 1996). Yuan et al. (2012) found higher fractions of 41–60% of CH_4 derived from root carbon in greenhouse experiments. This 40–60% fraction of CH_4 derived from root C was also confirmed in free air carbon dioxide enrichment (FACE) experiments by Tokida et al. (2011). In pot experiments of Lu et al. (2000), root exudation led to a massive increase of dissolved organic carbon (DOC) concentrations up to levels of 24 mmol DOC L^{-1}, illustrating the importance of root-derived C as source of DOC in the rhizosphere of paddy soils (Lu et al., 2002b). This DOC pool is highly dynamic in terms of internal turnover and comprises compounds that act as microbial substrates as well as intermediates and end products of organic matter decomposition processes (Bolan et al., 2011; Kaiser and Kalbitz, 2012). In summary, DOC is a precursor of a greenhouse gas (CH_4) under flooded conditions–although it should be noted that this applies only to 50% of the organic carbon while the other end product of the anaerobic decay is CO_2. Under non-flooded conditions, DOC is both, substrate and by-product in the sequential (aerobic) decomposition of organic matter. As such, DOC is a crucial organic carbon fraction of non-flooded soils and plays an important role in the source/sink function of the soil for greenhouse gases after conversion between different cropping systems. Yet little is known on the turnover rates of rice-derived DOC under field conditions of flooded soils–and even less under changing agricultural practices.

In dry soils or in soils undergoing wetting and drying cycles, roots might experience a higher mechanical resistance due to the formation of hardened aggregates. Mechanical resistance has been shown to increase root exudation (Barber and Gunn, 1974; Boeuf-Tremblay et al., 1995). Moreover, maize cropping likely increases N supply via mineralization of soil organic N and increasing N supply increases root growth, root surface area, root length and root turnover rate (Marschner, 1995). Indeed using a $^{14}CO_2$ labeling approach, Tian et al. (2013) observed a higher C release from rice roots under non-flooded and alternating water regime than under continuous flooding during a 45 day observation period.

In addition to DOC, CO_2 produced from root and microbial respiration dissolves in soil water as dissolved inorganic carbon (DIC), with DIC concentrations depending on the CO_2 partial pressure and the pH value of soil water (Kindler et al., 2011). In the FACE experiment of Tokida et al. (2011), the fraction of dissolved CO_2 produced from recent rice assimilates increased during rice development and reached a constant level of 50% fifty days after transplanting.

Based on the information available from literature we hypothesized (i) that C release from rice roots into soil changes when shifting from a continuous double paddy rice cropping system to a maize–paddy rice cropping system and (ii) that with regard to the fate of root-derived C, DIC is at least as important as DOC in these changing cropping systems. These hypotheses were tested using a stable C isotope pulse labeling of rice plants in a greenhouse experiment and in field experiments. Pulse labeling provides information on the assimilate-C distribution in plant and soil compartments (Kuzyakov and Domanski, 2000) and allows calculating turnover times for SOC and single fractions and compounds in the SOC pool (Watanabe et al., 2004).

2. Material and methods

2.1. Greenhouse experimental setup and ^{13}C labeling

Rice plants for the greenhouse experiment (variety Rc 222) were grown in a nutrient solution (457.0 mg NH_4NO_3 L^{-1}, 201.5 mg $NaH_2PO_4{\cdot}2H_2O$ L^{-1}, 357.0 mg K_2SO_4 L^{-1}, 443.0 mg $CaCl_2$ L^{-1}, 1620.0 mg $MgSO_4{\cdot}7H_2O$ L^{-1}, 15 mg $MnCl_2{\cdot}4H_2O$ L^{-1}, 0.37 mg $(NH_4)_6Mo_7{\cdot}7H_2O$ L^{-1}, 4.67 mg H_3BO_3 L^{-1}, 0.175 mg $ZnSO_4{\cdot}7H_2O$ L^{-1}, 0.155 mg $CuSO_4{\cdot}5H_2O$ L^{-1}). Roots of the rice plants were sterilized before transferring them into the hydroponic system. The nutrient solution was replaced every 2–4 days during the experiment period. The light cycle in the greenhouse was 13 h a day with an intensity of 56,500 lm.

The ^{13}C labeling was conducted during the booting stage of rice plants at daytime. On the day before ^{13}C labeling, ten rice plants were transferred to ten hydroponic growth chambers. Each chamber was composed of an upper, transparent part made of PMMA (Polymethyl methacrylate) with a volume of 0.0565 m^3 for the rice shoot and a non-transparent bottom part for the roots with a volume of 0.026 m^3 that contained the nutrient solution (Fig. 1a). The root compartment and the transparent chamber for shoots were separated by a silicone sealant that inhibited gas exchange. Rice plants were labeled using a modification of the method of Wiesenberg et al. (2009). A flask with $Na_2{}^{13}CO_3$ (99 atom- %) dissolved in deionized water was fixed in the top of the PMMA chamber. $^{13}CO_2$ was released from this solution after adding 2 M H_2SO_4 via a tubing. A 12 V ventilator homogenized the air inside each chamber during six hours fumigation. Five chambers were fumigated with $^{13}CO_2$, while the other five chambers were treated with $^{12}CO_2$ as control.

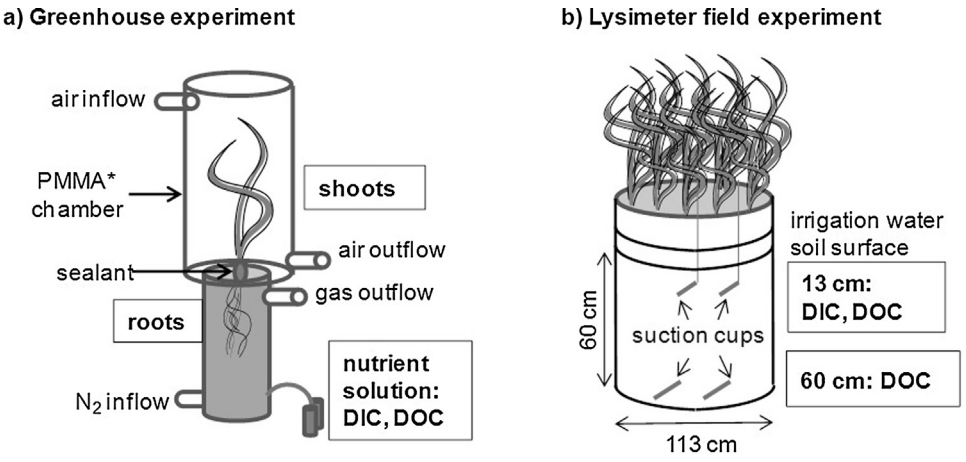

Fig. 1. Set up of greenhouse experiment (a) and lysimeter field experiment (b). *PMMA: Polymethyl methacrylate.