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Impact of residue addition on soil nitrogen dynamics in intercrop and sole crop agroecosystems

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ABSTRACT

Soil nitrogen (N) is one of the most important nutrients for plant productivity and microbial activity in terrestrial ecosystems. However, soil N is also readily affected by land management practices, influencing N_2O emissions. This study assessed N dynamics in soil from different crop systems including a 1:2 (one row of maize and two rows soybean) and 2:3 (two rows of maize and three rows of soybean) intercrop and a maize and soybean sole crop as a result of residue addition from maize or soybeans. This was achieved through a 140-day incubation study using $\delta^{15}N$ natural abundance. The effect of residue addition on soil TN was greater than its influence on crop systems when compared to treatments with no residue addition (Cont). The influence of residue addition on intercrops was most readily observed in the fractionated soil. Light fraction N (LF-N) and soil microbial biomass N (SMB-N) were significantly greater ($p < 0.05$) in the intercrops than in the sole crops. Residue amended treatments were significantly ($p < 0.05$) depleted in $\delta^{15}N$-TN, $\delta^{15}N$-LF and $\delta^{15}N$-SMB compared to Cont treatments. The $\delta^{15}N$-SMB was significantly enriched ($p < 0.05$) compared to that of the residue, TN and LF-N. Residue amended treatments had significantly lower ($p < 0.05$) N_2O emissions than Cont treatments. However, N_2O emissions were not significantly different ($p < 0.05$) between soybean and maize amended treatments, nor between intercrops and sole crops. Our results demonstrate that the addition of contrasting residue types influenced short-term N dynamics in intercrops differently than sole crops.

1. Introduction

Nitrogen (N) is constantly cycled through the soil-plant-atmosphere continuum and is one of the most important nutrients for plant productivity and microbial activity in terrestrial ecosystems (Urakawa et al., 2014). Although microbial activity is influenced by soil environmental conditions, including moisture and temperature, it also controls soil organic matter decomposition, N mineralization and immobilization (Dijkstra et al., 2008). In agroecosystems, the type of crop residue added to the soil dictates microbial activity and it can contribute up to 0.6 Tg N $year^{-1}$ to the atmosphere via N_2O emissions (Nieder and Benbi, 2008). Therefore understanding N in the soil-plant continuum in agroecosystems under various land management practices is crucial because N is a limiting nutrient in temperate environments and contributes to greenhouse gas (GHG) emissions.

Decaying organic matter is an important source of N (Nieder and Benbi, 2008). In intensively managed agricultural soils, crop residues play an important role in providing N in addition to external sources such as mineral fertilizer or manure. Incorporating easily degradable crop residues with a low C:N ratio from legumes enhances N mineralization and N uptake by plants and reduces the need for external N sources (Nieder and Benbi, 2008). Contrary to this, when residues from cereal crops are added, their high C:N ratio causes N to be immobilized by soil microorganisms, making it unavailable for plant uptake (Gentile et al., 2013). Therefore, changes in the type of crop residue returned alter the environment of the soil (Tenesaca and Al-Kaisi, 2015). For example, N cycling is enhanced when integrating crops with low (legumes) and high (cereals) C:N ratios in rotation or as an intercrop.

Intercropping, where crop intensification occurs in both time and space, is defined as the simultaneous growth of more than one species in the same field (Vandermeer, 1992). In temperate regions, where crops are commonly produced in single stands (sole crops), intercropping is of particular interest because soil resources are used more efficiently (Hauggaard-Nielsen et al., 2001). For example, legume residue incorporation increased soil N via enhanced microbial activity and tighter nutrient cycling, leading to a complementary use of N (Sierra and Motisi, 2012; Bedoussac et al., 2014). The mixing of two resource types also benefits agroecosystem functioning through interactive biotic and abiotic effects that create a synchrony between N supply and crop demand (Gentile et al., 2011; Cong et al., 2015; Redin

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et al., 2014). For example, intercropping rapeseed (*Brassica napus* L.) with faba bean (*Vicia faba* L.) accumulated 20% more N per crop species compared to a rapeseed sole crop (Jamont et al., 2013). Spatial and temporal complementarity in intercrops also causes interspecific interactions that enhance N acquisition by the cereal crop and through N_2-fixation by the legume (Bedoussac et al., 2015). Additionally, N stored in the soil and in crop residues from previous cropping seasons (legacy N) influences N dynamics differently in intercrops than in sole crops (Regehr et al., 2015).

To date, most researchers in temperate intercropping systems focused on performance metrics including yield, competition, land equivalent ratio and weed control (Hauggaard-Nielsen et al., 2001; Prasad and Brook, 2005; Waddington et al., 2007; Echarte et al., 2011; Klimek-Kopyra et al., 2013). However, knowledge on the underlying processes of N cycling in agroecosystems when single-source residues are added to soil derived from mixed residue sources are lacking. Therefore, a thorough evaluation of soil biochemical characteristics, especially those that respond rapidly to changes in land management practices, increases our fundamental understanding of N cycling in intercrops. Additionally, understanding how residue types and residue legacy influence N at the soil-crop level advances our knowledge on the underlying processes that govern soil N dynamics in intercrops. The objective of this study was to evaluate N dynamics from added legume or cereal residues to soils from two differently configured cereal-legume intercrops, and cereal and legume sole crops. This was achieved through a 140-day incubation study using $\delta^{15}N$ natural abundance to quantify changes in N and its associated fractions (light fraction, microbial biomass), and to determine the effect of residue addition and crop management system on N_2O emission.

2. Materials and methods

2.1. Field site and sample collection

The research site was located in the southern Argentine Pampa, outside the city of Balcarce (37°45′S, 58°18′W). The climate in this area was classified as temperate humid without a dry season (Köppen classification). The site was located 130 m above sea level. The mean annual rainfall, potential evapotranspiration and the annual mean air temperature (1980–2012) were 860 mm $year^{-1}$, 856 mm $year^{-1}$, and 14.3 °C (maximum 24.2 °C and minimum 7.6 °C), respectively (Unidad Integrada Balcarce Weather Station). The soil was classified as a Luvic Phaeozem (FAO, 2006) with a soil texture of 41.1% sand, 35.8% silt and 23.1% clay (Studddert and Echeverría, 2000). The soil (0–20 cm) was moderately acidic with a pH of 5.77. Soil organic C (SOC) and total N (TN) were 30.6 g C kg^{-1} and 1.64 g N kg^{-1}, and soil C:N ratio was 18.66. The soil had a low available phosphorus (P) of 7.83 mg P kg^{-1} (Bray-extractable P).

Experimental intercrop and sole crop plots were established in 2007 and soil used in the present study was collected in May 2011. The experimental plots were established on land previously under alternating sunflower (*Helianthus annuus* L.) and pasture. The previous crop was 2 years of sunflower and the soil was prepared using a disk harrow followed by a spike harrow. The intercrop study was a randomized complete block design (RCBD) with four crop systems: maize sole crop, soybean sole crop, 1:2 intercrop (one row of maize and two rows of soybeans) and 2:3 intercrop (two rows of maize and three rows of soybeans). Each crop system was replicated three times, and each crop system plot size was 8.8 m × 12 m. The maize and soybean sole crops were rotated annually, but the intercrops were not. Plant density (plants m^{-2}) was 4.3 (1:2 intercrop), 5.3 (2:3 intercrop), 8.0 (maize sole crop) and 29 (soybean sole crop), with a 0.52 m distance between crop rows in all treatments. The soil was disk harrowed three times and spike harrowed once before each crop seeding. Weeds were controlled by *N*-phosphonomethyl glycine (Glyphosate). All crops received P fertilizer annually at a rate of 35 kg P ha^{-1} $year^{-1}$. Maize in the sole crop and in the intercrops received N fertilizer annually at 150 kg N ha^{-1} $year^{-1}$ in the form of urea. Fertilizer was applied by hand at the bottom of the maize stems at the 6th leaf stage in the intercrops. Soybeans were inoculated with *Bradyrhizobium japonicum*. Maize was seeded in late October to early November and harvested in April; soybeans were seeded in November and harvested in May. Crop residues were returned to all treatments after each harvest.

In May 2011, five soil samples (0–20 cm) were extracted from the centre of each crop system replicate to avoid edge effects using a soil corer with a 5 cm inner diameter. Soil was extracted between all possible combinations of rows, including between two maize rows, between two soybean rows and between maize and soybean rows in the intercrops. Soil from each crop system replicate was combined, air dried and sieved to 2 mm. In 2011, after crop harvest, soybean and maize stems and leaves were randomly collected from each crop system replicate, representative of crop residues retained on the field after harvest. Approximately 100 g of soybean or maize residue from each crop system was combined and oven-dried at 65 °C for 48 h. A subsample of the oven-dried residue was ground to a fine powder using a ball mill (Retsch® ZM1, Haan, Germany) and analyzed for N content and $\delta^{15}N$ stable isotope values on a Costech 4010 (Cernusco, Italy) interfaced with a Europa Scientific Tracermass Isotope Mass Spectrometer (Crewe, UK). In all treatments mean values of C and N concentration of crop residue biomass were 422 g kg^{-1} (C) and 6.6 g kg^{-1} (N) for maize, and 448 g kg^{-1} (C) and 14 g kg^{-1} (N) for soybeans. The $\delta^{15}N$ of maize was 3.21‰ and 3.64‰ for soybean residue.

2.2. Experimental design

Prior to the incubation experiment, soil was pre-conditioned for 7 days at 21 °C by adding deionized water to reach a water holding capacity of 60% (wt/wt) (Ross, 1989). For the incubation, 60 g pre-conditioned soil from the soybean sole crop, 1:2 and 2:3 intercrops were placed into 1 L glass jars and mixed thoroughly with 1.5 g soybean residue (Table 1). An additional set of jars containing 60 g pre-conditioned soil from the maize sole crop, 1:2 and 2:3 intercrops was mixed thoroughly with 1.5 g maize residue. A set of jars with no added residue for the intercrops and sole crops was used as a control (Cont). Soil in the Cont jars was also mixed thoroughly to simulate similar conditions to those soils that received residue. Blank jars containing no soil or residue were also included. Each residue addition treatment was replicated three times. All jars were sealed with lids containing septa for gas sampling and kept in the dark at 21 °C for 140 days. Throughout the incubation, soil moisture was maintained at 60% (wt/wt) of field capacity by adding deionized water. The quantity of residue application for all treatments was based on aboveground residue input for the 2010/11 crop season for the intercrops.

Table 1
Experimental treatment acronyms and their description used in the 140 day incubation.

Treatment	Description
C_3-S	Soybean sole crop (S) with added soybean residue
C_3-1:2	1:2 intercrop with added soybean residue
C_3-2:3	2:3 intercrop with added soybean residue
C_4-M	Maize sole crop (M) with added maize residue
C_4-1:2	1:2 intercrop with added maize residue
C_4-2:3	2:3 intercrop with added maize residue
Cont-S	Soybean (S) sole crop control soil (no residues added)
Cont-M	Maize (M) sole crop control soil (no residues added)
Cont-1:2	1:2 intercrop control soil (no residues added)
Cont-2:3	2:3 intercrop control soil (no residues added)