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Contributions of residue-C and -N to plant growth and soil organic matter pools under planted and unplanted conditions

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ABSTRACT

Soil microorganisms are considered the most effective decomposers of applied crop residues, but it is poorly understood which communities are primarily responsible for decomposition under different conditions. A pot experiment was conducted in a greenhouse to follow the cycling of C and N derived from maize (*Zea mays* L.) residues labeled with both ^{13}C and ^{15}N to a subsequent winter wheat (*Triticum aestivum* L.) crop and to soil pools under planting with winter wheat (+P) or an unplanted control (–P), both in soil maintained at field moisture capacities of 40% and 80%. Soil microbes involved in residue decomposition were investigated by ^{13}C phospholipid fatty acid (^{13}C-PLFA) analysis technique. At wheat maturity, a total of 68% of residue N was recovered in the +P treatments, in which 26% was recovered from wheat plants and another 42% from soil total N (TN), independent of the water regimes, while only 50% was recovered from TN in the –P treatments. More residue C was recovered as soil organic carbon in +P than –P treatments (33% *vs.* 27%), and the trend became more significant with soil moisture. In addition, the +P soil had 35–48% larger microbial biomass carbon (MBC) than the –P soil, and more residue C was recovered as MBC in +P than –P treatments (7% *vs.* 4%), suggesting the induced microbial utilization of the applied residues. The distribution of the residue-derived PLFA-C showed that only 16:1ω7c and 18:1ω7c had larger relative abundances in the +P than the –P soils, suggesting that they were mainly stimulated by the presence of wheat and that they may be the most important fatty acids to define the different recoveries of residue N and C between the planted and unplanted conditions. Our results demonstrate that the enhanced recovery of residue-C and -N by the presence of wheat plants was mainly from the induced microbial utilization of applied residues by altering the activities of specific microorganisms.

1. Introduction

Several billion tons of crop residues are produced globally every year (Lal, 2005). These residues contain abundant carbon and various macronutrients and micronutrients and are considered as an important organic fertilizer. Returning crop residues to soil is considered a good management practice in agricultural production systems as it represents a valuable recycling strategy (Cayuela et al., 2009), which may partly reduce our dependence on mineral fertilizers, directly resulting from residue nutrients release (Blanco-Canqui et al., 2009; Lal, 2009) and indirectly through increased nutrient availability resulting from soil organic carbon (SOC) accumulation (Lal, 2004).

Some studies have reported the contributions of crop residue N to subsequent crop and/or soil nitrogen pools using the ^{15}N stable isotope technique (Mayer et al., 2003; Jannoura et al., 2012; Arcand et al., 2014; Li et al., 2015). Li et al. (2015) showed that only 8.3% of wheat residue N was recovered in the succeeding wheat plants in a two-year field experiment. Luce et al. (2014) found that 13–20% and 4–8% of wheat residue N was recovered in mineral N and microbial biomass nitrogen, respectively, using a 112-day incubation experiment. Crop residues also have a considerable effect on SOC accumulation (Liu et al., 2014). Addition of ^{13}C-labeled crop residues to soil has been used to evaluate their contributions to SOC for annual ryegrass (*Lolium multiflorum* Lam.) and crimson clover (*Trifolium incarnatum* L.) (Williams et al., 2006) and maize (*Zea mays* L.) (An et al., 2015). The sequestration of residue C into soil could improve soil structure and increase soil microbial activity (Lal, 2004), which in turn may influence the balance of residue N immobilization-mineralization in soils, affecting plant N

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uptake.

Soil moisture is amongst the most frequently studied environmental factors that affect turnover of residue C and N. As drying of soil could reduce soil microbial activity through physiological stress or limiting diffusion of substrates to microbes (Manzoni et al., 2012), low soil moisture decreases release of residue C and N into soil (Abera et al., 2012; Li et al., 2016). In addition, soil moisture affects C and N turnover through changes in community composition and abundance of microorganisms (Allison et al., 2013) because bacteria and fungi show different thresholds and response patterns to soil water availability (Manzoni et al., 2012). However, high soil moisture that reduces soil aeration below the optimum would also reduce aerobic microbial activity. For example, Hassan (2013) reported a significant decrease in the release of residue C in the form of CO_2 and dissolved organic matter under 100% of water holding capacity conditions. Furthermore, nitrogen loss as nitrogen oxide emission often increase with soil moisture, though the increase is not necessarily linear (Bateman and Baggs, 2005), leading to the decrease in the contribution of residue-derived N to soil N sequestration. The investigation of soil moisture would improve our understanding about soil abiotic influences on ecosystem processes in soil.

The microbial turnover and mineralization of residue C and N may not only be influenced by soil environmental parameters such as moisture and temperature, but it can also be affected by living plants in different ways. Living plants may affect microbial decomposition/mineralization of returned crop residues by competing with soil microbes for water and nutrients (Muhammad et al., 2007; Jannoura et al., 2012), or changing the environments for microbial growth by excreting root exudates which contain considerably more easily available organic C and N compared to crop residue C and N (Wichern et al., 2007). These different interactions of plants and microbes may potentially alter microbial use of residue C and N compared to unplanted soils, and finally to different fates of residue C and N between planted and unplanted soils.

Crop residues are usually returned to the soil at harvest, which is followed by either a subsequent cropping period or a fallow. Decomposition of crop residues may differ under these two options, resulting in different amounts of nutrient release. Using maize residues labeled with both ^{13}C and ^{15}N, the aim of this study was to investigate the fates of residue-derived C and N in a winter wheat (*Triticum aestivum* L.)-soil system, in comparison to an unplanted control soil, representing a fallow. We hypothesize that relative to the fallow control, the presence of living plants causes a shift in microbial community composition and hence the microorganisms responsible for residue decomposition, leading to altered nutrient cycling and availability including the recovery of residue N in the soil-plant system and the recovery of residue C in soil. To test this hypothesis, we examined (i) the distribution of residue-derived N in multiple plant parts (i.e. root, grain, and straw), soil microbial biomass nitrogen (MBN), and soil total N (TN), (ii) the incorporation of residue-derived C into microbial biomass carbon (MBC) and soil organic carbon (SOC), and (iii) the microbial community members responsible for residue decomposition using ^{13}C phospholipid fatty acid (^{13}C-PLFA) analysis under planted and unplanted conditions. Considering the low content of PLFA-C and detection precision, labeled maize residue is required for quantitative study of the microbial utilization of the added maize residues in the present study.

2. Material and methods

2.1. Soil

Soil was collected from the Fengqiu Agro-ecological Experimental Station of the Chinese Academy of Sciences in Pandian, Fengqiu County, Henan Province of China (114° 24′E, 35° 00′N). In September 2012 (immediately following the harvest of summer maize), it was taken from the top 20-cm soil layer using a shovel before it was air-dried and passed through a 4-mm sieve. The soil was derived from alluvial sediments of the Yellow River and classified as a Calcaric Fluvisols according to the FAO, with a sandy loam texture, 8.50 g organic C kg^{-1}, 0.64 g total N kg^{-1}, and pH (H_2O) 8.19.

2.2. Preparation of ^{13}C- and ^{15}N-labeled crop residues

One maize plant was grown in a pot containing 10 kg soil (dry weight equivalent) which had been thoroughly mixed with ^{15}N-urea fertilizer (30 atom %) at the rate of 156 mg N kg^{-1}, Ca phosphate at the rate of 70 mg P kg^{-1}, and K sulphate at the rate of 65 mg K kg^{-1}. After growth for 33 days, three maize plants in three independent pots were transferred into a plexiglass chamber (150 cm × 75 cm × 200 cm; length by width by height) and labeled for 4 h (09:00–13:00) with 1000 ml ^{13}C-CO_2 (99 atom %). This labeling procedure was repeated for 7 days (i.e. from day 34 to day 40). Maize stems and leaves were then harvested at day 40 at the elongation growth stage, dried at 60 °C and ground to < 2 mm. They had a $\delta^{15}N$ value of +2745.23‰ and a $\delta^{13}C$ value of +35.43‰ which were measured by an isotopic ratio mass spectrometer (IRMS) (EA-IRMS, DeltaV, Thermo Finnigan, Germany). These significant enrichments of ^{13}C and ^{15}N are quite different from the isotopic compositions of: (i) the soil which had $\delta^{15}N$ and $\delta^{13}C$ value of 6.72‰ and −22.09‰, respectively, (ii) the winter wheat (*Triticum aestivum* L.) materials which had $\delta^{15}N$ value of +5.91‰ and $\delta^{13}C$ value of around −27‰, respectively, and (iii) the chemical fertilizer nitrogen which had a $\delta^{15}N$ value of around 0. The maize residues contained 439.1 g C kg^{-1}, 22.8 g N kg^{-1}, 1.7 g P kg^{-1}, and 7.9 g K kg^{-1}, yielding a C:N ratio of 19.2.

2.3. Experimental design

Winter wheat (*Triticum aestivum* L., Aikang 58) was grown in pots from November 10, 2012 to May 10, 2013 (180 days) in a greenhouse. Treatments consisted of two planting conditions (planted with winter wheat (+P) and an unplanted control (-P)) under two water regimes (40% (W1) and 80% (W2) of the field capacity), with application of labeled maize residues (+R). Each treatment had its corresponding control treatment with no residue application (-R). The specific treatments were (1) W1-P + R– with residue application at W1, which was accompanied by a control of unplanted with no residue application at W1 (W1-P-R), (2) W2-P + R– with residue application at W2, which was accompanied by a control of unplanted with no residue application at W2 (i.e. W2-P-R), (3) W1 + P + R– with residue application at W1, which was accompanied by a control of planted with no residue application at W1 (W1 + P-R), and (4) W2 + P + R– with residue application at W2, which was accompanied by a control of planted with no residue application at W2 (W2 + P-R). This design allowed us to compare the amount of C and N derived from the applied ^{13}C- and ^{15}N-labeled maize residues in the soil under planted vs. unplanted conditions at each water regime. Each treatment and its corresponding control were replicated three times, giving a total of 24 pots.

Each pot (23 cm diameter × 25 cm height) was filled with 6 kg air-dry soil (< 2 mm) which was thoroughly mixed with urea at the rate of 150 mg N kg^{-1}, Ca phosphate at the rate of 48 mg P kg^{-1}, and K sulphate at the rate of 68.5 mg K kg^{-1}. For the +R treatments, 12 g of the ^{13}C- and ^{15}N-labeled maize residues were added to each pot, followed by thorough mixing. This residue application rate corresponded to estimated field application rates, presuming a bulk density of 1.46 g cm^{-3} for the 0–20 cm soil layer (Zhao et al., 2007) and an average application rate of 6000 kg maize residue ha^{-1} in the local farming area. For the +P treatments, wheat was sown at 30 seeds per pot on November 10, 2012, and then thinned to 15 seedlings per pot at the seedling stage. The soil moisture regimes of W1 and W2 were maintained by weighing the pots daily and, on the basis of weight loss, adding water every day from the bottom. All the pots were kept on a table outdoors, except