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Contribution of green manure legumes to nitrogen dynamics in traditional winter wheat cropping system in the Loess Plateau of China

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ABSTRACT

Excessive application of N fertilizer in pursuit of higher yields is common due to poor soil fertility and low crop productivity. However, this practice causes serious soil depletion and N loss in the traditional wheat cropping system in the Loess Plateau of China. Growing summer legumes as the green manure (GM) crop is a viable solution because of its unique ability to fix atmospheric N_2. Actually, little is known about the contribution of GM N to grain and N utilization in the subsequent crop. Therefore, we conducted a four-year field experiment with four winter wheat-based rotations (summer fallow-wheat, *Huai* bean–wheat, soybean–wheat, and mung bean–wheat) and four nitrogen fertilizer rates applied to wheat (0, 108, 135, and 162 kg N/ha) to investigate the fate of GM nitrogen via decomposition, utilization by wheat, and contribution to grain production and nitrogen economy through GM legumes. Here we showed that GM legumes accumulated 53–76 kg N/ha per year. After decomposing for approximately one year, more than 32 kg N/ha was released from GM legumes. The amount of nitrogen released via GM decomposition that was subsequently utilized by wheat was 7–27 kg N/ha. Incorporation of GM legumes effectively replaced 13–48% (average 31%) of the applied mineral nitrogen fertilizer. Additionally, the GM approach during the fallow period reduced the risk of nitrate-N leaching to depths of 0–100 cm and 100–200 cm by 4.8 and 19.6 kg N/ha, respectively. The soil nitrogen pool was effectively improved by incorporation of GM legumes at the times of wheat sowing. Cultivation of leguminous GM during summer is a better option than bare fallow to maintain the soil nitrogen pool, and decrease the rates required for N fertilization not only in the Loess Plateau of China but also in other similar dryland regions worldwide.

1. Introduction

As a typical rain fed agricultural region, the intensive agricultural development and crop production of dryland farming in the Loess Plateau in China is gradually facing the severe challenge of soil nutrient deficiencies (Li et al., 2009). Extensive wind and water erosion and local unreasonable cultivation practices, including a shortage of organic fertilizer inputs and intensive soil cultivation, exacerbate the degradation of soil quality, resulting in soil with a more fragile physical structure and low organic matter content (in more than 67% of this area, the organic matter is below 1.1%) (Tang, 2004). Therefore, the excessive application of mineral N fertilizer in pursuit of higher yields is a common practice in the traditional winter wheat production system in the Loess Plateau, with the traditional approach of "more fertilizer, more yield". According to a four-year survey on the status of chemical fertilizer applications, as many as 60% of farm households applied pure N fertilizer to wheat at an average rate of over 160 kg N/ha, which is recommended as the suitable N application rate in the Weibei dryland area (Zhao et al., 2013). Excessive applications of chemical N fertilizer may not only reduce crop yields and economical profitability (Qiao et al., 2012) but may also lead to serious soil deterioration and eutrophication from drainage (Vitousek et al., 2009), resulting in nutrient imbalances in the soil, inefficient fertilizer use and large losses to the environment (Ju et al., 2009; Liu et al., 2013). The inorganic N loss from the agro-ecosystem runoff in China has been estimated

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to exceed 1.74×10^9 kg/yr and is a major contributor to pollution of the water system (Duan et al., 2000; Yu et al., 2013). To establish a sustainable dryland cropping system, stable and high crop yields with suitable application of mineral N fertilizer are urgently required.

The cultivation of green manure (GM) crops in agro-ecosystems is an alternative method to resolve the problems of excessive N fertilizer use (Cherr et al., 2006). Because of the unique ability to fix atmospheric N_2 via root nodules and substantial biomass and nutrient accumulation, legumes are the most common plant type used as a GM crop. In different regions of the world, the incorporation of GM legumes (i) enhances the subsequent crop growth and productivity (Seymour et al., 2012), (ii) reduces the risk of nitrate-N leaching (Rinnofner et al., 2008; Yu et al., 2013) and maintains soil fertility and biological activity (Larkin, 2008), and (iii) improves the N economy of the cropping system with the additional N (Mazzoncini et al., 2011). Thus, a viable option is to grow the legumes during the summer fallow period as the GM crop to maintain soil fertility, to improve subsequent crop productivity, and to reduce the application of synthetic N fertilizer.

Few studies have quantified the pattern of N release from different parts of GM legumes, the GM N contribution to grain production, the subsequent crop N-use efficiency of the N fertilizer and GM legumes, the N fertilizer economy, as well as the N balance in the dryland conditions. Hence, a four-year field experiment was conducted to reveal the role of GM legumes in the N dynamics of the traditional summer fallow-wheat cropping system in the Loess Plateau of China. The results of this research will be used to develop a sustainable GM-based cropping system, providing a theoretical basis, and to guide field management strategies for local and other similar dryland regions.

2. Materials and methods

2.1. Experiment I: green manure—winter wheat rotation trial

A four-year field experiment was conducted at the Station of Agricultural Technology Demonstration Center of Changwu County, Shaanxi Province (35°12′N, 107°44′E, and an altitude of 1220 m), on the southern Loess Plateau, beginning in 2008 (Fig. 1). Changwu County has a semiarid continental climate with 50–60% of the annual rainfall from June to September. The average annual sunlight is 2230 h. The average annual temperature is 9.1 °C, with typically 171 frost-free days each year. Agricultural production in this region is completely dependent on natural precipitation. The monthly precipitation (including snow during the winter months) was measured during the experiment. The 56-year average annual (from 1957 to 2012) precipitation is 580 mm.

The soil at the study site had a loose and uniform silt loam texture according to the USDA texture classification system, with moderate fertility and high permeability (Zhang et al., 2011). The soil pH, organic matter, total N, total P, mineral N, available P, available K, and the field capacity at the 0–20 cm depth were 8.11, 12.0 g/kg, 0.79 g/kg, 0.66 g/kg, 13.7 mg/kg, 24.6 mg/kg, 161 mg/kg, and 22.4%, respectively.

The GM and wheat rotation experiment was arranged in a split-plot design. The four main treatments were (1) summer fallow—winter wheat (*Triticum aestivum* L.) (FW, as the control), (2) *Huai* bean (*Glycine ussuriensis* Regel et Maack)—winter wheat (HW), (3) soybean [*G. max* (L.) Merr.]—winter wheat (SW), and (4) mung bean (*Phaseolus radiatus* L.)—winter wheat (MW). The subplot treatments were four rates of N fertilization: 0 (N0), 108 kg N/ha (N108, 67% of N162), 135 kg N/ha (N135, 83% of N162), and 162 kg N/ha (N162, which was the typical rate of N fertilizer application in the study area). The main plots were 6×60 m, and the subplots were 6×5 m. Each main treatment had three replications in this study.

The summer legumes were sown from late June to early July and were terminated at approximately full bloom from the end of August to early September. The plots with mung bean, soybean, and *Huai* bean were established at seeding rates of 135, 150, and 165 kg/ha, respectively. To increase the aboveground biomass and nutrient accumulation, P fertilizer was added as triple superphosphate (TSP, 46% P_2O_5) at a rate of 40 kg/ha before planting in 2008 and 2009. Glyphosate [*N*-(phosphonomethyl) glycine] was used to control weeds in all treatments in early August. After seven or eight weeks, the fresh aboveground biomass of the legumes was manually harvested from the entire plot and weighed. The fresh weights of roots were determined from 3×1 m long randomly selected rows. The aboveground portions of the legumes were cut into approximately 5 cm pieces using the blade of a local farmer and were immediately incorporated into the soil to a depth of 20 cm using a rotary tiller. After the legumes decomposed for two or three weeks, winter wheat was planted at a seeding rate of 180 kg/ha with varying amounts of N fertilizer (urea, 46% N) and 120 kg P_2O_5/ha (TSP, 46% P_2O_5) for each treatment in late September. To control weeds, glyphosate was used again in all treatments in mid-November and mid-March. After harvesting the wheat in late June, the field was plowed with a rotary tiller to prepare the GM seedbed. The wheat stubble was removed from the plots. To test the soil nitrate-N content, soil samples in each plot were collected with an auger from 0 to 200 cm in 20 cm increments at the approximately full bloom stage for the summer legumes, at winter wheat sowing, and at harvest.

2.2. Experiment II: decomposition trial

The decomposition and subsequent nutrient release pattern of the summer legumes (mung bean, soybean and *Huai* bean) were monitored in a field next to the GM-wheat rotation experiment from 2010 to 2011. The above- and belowground parts of the summer legumes were collected at the approximately full bloom stage on September 8, 2010. After cleaning with water and air-drying for 4 h, the above- and belowground parts of the three GM legumes were cut into 2–3 cm lengths. One set of nylon net bags (1 mm mesh, 20×15 cm) contained 75 g of fresh aboveground and 15 g of belowground parts of the GM legumes to determine the patterns of biomass breakdown and nutrient release. Another set of bags (1 mm mesh, 20×20 cm) was used to contain the smaller bags to prevent the interference of litter from the surrounding soil, but the bags were still sufficiently large for microbial access. At the time of the GM legume incorporation, the nylon bags were buried at 10 cm. The bags were collected on eleven sample dates: 0, 3, 7, 14, 21, 28, 56, 112, 176, 286, and 374 d after the incorporation of summer legumes. Three buried bags for each treatment were retrieved on each sample date.

2.3. Laboratory measurements

The winter wheat and summer legume samples were dried at 95 °C for 0.5 h and at 65 °C for 24 h until a constant weight was achieved. These samples were then crushed, homogenized, and analyzed for total N concentration. The N concentration in wheat and summer legume samples was determined with the Kjeldahl method after digestion with concentrated sulfuric acid (H_2SO_4, AR, 98%) and hydrogen peroxide (H_2O_2, GR, ≥30%) (Bao, 2007). The soil nitrate-N was extracted from 5 g of fresh soil with 50 ml of 1 mol/L KCL and was determined with an AutoAnalyzer3 (AA3) continuous flow analyzer.