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Grain legume-based rotations managed under conventional tillage need cover crops to mitigate soil organic matter losses

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ABSTRACT

Inserting legumes in low-input innovative cropping systems can represent a good strategy to reduce current N fertilizer dependency while enhancing ecosystem services. However, although the impact of the use of legumes as cover crops has been broadly studied, very little is known about the effects of grain legume-based rotations on soil organic carbon (SOC) and nitrogen (SON). A cropping system experiment with three 3-year rotations with different levels of inclusion of grain legumes: GL0, GL1 and GL2 (none, one, and two grain legumes, respectively), with (CC) or without (BF, bare fallow) cover crops was established in SW France (Auzeville) under temperate climate. Durum wheat was present in all the rotations to act as an indicator of their performance. Soil organic C and SON were quantified before the beginning of the experiment and after 3 and 6 years (i.e., after one and two complete 3-yr rotations). Aboveground C and N inputs to the soil, and C and N harvest indexes and grain yield of the cash crops were also measured. Inserting grain legumes in the rotations significantly affected the amount of C and N inputs and consequently SOC and SON. After two cycles of the 3-yr rotation, the GL1 and GL2 treatments showed a greater decrease in SOC and SON when compared to GL0. However, the inclusion of cover crops in the rotations led to mitigate this loss. Durum wheat produced significantly greater grain yields in GL1 when compared to GL0, while GL2 presented intermediate values. In turn, the incorporation of cover crops did not reduce C and N harvest indexes or the grain yield of the different cash crops. We concluded that, in such conventionally-tilled grain legume-based rotations, the use of cover crops was efficient to mitigate SOC and SON losses and then increase N use efficiency at the cropping system level without reducing productivity.

1. Introduction

Agricultural activity faces the challenge of maintaining current productivity while minimizing environmental risks in order to attain its sustainability. Nitrogen nutrition is a key element to reach this objective due to its implications in crop productivity. Since the discovery of the Haber–Bosch process, the anthropogenic fixation of reactive nitrogen has doubled the natural terrestrial sources of this element (Fowler et al., 2013). In arable cropping systems an overuse of this nutrient has led to major losses such as nitrate leaching to groundwater or gaseous emissions to the atmosphere as nitrous oxide (N_2O) (Bouwman et al., 2013). Moreover, substantial quantities of carbon dioxide (CO_2) are produced during the synthetic fixation of N_2 to NH_3, given the large energetic requirements of this process (Jenkinson, 2001). As a consequence, research efforts must be placed on the design and optimization of arable cropping systems in order to better couple crop N needs and nutrient availability while reducing current dependence on synthetic N fertilizers.

The design of low-input innovative cropping systems with the inclusion of legumes in the rotations as cash or cover crops is a major tool for reducing N losses and N fertilizer-dependence. Crop diversification with legumes not only has advantages in terms of plant N nutrition but also contributes to a breakage effect on pest and disease cycles and to the development of populations of beneficials for crop defense (Voisin et al., 2014). Moreover, the establishment of those cropping systems can improve the current budget of N in areas of the world such as Europe, where nitrogen efficiency (being the quotient between the product output and the total N inputs in the system) is calculated to be around 36% compared to a global average of 50% (Erisman et al., 2011). However, a proper cropping systems design must also take into

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account the effects on soil quality and fertility, natural resource conservation and agricultural productivity.

Soil organic matter represents one of the main indicators of soil quality and fertility (Franzluebbers, 2002). As a consequence, it has a direct impact on plant productivity. Carbon sequestration in soils is assumed to be a useful strategy to reduce the concentration of CO_2 in the atmosphere (Lal, 2004). Recent meta-analyses have summarized the impact of cropping intensification and different management practices such as tillage and fertilization on soil organic matter (e.g., Luo et al., 2010; Maillard and Angers, 2014; McDaniel et al., 2014). Cropping intensification, i.e., the reduction of the bare fallow periods between cash crops, usually results in SOC and SON sequestration due to the increase in the amount of C and N returned to soil as a result of a longer photosynthesis and improved N cycling by legumes (Franzluebbers, 2005; Sainju et al., 2003). In this line, the use of autumn cover crops with the ability to scavenge nutrients can lead to the reduction of nitrate leaching to groundwater (Brennan and Boyd, 2012; Tosti et al., 2014) and other ecosystem services such as an increase in biodiversity (Lal, 2004) and the abatement of soil erosion (Dabney et al., 2001).

In addition to C and N inputs, one determinant aspect of the cropping system capacity to increase SOC and SON is the C:N ratio of crop residues. This ratio is affected by the nutrition status of the plants and their phenological stage. The ratio is greater in mature plants as a consequence of a reduction in N concentration followed by a diminution of water soluble compounds and an increase of more lignified constituents. All the last biochemical attributes are directly related to the decomposition of biomass (Justes et al., 2009; Thorup-Kristensen et al., 2003) which is faster for crop residues with a low C:N ratio such as the leguminous (Sanchez et al., 2004). The addition of easily decomposable plant material to the soil can also lead to a priming effect which entails a burst of microbial activity leading to enhanced SOC decomposition (Kuzyakov, 2010). Regarding to this, Jensen et al. (2012) pointed out the key role of the net N-balance of the soil-plant system as a driver of soil C changes. They also suggested that legumes with a high N harvest index such as soybean do not maintain SOC levels due to the large amount of N that is exported. Moreover, other aspects can also regulate the stocks of SOC and SON when legumes are incorporated in the rotations: (i) the inherent characteristics of legumes in below-ground biomass production, (ii) the amount and quality of root exudates, (iii) the impacts on the microbial community and (iv) the effects on soil structure and C and N protection within soil aggregates (Drinkwater et al., 1998).

In contrast to cereal-based cropping systems, less attention has been paid to the effect of cover crop use on SOC and SON in grain legume-based rotations. Therefore, our objective was to quantify the impact of the incorporation of grain legumes and cover crops on SOC and SON in rotations with an increasing number of grain legumes managed under conventional tillage. We hypothesized that the inclusion of cover crops in grain legume-based rotations would mitigate the loss of SOC caused by the lower C inputs and C:N ratio of leguminous crop residues.

2. Materials and methods

2.1. Experimental site and treatments

The study was carried out in one experimental field of the Institut National de la Recherche Agronomique (INRA) station in Auzeville (SW France) established in 2003. Site characteristics and soil properties at the beginning of the experiment are detailed in Table 1. The location represents a temperate climate. Three 3-year rotations with different number of grain legumes (GL0, GL1 and GL2; no, one and two grain legumes included in the rotation, respectively) with (CC) and without (BF, bare fallow) cover crops were compared, resulting in six different cropping systems. The GL0 treatment consisted of a Sorghum (*Sorghum bicolor L.*) – sunflower (*Helianthus annuus L.*) – durum wheat (*Triticum turgidum L.*) rotation. The GL1 treatment was based on a sunflower – winter pea (*Pisum sativum* L.) – durum wheat rotation while the GL2 treatment consisted of a soybean (*Glycine max L.*) – spring pea – durum wheat rotation. Mustard (*Sinapis alba L.*), vetch (*Vicia sativa L.*) and a vetch – oat (*Avena sativa L.*) mixture were used as cover crops. Durum wheat was established in all rotations as an indicator of the performance of the different cropping systems studied. A conceptual diagram of the six cropping systems studied in the experiment is given in Fig. 1. The different cultivars and seeding rates of the cash and cover crops used in each rotation are shown in Table 2. Depending on the rotation, the use of cover crops aimed to (i) reduce nitrate leaching and (ii) reduce mineral fertilization needs with the use of a legume as a cover crop. The present work covers two rotation cycles (i.e., 2003–2006 for the first cycle and 2006–2009 for the second one). The experiment was laid out with a split-plot design with three blocks with the amount of grain legumes in the rotation as the main plot and the cover crop treatments as the sub-plot. Sub-plot size was 200 × 15 m. Within each rotation, each crop was grown each year in order to take into account the interannual weather variability; hence, each rotation was replicated three times but started with a different crop.

Prior to the establishment of the experiment the field had been devoted to low-input field crops production under conventional tillage. Further information regarding the set-up of the experiment can be found at Plaza-Bonilla et al. (2015).

Table 1
General site and soil characteristics in the 0- to 30-cm and 30- to 60-cm soil depths at the beginning of the experiment in 2003. Values between brackets correspond to the standard deviation.

Site and soil characteristics		
Latitude	43°31′N	
Longitude	1°30′E	
Elevation (m)	150	
Soil depth (cm)	0–30	30–60
pH (H_2O, 1:2.5)	7.0 (0.5)	7.3 (0.7)
CEC ($cmol^+ kg^{-1}$)	18.1 (3.6)	
Organic C ($g kg^{-1}$)	8.7 (1.0)	6.6 (0.8)
Organic N ($g kg^{-1}$)	1.1 (0.1)	0.9 (0.1)
Particle size distribution (%)		
Sand (2000–50 μm)	37.6 (6.4)	29.9 (5.1)
Silt (50–2 μm)	36.8 (2.9)	37.9 (2.1)
Clay (<2 μm)	25.6 (3.7)	30.0 (2.8)

2.2. Crop management

Soil tillage was performed with one pass of rotary harrow to prepare the soil for seeding, followed, when needed, by a pass of cultipacker. A disk plow was used to incorporate the cover crops into the soil. Moreover, when needed, a pass of moldboard plough was performed to 30 cm depth to mechanically control weeds reducing the use of herbicides. Durum wheat and winter and spring peas were seeded with a commercial combined seeding machine while summer crops (soybean, sunflower and sorghum) were seeded with a precision air seeder. Durum wheat was sown in November and harvested within the first fortnight of July. Winter pea was sown in December and harvested during June. Spring pea was sown during February and harvested late June. Sorghum cycle covered the period from late April-beginning of May to late September. Sunflower was sown during the last fortnight of April and harvested during September. Finally, soybean was sown the first week of May and harvested between late September and early October. Crops were sown at a depth of 2–4 cm. The distance between rows was 17 and 50 cm for winter and summer crops,