Europ. J. Agronomy 82 (2017) 331–341

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Innovative cropping systems to reduce N inputs and maintain wheat yields by inserting grain legumes and cover crops in southwestern France

Daniel Plaza-Bonilla, Jean-Marie Nolot, Didier Raffaillac, Eric Justes*

INRA, UMR AGIR 1248, 24 Chemin de Borde Rouge – Auzeville, CS 52627, 31326 Castanet Tolosan Cedex, France

ARTICLE INFO

Article history:
Received 1 September 2015
Received in revised form 29 April 2016
Accepted 20 May 2016
Available online 1 July 2016

Keywords:
Crop diversification
Mineral N fertilization
Sorghum
Soybean
Sunflower
Pea

ABSTRACT

The reduction in crop diversity and specialization of cereal-based cropping systems have led to high dependence on synthetic nitrogen (N) fertilizer in many areas of the globe. This has exacerbated environmental degradation due to the uncoupling of carbon (C) and N cycles in agroecosystems. In this experiment, we assessed impacts of introducing grain legumes and cover crops to innovative cropping systems to reduce N fertilizer application while maintaining wheat yields and grain quality. 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 during six cropping seasons. Durum wheat was included as a common high-value cash crop in all the cropping systems to evaluate the carryover effects of rotation. For each cropping system, the water use efficiency for producing C in aerial biomass and yield were quantified at the crop and rotation scales. Several diagnostic indicators were analyzed for durum wheat, such as (i) grain yield and 1000-grain weight; (ii) aboveground biomass, grain N content and grain protein concentration; (iii) water- and N-use efficiencies for yield; and (iv) N harvest index. Compared to the GL0-BF cropping system, which is most similar to that traditionally used in southwestern France, N fertilizer application decreased by 58%, 49%, 61% and 56% for the GL1-BF, GL1-CC, GL2-BF and GL2-CC cropping systems, respectively. However, the cropping systems without grain legumes (GL0-BF and GL0-CC) had the highest water use efficiency for producing C in aerial biomass and yield. The insertion of cover crops in the cropping systems did not change wheat grain yield, N uptake, or grain protein concentration compared to those of without cover crops, demonstrating a satisfactory adaptation of the entire cropping system to the use of cover crops. Winter pea as a preceding crop for durum wheat increased wheat grain production by 8% (383 kg ha^{-1}) compared to that with sunflower – the traditional preceding crop – with a mean reduction in fertilizer application of 40–49 kg N ha^{-1} during the six-year experiment. No differences in protein concentration of wheat grain were observed among preceding crops. Our experiment demonstrates that under temperate sub-mediterranean conditions, properly designed cropping systems that simultaneously insert grain legumes and cover crops reduce N requirements and show similar wheat yield and grain quality attributes as those that are cereal-based.

1. Introduction

It is estimated that the global population will reach nearly nine billion by 2050, a prospect that poses the challenge of producing food sustainably around the globe given the current scenario of severe environmental degradation and climate change (Pretly et al., 2010). As a consequence, the design of modern cropping systems must focus on the best agronomic, environmental and socio-economic performances. Agricultural systemas have become specialized in many areas of the world, leading to a decrease in crop diversity (FAO, 2011). In Europe, the percentage of arable area cropped with legumes has declined from 4.7% in 1961–1.8% in 2011 (Bues et al., 2013). This reduction is explained by the high yield potential of cereals in temperate regions of Europe, the impact of the European Common Agricultural Policy reforms and agro-

Abbreviations: NAR, apparent nitrogen recovery efficiency; NHI, nitrogen harvest index; NUE_y, nitrogen use efficiency for yield; $WUE_{b\text{-}C}$, rotation water use efficiency for production of aboveground biomass C; $WUE_{y\text{-}C}$, rotation water use efficiency for production of grain C; WUE_y, water use efficiency for yield.

* Corresponding author.
E-mail address: Eric.Justes@toulouse.inra.fr (E. Justes).

http://dx.doi.org/10.1016/j.eja.2016.05.010
1161-0301/

nomic difficulties of growing legumes (e.g. low yields and low yield stability, weed competition, disease resistance and grain loss due to lodging and pod dehiscence) (Bues et al., 2013; Preissel et al., 2015). Agronomic research must obtain knowledge about suitable agroecosystems with higher crop diversity that can profit from the broad range of technological tools that are currently available (Tanaka et al., 2002). Increased diversity in cropping systems not only results in lower risks of weeds, pests and diseases, but can also increase a farms'economic resilience to market fluctuations (Ratnadass et al., 2012; Pacín and Oesterheld, 2014).

Nitrogen (N), as one of the most limiting nutrients in agriculture, is a key component in the proper functioning of cropping systems. The availability of relatively inexpensive synthetic N fertilizer in recent decades has led to the decoupling of the N cycle in agroecosystems (Galloway et al., 2003; Tonitto et al., 2006). The specialization of cropping systems in cereal production has exacerbated the dependence on synthetic N fertilizers. This pattern has been worsened by an increase in the share of animal products in the human diet, which has reduced the consumption of plant protein (Lassaletta et al., 2014). The mismanagement of N fertilizer to produce grain in cereal-based cropping systems has adverse environmental consequences, such as nitrate pollution of groundwater, atmospheric pollution from ammonia, and contribution to global warming due to nitrous oxide emissions (Bouwman et al., 2013).

The most common strategy to reduce N fertilizer requirements in cropping systems is the inclusion of legume crops in the rotations (Peoples et al., 2009), whether as a cash or a cover crop. Legumes do not require N fertilizer application because they establish symbiosis with native or inoculated soil bacteria to fix atmospheric N_2. Given the low C:N ratio of their crop residues, they leave higher amounts of N available for subsequent crops due to lower N immobilization during their decomposition (e.g. Justes et al., 2009) and, in some cases, they can also accelerate the decomposition of native soil organic matter (Kuzyakov, 2010). Once legumes are included in a rotation, the key objective is to reach synchrony with the N requirements of the subsequent crop (Stute and Posner, 1995; Hauggaard-Nielsen et al., 2009). Because of this, the cropping system must be completely adapted, beyond the inclusion of legume crops. As demonstrated by Gan et al. (2003), arranging crops in an appropriate sequence leads to more efficient use of resources, which improves soil productivity at the system level. In turn, the crop sequence must be accompanied by the best crop-management practices (e.g. N fertilization rates and timing, soil management, weeding, irrigation).

Unfortunately, cropping systems are not always completely adapted in practice. For instance, Preissel et al. (2015) claimed that some farmers do not significantly reduce N fertilizer application after a legume crop. Hauggaard-Nielsen et al. (2009) and Plaza-Bonilla et al. (2015) stressed the greater risks of nitrate leaching after grain legumes, which results in the need to include cover crops, a practice not usually considered on commercial farms.

Previous studies mainly focused on the influence of legume presence or absence on one performance factor of the subsequent crop, which seems insufficient for a complete analysis of effects of grain legumes in cropping systems. The objective of our study was to evaluate impacts of introducing grain legumes and cover crops in completely redesigned cropping systems (i.e. adapting all management practices) on wheat yield and grain quality to reduce N fertilizer and irrigation dependence. We focused on durum wheat as an indicator of the carryover effects of the cropping system.

2. Materials and methods

2.1. Experimental site and treatment design

A field experiment was established in 2003 at the Auzeville station of the Institut National de la Recherche Agronomique (southwestern France, 43° 31′N, 1° 30′ E, 150 m.a.s.l.). Over the last three decades, mean annual rainfall was 685 mm, air temperature was 13.7 °C and potential evapotranspiration was 905 mm. At the beginning of the experiment, in the upper 30 cm of soil, soil texture was clay loam and mean (±1 standard deviation) pH (H_2O, 1:2.5) was 7.0 ± 0.5, CEC was 18.1 ± 3.6 cmol+ kg^{-1}, organic C was 8.7 ± 1.0 g kg^{-1} and organic N was 1.1 ± 0.1 g kg^{-1}. 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 (Fig. 1). Cover crops differed among cropping systems to reduce susceptibility to nitrate leaching and increase N availability for the subsequent cash crop (Fig. 1). Durum wheat, a traditional cereal in this region, was established in the six cropping systems since it is a high-value cash crop and is sold for semolina and pasta production. Durum wheat acted as an indicator of each system's performance since it was present each year in all rotations, which enabled evaluating the carryover effects of rotation. Within each 3-year rotation, each crop was grown every year to account for interannual climatic variability. The experiment was replicated in two contiguous blocks to include variability in soil texture. Regarding to this, sand and clay proportion was 32 ± 5% and 28 ± 4% for block 1 and 40 ± 5% and 28 ± 4% for block 2. Consequently, 36 plots were cropped (6 rotations × 3 crops × 2 replicates). Plot size was 87.5 × 15 m.

2.2. Crop management

N fertilization was adapted each year for each cash crop according to the balance-sheet method (e.g. Meynard et al., 1997), which considered the N requirements of the cash crop, the availability of soil N and N mineralization estimated using a predicted mineral

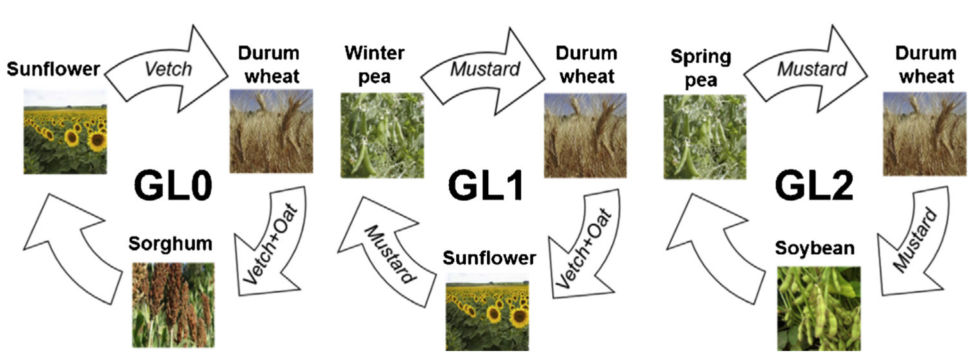

Fig. 1. Conceptual diagram of the cropping systems compared. GL0, GL1 and GL2 correspond to three-year rotations with 0, 1 and 2 grain legumes, respectively. Cash crops are shown in bold. Arrows represent the period between cash crops, under bare fallow (BF) in the GL0-BF, GL1-BF and GL2-BF cropping systems. Cover crops (CC) used in the GL0-CC, GL1-CC and GL2-CC cropping systems are shown inside the arrows and in italics.