Improving soil nutrient availability increases carbon rhizodeposition under maize and soybean in Mollisols

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HIGHLIGHTS

- Rhizodeposited carbon is an important source of soil organic carbon.
- High soil fertility and organic amendment favor carbon rhizodeposition.
- Soybean has greater carbon rhizodeposition than maize.
- ^{13}C labelling was used to track the allocation of fixed C to soil and lost.

GRAPHICAL ABSTRACT
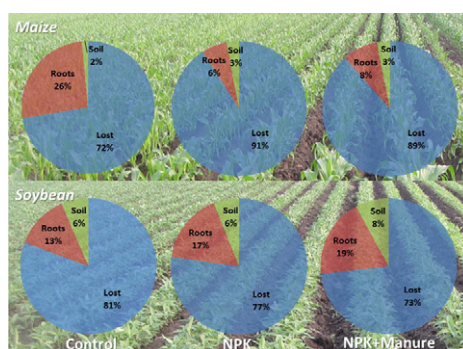
Distribution of labelled $^{13}CO_2$ to roots, soil and lost as CO_2 at maturity in maize and soybean systems with various levels of nutrient supply.

ARTICLE INFO

ABSTRACT

Rhizodeposited carbon (C) is an important source of soil organic C, and plays an important role in the C cycle in the soil-plant-atmosphere continuum. However, interactive effects of plant species and soil nutrient availability on C rhizodeposition remain unclear. This experiment examined the effect of soil nutrient availability on C rhizodeposition of C4 maize and C3 soybean with contrasting photosynthetic capacity. The soils (Mollisols) were collected from three treatments of no fertilizer (Control), inorganic fertilizer only (NPK), and NPK plus organic manure (NPKM) in a 24-year fertilization field trial. The plants were labelled with ^{13}C at the vegetative and reproductive stages. The ^{13}C abundance of shoots, roots and soil were quantified at 0, 7 days after ^{13}C labelling, and at maturity. Increasing soil nutrient availability enhanced the C rhizodeposition due to the greater C fixation in shoots and distribution to roots and soil. The higher amount of averaged below-ground C allocated to soil resulted in greater specific rhizodeposited C from soybean than maize. Additional organic amendment further enhanced them. As a result, higher soil nutrient availability increased total soil organic C under both maize and soybean systems though there was no significant difference between the two crop systems. All these suggested that higher soil nutrient availability favors C rhizodeposition. Mean 80, 260 and 300 kg fixed C ha^{-1} were estimated to transfer into soil in the Control, NPK and NPKM treatments, respectively, during one growing season.

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1. Introduction

Rhizodeposition is an important process of the exchange at the plant-soil interface by releasing organic compounds to soil and enhancing nutrient availability for plants (Nguyen, 2003). The organic C input to soil from released organic compounds was up to 30% of net plant-fixed C (Jones et al., 2009). It modifies the community and activity of soil microorganisms, and impacts on soil carbon (C) and nutrient cycling, and plant growth (Mwafulirwa et al., 2016). Clearly, C rhizodeposition plays an important role in the soil C cycling in the plant-soil system (Kuzyakov, 2002).

It is well known that plant photosynthetically fixed C is the primary source of rhizodeposited C, and thus its quantity and quality would be controlled by various factors that affect plant growth, such as plant species and genotypes (Mwafulirwa et al., 2016), fertilizer application (Baptist et al., 2015), photosynthetic capacity of the plant (Kuzyakov and Cheng, 2001), atmospheric CO_2 concentration (Li et al., 2004), soil tillage (Huggins et al., 2007) and water supply (Lucero et al., 2002). Among these factors, plant biomass and the allocation of photosynthetically fixed C directly drive the rhizodeposition (Baptist et al., 2015). Kuzyakov and Schneckenberger (2004) showed that the amount of rhizodeposited C allocated to soil was <5% of total assimilated C for wheat, pasture plants and maize after reviewing 28 experiments using C isotope pulse-labelling. In later studies, there was 10.8% of assimilated C in rice (Tian et al., 2013) and 2.7% in maize (He et al., 2008) were estimated to transfer to soil. Jin et al. (2011) indicated that soybean allocated 12.4% of net assimilated C to the soil at the four-node stage and only 2.1% at maturity. Clearly, the amount of rhizodeposited C varies across plant species and growth stage. The variation of species, such as between C3 and C4 plants, might be ascribed to the difference in photosynthetic capacity. The C4 plants have the higher photosynthetic capacity and nutrient-use efficiency by means of the C4 photosynthetic pathway compared to C3 photosynthetic pathway in C3 plants (Hatch, 1987). Both photosynthetic capacity and C rhizodeposition depend on the C requirement for plant growth at different growth stages (Anten et al., 1995). A clear understanding of the dynamics of C rhizodeposition at different growth stages between C3 and C4 plants would improve our understanding of how plant growth influences the below-ground C input from roots and rhizodeposits.

Fertilizer application is another important factor affecting C rhizodeposition. It can affect the amount of assimilated C through changes in plant biomass (Saggar et al., 1997), and the partitioning in shoots, roots and soil (Hill et al., 2007). It is generally accepted that application of N fertilizers increases plant biomass (Ge et al., 2014) and the rate of organic C released by plant roots (Henry et al., 2005). However, the application of N fertilizers was shown to decrease the proportion of assimilated C allocated to soil under lettuce (Kuzyakov et al., 2002). Nutrient limitation facilitated the distribution of photo-assimilated C to roots while nutrient-rich soils favored the production of above-ground biomass (Chowdhury et al., 2014). Furthermore, organic amendment increased the root C input in the winter wheat-spring barely-potato crop rotation (Chirinda et al., 2012). The shift of crop assimilate distribution in favor of the root system (Gregory, 2006) would benefit C rhizodeposition. Although there are many studies showing changes of the allocation of assimilated C following fertilization, it is not clear how soil nutrient availability and plant growth interactively affect C rhizodeposition.

This study aimed to examine the effect of soil nutrient availability on rhizodeposited C under two contrasting plant species (C4 maize and C3 soybean) in Mollisols. We hypothesized that higher soil nutrient availability would lead to higher photosynthetic capability of the plants which in turn would increase the amount of newly fixed C translocated to plant roots, and enhance rhizodeposition. The soils were collected from plots of different fertilizer treatments in a long-term fertilizer trial. A pulse ^{13}C-labelling technique was used to differentiate newly incorporated C derived from plants and that from the decomposition of native soil organic C (SOC).

2. Materials and methods

2.1. Soil preparation and plant culture

Soils were collected from the 0.2-m tillage layer of a 24-year fertilization experiment located at the State Key Experimental Station of Agroecology, Hailun County, Heilongjiang, China (47°26′N, 126°38′E). The mean annual temperature is 2.2 °C, and mean annual precipitation is about 550 mm. The soil was a silty clay loam including 400 g kg^{-1} clay and 258 g kg^{-1} silt. The soil bulk density was 1.0 Mg m^{-3}. Three soil nutrient availability treatments were 1) inorganic fertilizer only (NPK), 2) organic amendment in combination with inorganic fertilizer (NPKM), and 3) no-fertilizer (Control). The annual application rates of nutrients in NPK and NPKM treatments were (kg ha^{-1}): 113 nitrogen (N), 20 phosphorus (P) and 25 potassium (K) for maize and wheat, and 20, 23 and 16 for soybean, correspondingly. The N, P and K were applied as urea, $(NH_4)_2HPO_4$ and K_2SO_4. The amount of organic amendment was 2.25 Mg ha^{-1} of pig manure, which provided 36 kg N ha^{-1}, 4.4 kg P ha^{-1} and 54 kg K ha^{-1}. The detailed information on the amount and method of fertilizer application was described by Qiao et al. (2014). Briefly, the crop management was a wheat-soybean-maize rotation, with the maize being the crop plant prior to soil collection for this study. Each year, the above-ground parts were harvested in autumn and the below-ground parts were retained in the field. The soil was tilled to 20 cm depth manually. The soil is a typical Mollisol without carbonate reaction. The basic properties of the soil are shown in Table 1, in which available N in soil was measured using the alkaline diffusion method (Black, 1965), available P with NaHCO$_3$ extraction (0.5 mol L^{-1}, pH 8.5) (Olsen et al., 1954), and available K with 1 N NH$_4$OAc extraction (Jones, 1973). Soil pH was measured with a Mettler Toledo pH meter (S210 Switzerland) after shaking soil in water suspension (1:2.5) for 30 min and centrifuged for 10 min.

Every composite sample was formed by fifteen cores collected from 0 to 20 cm depth of each fertility treatment from three field replicates. The soil samples were gently crushed and thoroughly mixed, and the visible roots and residues were removed. All soil samples were sieved through a 4-mm sieve. The 6.5 kg of each composite sample was filled into each pot (20 cm in height and 20 cm in diameter). To obtain the same fertility status as that under field condition, the inorganic nutrients of NPK and NPKM treatments were applied at the following rates (g pot^{-1}): 0.37 (NH$_4$)$_2$HPO$_4$ and 0.70 K$_2$SO$_4$ for soybean, and 1.53 urea (0.51 was applied at sowing and 1.02 applied at the jointing stage), 0.70 (NH$_4$)$_2$HPO$_4$ and 0.70 K$_2$SO$_4$ for maize. The additional 70 g pot^{-1} of compost pig manure (including 2.1 g C kg^{-1} pig manure) was added to the NPKM treatment. All fertilizers were fully mixed with the soil, which was then compacted to a bulk density of 1.05 Mg m^{-3}.

A pot experiment was conducted in a naturally lit greenhouse with day/night temperatures of 24–28/16–20 °C during the experiment. It was completely factorial, and consisted of two crop species, three levels of soil nutrient availability with three replicates. Pots were destructively sampled six times. A total of 108 pots for crop species and fertilizer treatments were prepared and additional 45 pots without plants were used as no-plant control. The two crops were maize (*Zea mays* L. cv. Haiyu 6), and soybean (*Glycine* max L. cv. Heinong 35) which are C4 monocotyledon and C3 dicotyledon species, respectively. Three uniformly germinated seeds were sown to each pot, and seedlings were thinned to one plant per pot one week after emergence. Soil water content was maintained at 60% of water-holding capacity by weighing every 3 days.

2.2. Labelling process and measurements

The pulse ^{13}C-labelling was performed at the vegetative and reproductive stages (jointing stage and grain-filling stage for maize, and branching stage and grain-filling stage for soybean, respectively). On the labelling day, plants were transferred into an air-tight glass chamber