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Cover crops mitigate nitrate leaching in cropping systems including grain legumes: Field evidence and model simulations

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ABSTRACT

Grain legume-based cropping systems need to be designed holistically by taking profit of their advantages (e.g. symbiotic fixation of N_2) while reducing environmental risks. In this experiment we studied the impact of the incorporation of cover crops in grain legume-based rotations on the mitigation of nitrate leaching and recycling of N for the subsequent cash crop. A cropping system experiment (2004–2010) with three 3-year rotations of different number 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 at INRA Auzeville (SW France). Soil water and mineral N contents of the entire profile (0–120 cm depth) were measured three times per season at key stages. Shoot cash and cover crop biomass and biomass N concentration were measured and the N acquisition of the different crops was calculated. In addition, the STICS soil–crop dynamic model was used to simulate the amount of daily water drained and N leached under the different rotations studied. STICS performed reasonably well when simulating soil water and soil nitrate contents, crop biomass and N acquired, allowing water drainage and nitrate leaching fluxes to be modelled with confidence. Globally, simulated N leaching was low due to amount of rainfall received during the experimental period which was lower than the 30-year average. As an average of the different crop sequences the cumulative N leaching during the experimental period (i.e. 2004–2010) increased when increasing the number of grain legumes in the rotation when no cover crops were used. However, the use of cover crops reduced N leaching. Within each rotation, cash crop N uptake did not differ between the BF and CC treatments. Our study highlights the importance of a proper design of entire cropping systems, i.e. simultaneously cash crop succession and cover crop, by adapting the crop rotation and the different management practices (i.e. N fertilization, irrigation, etc.) to mitigate the environmental impact of N leaching and reduce as much as possible pre-emptive competition phenomena due to cover crops.

1. Introduction

The introduction of grain legumes in crop rotations is seen as a viable means of reducing current dependence on synthetic N-fertilizers while providing different ecosystem services (Jensen et al., 2012). Compared to cereals, legume incorporation in cropping systems leads to changes in N cycling in the soil–plant–atmosphere continuum given (i) their ability to fix atmospheric N_2 in symbiosis with bacteria, (ii) different rooting traits (Gregory, 1988; Hamblin and Tennant, 1987), (iii) differences in crop development rates and harvest dates, and (iv) greater rate of crop residues turnover due to their inherent biochemical composition (Justes et al., 2009; Thorup-Kristensen et al., 2003). Leguminous residues not only can increase soil mineral N availability as a consequence of their turnover but can also accelerate the decomposition of native soil organic matter, a process known as priming effect (Kuzyakov, 2010). To be sustainable, the cropping systems based on grain legumes need to reach a good synchrony between the amount of N available after harvest and subsequent crop requirements, to avoid exacerbate N losses in terms of nitrate leaching and/or nitrous oxide emission to the atmosphere (Nemecek et al., 2008).

Nitrate leaching is still a major source of concern because of its direct impact on drinking water, its potential of eutrophication of costal sea water and its indirect contribution to the pollution of the atmosphere with ammonia or nitrogen oxides (Bouwman et al., 2013). Due to the increase in surface- and groundwater nitrate pollution in several agricultural areas of Europe, the member states of the European Union adopted the Nitrates Directive (91/676/EC),

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aimed at reducing and preventing water pollution caused by nitrate from agricultural sources (European Union, 1991).

Nitrate leaching from agricultural soils is a complex process that depends on soil characteristics, climatic variables and management aspects. Nitrate leaching losses range between 10% and 30% of the applied N in conventional grain-production systems (Meisinger and Delgado, 2002). Different laboratory and field methods have been tested to quantify N leaching: the use of lysimeters or ceramic suction cups are some examples. However, the use of those methods is surrounded by different limitations such as (i) the alteration of soil structure due to the creation of preferential flow paths when installing lysimeters or ceramic cups, and (ii) the large uncertainty that exists when calculating N losses with ceramic cup lysimeters under low soil water availability conditions that do not allow to obtain adequate sample volumes (Webster et al., 1993). In addition, some of those methods also need an estimation of water drainage at the base of soil profile, adding some uncertainty in the final calculations. In the same line, the estimation of N leaching by field methods is also hindered by the high spatial and temporal variability of this process (Schnebelen et al., 2004; Zhang et al., 2005).

The use of models can provide guidance in the design of cropping systems and the optimization of management practices aimed at reducing N leaching after evaluating the performance of a broad range of scenarios in the long-term (Meisinger and Delgado, 2002).

Different models have been developed to simulate the dynamics of soil and crop processes. Among them, the model STICS has been extensively used for analyzing the impact of different management practices on N leaching under multiple environmental conditions (Constantin et al., 2012; Coucheney et al., 2015; Poch-Massegú et al., 2014), an aspect that proves its adaptability and adequacy.

A range of management practices can help to mitigate N leaching in arable soils including proper soil management practices or the use of precision farming (Di and Cameron, 2002). Another important strategy to reduce the risk of N leaching is the establishment of nutrient-scavenging cover crops (Constantin et al., 2011; Tosti et al., 2014; Thorup-Kristensen et al., 2003). Besides their effect on the reduction of N losses as leaching, cover crops can also provide many other ecosystem services such as an increase in the amount of soil organic matter, an improvement of soil structure, the suppression of diseases, etc. (Alonso-Ayuso et al., 2014; Poeplau and Don, 2015). However, to be efficient, the design of cropping systems with cover crops needs to avoid the pre-emptive competition for water and nutrients in subsequent crops. The date of termination is a critical issue in order to take the maximum advantage of cover crops without compromising the N needs and the performance of the subsequent cash crops (Alonso-Ayuso et al., 2014).

The aim of this study was to investigate and quantify the impact of different low-input cropping systems based on grain legumes without and with cover crops during fallow period, in order to produce a nitrate catch crop effect for mitigating N leaching. Specifically, we wanted to (i) test if an increase in the number of grain legumes in the rotation would led to an increase in N leaching, (ii) quantify the effect of the cover crops to mitigate N leaching, and (iii) explore the existence of a possible N pre-emptive competition as a drawback of the use of cover crops. Our hypothesis was that the introduction of cover crops in an holistic approach is a relevant option to reduce N leaching caused by the increase in soil mineral N availability after grain legumes allowing to improve the use of natural nitrogen resources (nitrate coming from soil mineralization and N_2 fixation).

2. Materials and methods

2.1. Experimental design

This study was carried out in a field experiment established in 2003 in the Institut National de la Recherche Agronomique station in Auzeville (43° 31′N, 1° 30′ E, 150 m.; SW France). Previously, the area was devoted to a low-input rotation managed under conventional tillage. The average of the 30-year annual precipitation, temperature and potential evapotranspiration is 685 mm, 13.7 °C and 905 mm, respectively. Soil texture was clay loam being the distribution of soil particles of 37.0%, 36.3% and 26.7% for sand, silt and clay, respectively. At the beginning of the experiment soil pH (H_2O, 1:2.5), organic C and organic N were 7.0, 8.7 g kg^{-1} and 1.1 g kg^{-1}, respectively, for the first 30 cm depth. Six cropping systems resulting from the combination of three 3-year rotations with 0, 1 and 2 grain legumes (GL0, GL1 and GL2, respectively) with (CC) or without (BF, bare fallow) cover crops were compared in the experiment. The different crop sequences of each rotation and the sowing and harvest/incorporation dates of the cash and cover crops are shown in Table S1 in the electronic supplement. GL0 was a sorghum (*Sorghum bicolor L.*)—sunflower (*Helianthus annuus L.*)—durum wheat (*Triticum turgidum L.*) rotation. GL1 was a sunflower—winter pea (*Pisum sativum* L.)—durum wheat rotation, and GL2 was 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. The experiment consisted in a split-plot design with the amount of grain legumes in the rotation as the main plot and the use of cover crops as the sub-plot. Sub-plot size was 175 × 15 m. Within each rotation, each crop was grown every year in order to take into account the interannual climatic variability, which is significant in

Table 1
Nitrogen fertilizer rates applied to the non-legume cash crops in the different treatments studied (GL0, GL1 and GL2, 3-year rotation with 0, 1 and 2 grain legumes, respectively; BF and CC, bare fallow and cover crops, respectively) during the experimental period.

Rotation	Preceding cash crop	Cash crop	N fertilizer application (kg N ha^{-1})															
			Bare fallow (BF)								Cover crop (CC)							
			2004	2005	2006	2007	2008	2009	2010	Mean	2004	2005	2006	2007	2008	2009	2010	Mean
GL0	Sunflower	Durum wheat	188	182	149	154	158	171	180	169	188	182	149	154	158	171	180	169
	Durum wheat	Sorghum	120	76	76	82	83	112	60	87	120	76	76	82	83	112	60	87
	Sorghum	Sunflower	46	56	51	51	62	67	40	53	46	56	51	51	62	67	40	53
GL1	Winter pea	Durum wheat	188	116	100	104	97	161	140	129	188	116	149	154	127	161	160	151
	Durum wheat	Sunflower	46	0	0	0	0	34	0	11	46	0	0	0	0	34	0	11
GL2	Spring pea	Durum wheat	168	138	100	104	97	134	130	124	168	138	149	154	127	153	110	143

The preceding cash crop is shown for informative purposes.