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Carbon footprint of cropping systems with grain legumes and cover crops: A case-study in SW France

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ABSTRACT

Agriculture contributes to a significant proportion of global emissions of greenhouse gases (GHG) but can also participate in climate change mitigation. The introduction of legumes in crop rotations reduces the dependence on N fertilizers and may mitigate the carbon (C) footprint of cropping systems. The aim of this study was to quantify the C footprint of six low-input arable cropping systems resulting from the combination of three levels of grain legumes introduction in a 3-yr rotation (GL0: no grain legumes, GL1: 1 grain legume, GL2: 2 grain legumes) and the use of cover crops (CC) or bare fallow (BF) between cash crops, covering two rotation cycles (6 years). The approach considered external emissions, on-site emissions and soil organic carbon (SOC) stock changes, and prioritized (i) field observations and (ii) simulation of non-measured variables with the STICS model, rather than default emission factors. As expected, fertilizers accounted for 80–90% of external emissions, being reduced by 50% and 102% with grain legumes introduction in GL1-BF and GL2-BF, compared to the cereal-based rotation (GL0-BF). Cover crops management increased machinery emissions by 24–35% compared to BF. Soil nitrous oxide (N_2O) emissions were low, ranging between 205 and 333 kg CO_2 eq. $ha^{-1}\,yr^{-1}$ in GL1-BF and GL0-BF, respectively. Nitrate leaching represented the indirect emission of 11.6 to 27.2 kg CO_2 eq. $ha^{-1}\,yr^{-1}$ in the BF treatments and 8.2 to 10.7 kg CO_2 eq. $ha^{-1}\,yr^{-1}$ in the CC treatments. Indirect emissions due to ammonia volatilization ranged between 8.4 and 41.8 kg CO_2 eq. $ha^{-1}\,yr^{-1}$. The introduction of grain legumes strongly influenced SOC changes and, consequently, the C footprint. In the BF systems, grain legumes introduction in the rotations led to a significant increase in the C footprint, because of higher SOC losses. Contrarily, the use of cover crops mitigated SOC losses, and lowered the C footprint. These results indicated the need of CC when increasing the number of grain legumes in cereal-based rotations. Despite the multiple known benefits of introducing grain legumes in cropping systems our research highlights the need to consider soil organic carbon changes in environmental assessments.

1. Introduction

Agricultural production contributes to a significant proportion of global emissions of greenhouse gases (GHG), which contribute to global warming. The emissions related to fertilizer production and application to crops, machinery use, and various soil processes represent the main mechanisms underlying GHG emission to the atmosphere from arable crop production (Gan et al., 2012). In this context, the quantification of the carbon footprint is an appropriate tool to estimate the impact of crop production on climate (Knudsen et al., 2014). The C footprint is defined as “the quantity of GHG expressed in terms of carbon dioxide equivalents emitted to the atmosphere by an individual, organization, process, product or event from within a specified boundary” (Pandey et al., 2011).

During the last decades, agricultural production in western countries has relied strongly on the application of nitrogen (N) fertilizers. The availability of synthetic N facilitated the specialization of arable cropping systems on the production of cereals, and made European agriculture highly dependent on synthetic fertilizer-N. However, the mismanagement of this fertilizer, e.g. use of excessive rates and/or application at periods of low crop needs, leads to negative environmental impacts. Among other, nitrate pollution of groundwaters,

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Fig. 1. Cropping systems studied in the field experiment. GL0, GL1 and GL2 stand for three-year rotation with 0, 1, and 2 grain legumes. Cash crops (big circles) and cover crops (small circles) are shown. For color version of this figure, the reader is referred to the online version of this article.

atmospheric pollution from ammonia volatilization, and contribution to global warming due to nitrous oxide (N_2O) emissions constitute main environmental risks derived from inadequate N fertilizer management in agriculture (Bouwman et al., 2013). The diversification of cropping systems with the introduction of legumes as cash crops, cover crops or intercrops represents a key strategy to reduce N fertilizer needs at the crop- and rotation scale (e.g. Bedoussac et al., 2015; Plaza-Bonilla et al., 2017b). Crop rotation with legumes also leads to other agronomic and environmental benefits such as a break-crop effect, which encompasses a range of factors that enhance the production of the subsequent crop due to the improvement of growing conditions (Watson et al., 2017). However, to maximize their benefits, the introduction of legumes requires the adaptation of the cropping system (Plaza-Bonilla et al., 2017b; Reckling et al., 2015).

Currently, the environmental assessments of crop production, such as the C footprint face different limitations. Knudsen et al., (2014) stressed the importance of analyzing the full crop rotation when quantifying the C footprint of low-input cropping systems. The statement of Knudsen et al., (2014) was based on the high reliance of low-input systems on nutrient recycling and green manuring, where the different cash and cover crops of a rotation are interlinked. Different authors also highlighted the need to include soil organic carbon (SOC) changes in C footprint assessments, given the impact of crop rotations and management practices on SOC (Gan et al., 2012; Knudsen et al., 2014; Pandey and Agrawal, 2014). In this line, the inclusion of cover crops in cropping systems has been reported as a feasible strategy to increase the amount of soil organic C (Poeplau and Don, 2015), highlighting the need to include SOC changes in environmental assessments (Prechsl et al., 2017). SOC change is a dynamic, equilibrium oriented process, with constant in- and outflows that depend on management and environmental conditions. Inherent to this perception is that a given stock of SOC can only be depleted once; changes in management would always leave the soil carbon and N cycles strive to a new equilibrium. Essential is thereby the time required to arrive at a new equilibrium and how to set up an experimental approach that captures the new equilibrium.

Another aspect of controversy is the use of global default values for estimating soil GHG emissions, given the extreme variability of pedoclimatic conditions and cropping systems in which crop production takes place, which leads to significant uncertainties in the calculation of some processes such as the emission of N_2O from soils. Regarding to this, Barton et al. (2014) pointed out the need to use site-specific field-based measurements to assess greenhouse gases emissions from cropping systems including grain legumes. Consequently, the collection of empirical data and the use of biogeochemical models can help to increase the accuracy of current GHG emissions assessments (Lares-Orozco et al., 2016). The aim of this study was to quantify the impact of introducing grain legumes and cover crops on the C footprint of low-input cropping systems in an area of SW France. We hypothesized that the diversification of cropping systems with legumes would decrease the C footprint thanks to the savings in synthetic N fertilizer, while the use of cover crops would decrease the C footprint thanks to their positive impact on SOC by increasing the photosynthetic activity versus time according to calendar year. Cover crop residues allow adding C to the soil. The approach considered external emissions and on-site emissions. The impact of the inclusion of soil organic carbon (SOC) stock changes on the C footprint calculation was also assessed, as crop rotations and management practices play a major role on the capacity of soils to store C due to their effects on soil organic C mineralization and crop residues C inputs.

2. Materials and methods

2.1. Experimental design

A field experiment was established in 2003 in the Institut National de la Recherche Agronomique (INRA) in Auzeville (SW France, 43° 31′ 42″ N, 1° 28′56″ E), representative of the pedoclimatic conditions of the Garonne valley. The aim of the experiment was the design and assessment of different low-input innovative cropping systems based on the introduction of grain legumes and cover crops. The cropping systems mainly differed in the amount of synthetic N fertilizer required. Over the last three decades, mean annual rainfall, air temperature and potential evapotranspiration were 685 mm, 13.7 °C, and 905 mm, respectively. Soil characteristics (0–30 cm depth) were analyzed at the beginning of the experiment: soil texture was clay loam, mean ($\pm$ 1 standard deviation) pH (H_2O,1:2.5) was 7.0 $\pm$ 0.5, CEC was 18.1 $\pm$ 3.6 $cmol^+ \ kg^{-1}$, organic C was 8.7 $\pm$ 1.0 $g \ kg^{-1}$ and organic N was 1.1 $\pm$ 0.1 $g \ kg^{-1}$.

Six different cropping systems were compared being the result of the combination of three levels of grain legumes introduction in a 3-yr rotation (GL0: no grain legumes, GL1: 1 grain legume, GL2: 2 grain legumes) and the use of cover crops (CC) or bare fallow (BF) between cash crops (Fig. 1). The GL0 treatment consisted in a sorghum (*Sorghum bicolor* L.) – sunflower (*Helianthus annuus* L.) – durum wheat (*Triticum turgidum* L.) rotation, the GL1 treatment consisted in a sunflower – winter pea (*Pisum sativum* L.) – durum wheat rotation and the GL2 treatment consisted in a soybean (*Glycine* max L.) – spring pea – durum wheat rotation. Durum wheat was a common crop in the three rotations to act as an indicator of the carryover effect of the different cropping systems. Different cover crops were used on each cropping system. In the GL0-CC system cover crops were vetch (*Vicia sativa* L.) and a vetch – oat (*Avena sativa* L.) mixture aimed to increase soil nitrogen availability for subsequent crops and reduce mineral nitrogen applications. In GL1-CC winter pea was accompanied by previous and succeeding mustard (*Sinapis alba* L.) cover crops aimed at reducing nitrate losses, while durum wheat was followed by a vetch-oat mixture to increase soil nitrogen availability. Finally, in GL2-CC mustard was used after spring