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Nitrogen use efficiency and fertiliser fate in a long-term experiment with winter cover crops

J.L. Gabriel, M. Alonso-Ayuso, I. García-González, C. Hontoria, M. Quemada*

Technical University of Madrid, Dpto. Producción Agraria, Avd. Complutense s/n, 28040 Madrid, Spain

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ABSTRACT

The use of winter cover crops enhances environmental benefits and, if properly managed, may supply economic and agronomic advantages. Nitrogen retained in the cover crop biomass left over the soil reduces soil N availability, which might enhance the N fertiliser use efficiency of the subsequent cash crop and the risk of depressive yield and pre-emptive competition. The main goal of this study was to determine the cover crop effect on crop yield, N use efficiency and fertiliser recovery in a 2-year study included in a long-term (10 years) maize/cover crop production system. Barley (*Hordeum vulgare* L.) and vetch (*Vicia sativa* L.), as cover crops, were compared with a fallow treatment during the maize intercropping period. All treatments were cropped following the same procedure, including 130 kg N ha^{-1} with ^{15}N fertiliser. The N rate was reduced from the recommended N rate based on previous results, to enhance the cover crop effect. Crop yield and N uptake, soil N mineral and ^{15}N fertiliser recovered in plants and the soil were determined at different times. The cover crops behaved differently: the barley covered the ground faster, while the vetch attained a larger coverage and N content before being killed. Maize yield and biomass were not affected by the treatments. Maize N uptake was larger after vetch than after barley, while fallow treatment provided intermediate results. This result can be ascribed to N mineralization of vetch residues, which results in an increased N use efficiency of maize. All treatments showed low soil N availability after the maize harvest; however, barley also reduced the N in the upper layers before maize planting, increasing the risk of pre-emptive competition. In addition to the year-long effect of residue decomposition, there was a cumulative effect on the soil's capacity to supply N after 7 years of cover cropping, larger for the vetch than for the barley.

1. Introduction

Summer crop farmers are increasing the use of winter cover crops primarily for environmental benefits, as well as economic and agronomic advantages. Cover crops reduce nitrate leaching in many humid (Hargrove, 1991; McCracken et al., 1994; Thorup-Kristensen et al., 2003) and semiarid regions (Salmerón et al., 2010; Gabriel et al., 2012b) and they are an important tool to reduce the risk of diffused water pollution (Thorup-Kristensen et al., 2003). Moreover, cover crops increase organic matter (Kuo et al., 1997), water retention capacity (Quemada and Cabrera, 2002), soil aggregate stability (Roberson et al., 1991) and nutrient supply (Gabriel and Quemada, 2011), and the mulch provided by the residue contributes to soil erosion control (Hargrove, 1991). However, controversial effects on the yield and N uptake of the subsequent main crop have been reported depending on the region, the cover crop species and the management.

Because cover crops improve soil conditions and increase N recycling in the system, they should have a positive effect on the subsequent crop yield compared to the fallow treatment. However, the observed results are sometimes inconsistent, primarily in the case of non-leguminous cover crops (Tonitto et al., 2006; Quemada et al., 2013). A non-effect or a positive effect is common (e.g., Bundy and Andraski, 2005), however, in some situations, a depressive effect on the yield has been reported (e.g., Kramberger et al., 2009) due to water or nutrient competition. In the case of leguminous cover crops, the tendency to increase yield and N uptake is consistent (Hanly and Gregg, 2004; Haas et al., 2007; Campiglia et al., 2010; Kramberger et al., 2014). Furthermore, Kramberger et al. (2014) observed luxuriant N supplies to the maize after a crimson clover cover crop (*Trifolium incarnatum* L.). If cover crops aim to enhance the N effect and increase N use efficiency in the cropping system, an interesting strategy could be keeping soil mineral

* Corresponding author.
E-mail address: miguel.quemada@upm.es (M. Quemada).

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N at a level in which losses are minimised and crop availability is ensured.

Enriched ^{15}N fertilisation is a valuable method to differentiate between N uptake from the fertiliser and from other sources. Fertilisation rates close to the crop's N demand can result in fertiliser use efficiencies of approximately 50%, as observed by Reddy and Reddy (1993) in the Piedmont region (NC, USA), by Bundy and Andraski (2005) in Illinois, by Normand et al. (1997) in France and by Gabriel and Quemada (2011) in Spain. In the last study, it was reported that neither a legume nor a grass cover crop had an effect on the N use efficiency (NUE) with respect to fallow treatment. Even if more N was taken up by the main crop after a vetch cover crop than after a fallow period, the NUE did not increase, meaning that the extra N uptake by the main crop came from sources other than the fertiliser. In this case, there could be an effect of cover crops on the NUE when the fertiliser application is below the crop's N requirements. This is relevant because it may allow the cover crop N-effect and the NUE in the cropping system to be optimized. Bundy and Andraski (2005) observed that there was an effect of winter rye cover crop (*Secale cereale* L.) on maize grain, biomass and N uptake when the fertiliser rate was reduced, which could potentially be masked at non-limiting N fertiliser rates. Moreover, the initial soil mineral N (N_{min}) could be a relevant factor affecting maize NUE; however, this needs to be clarified, particularly at reduced fertiliser rates.

Cover crops can also lead to differences in the soil N availability at sowing time, as well as in the main cropping season (Gabriel et al., 2014). Leguminous cover crops do not reduce soil available N at sowing with respect to a fallow treatment (Gabriel and Quemada, 2011); however, non-leguminous cover crops are prone to reducing it (Wagger and Mengel, 1988; Thorup-Kristensen, 2001). This could lead to N pre-emptive competition with the main crop, which is often related to microbial immobilization, as reported by Garibay et al. (1997) or Kramberger et al. (2014) for grasses as cover crops. However, this initial competition and lower growth rate can be switched to an enhancement of growth in the later stages due to residue mineralization and N supply (Verhulst et al., 2011; Kramberger et al., 2014). The N immobilization can be minimised by using cover crops with low C/N ratio, mixing species or adjusting the cover crop killing date (Ruegg et al., 1998; Doane et al., 2009; Alonso-Ayuso et al., 2014). Reducing N fertilisation should highlight the effects between different cover cropping strategies.

Cover crops are usually grown under non-optimal meteorological conditions; therefore biomass and cover crop establishment can be deficient (Lal et al., 1991; Gabriel et al., 2013). Under semiarid conditions, grasses are usually better adapted because of their tolerance to drought conditions (Bilbro, 1991; Unger and Vigil, 1998; Ramirez-García et al., 2015). However, there are few a studies combining semiarid drought conditions with low N_{min} availability, where legumes could be better adapted. More information is needed concerning the performance of different cover crops as N catch crops under low N_{min} availability.

The main goal of this study was to examine the effect of replacing fallow periods with cover crops in a long-term maize production system with a limited N fertilisation supply. The specific objectives were to determine (i) if cover crops could increase the crop yield, N uptake and NUE of ^{15}N fertiliser applied to maize and (ii) if cover crops were adapted to low N availability conditions.

2. Material and methods

2.1. Soil and site

The study was conducted during 2 years (from October 8, 2012 to September 25, 2014) at La Chimenea field Station (40° 03′N, 03° 31′W, altitude 550 m) located in the central Tajo River Basin near Aranjuez (Madrid, Spain). The soil at the field site is mapped as silty clay loam (*Typic Calcixerept*; Soil Survey Staff, 2014), being deep with a fairly uniform texture for 1.2 m, rich in organic matter and alkaline. The climate of the area is Mediterranean semiarid (Papadakis, 1966) with a 14.2 °C mean annual temperature and approximately 350 mm average rainfall with high interannual variability. Additional information concerning the soil and climatic conditions can be found in Gabriel and Quemada (2011). Measurements during the experiment of the air and soil temperature, humidity, radiation, PAR (photosynthetically active radiation) and wind were recorded by a CR23X micrologger in a Campbell Scientific station located <100 m from the experiment (Fig. 1).

2.2. Experimental design and crop management

The study was conducted as a long-term experiment based on two winter cover crop treatments sowed every year since October 2006 and compared to fields with a fallow treatment. The two cover crop treatments were barley (*Hordeum vulgare* L., cv. Vanessa, 180 kg ha^{-1}) and vetch (*Vicia sativa* L., cv. Aitana, 150 kg ha^{-1}), and the design corresponded to four replications completely randomly distributed in 12 plots (12 m × 12 m). After killing the cover crops in 2013 and 2014, maize (*Zea mays* L.) was planted in all plots and one microplot (2 m × 2 m) was established within each plot to monitor the ^{15}N-labelled fertiliser uptake, recovery and fate. Different microplot positions were used each year with a minimum separation of 4 m. The preceding summer cash crops were maize between 2007 and 2010 and a fallow period in 2011, followed by a sunflower crop (*Helianthus annuus* L., var. Sambro) in 2012 to break the maize monoculture. Mineral N fertilisation during these years consisted of 210 kg ha^{-1} per year during the maize crops and nothing during

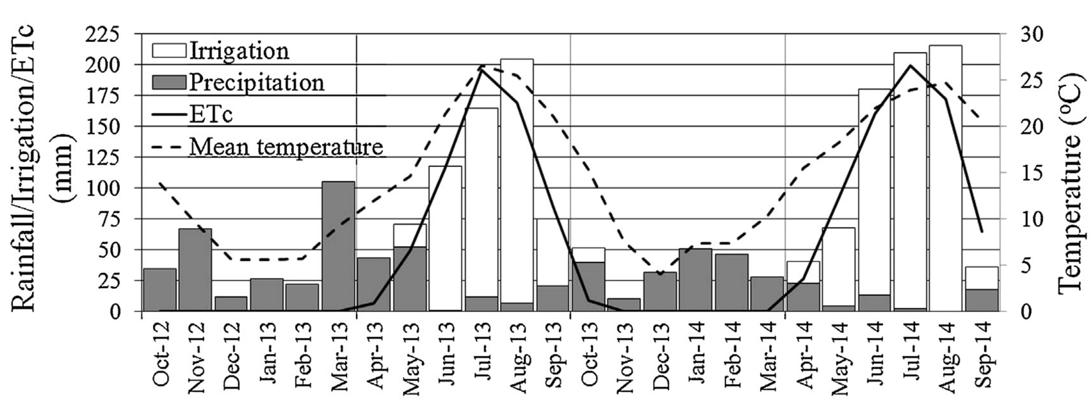

Fig. 1. Monthly mean temperature, rainfall, irrigation and maize evapotranspiration observed during the 2 year experimental period in Aranjuez (Madrid, Spain).