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Screen for sustainable cropping systems in the rain-fed area on the Loess Plateau of China

Zhiyuan Yao[a], Zheng Wang[a], Jing Li[a], Laurent Bedoussac[b], Suiqi Zhang[c], Yangyang Li[c], Weidong Cao[d], Bingnian Zhai[a], Zhaohui Wang[a], Yajun Gao[a,e,*]

[a] College of Natural Resources and Environment, Northwest A & F University, Yangling, 712100, PR China
[b] AGIR, Université de Toulouse, INRA, INPT, INP-PURPAN, ENSFEA, Castanet Tolosan, France
[c] Institute of Soil and Water Conservation, CAS & MWR, Yangling, 712100, PR China
[d] Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing, 100081, PR China
[e] Key Laboratory of Plant Nutrition and the Agri-environment in Northwest China, Ministry of Agriculture, Yangling, 712100, PR China

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ABSTRACT

A challenge for dryland crop production in China is closing the yield gap while propelling the sustainable development of agriculture when the natural resources are limited. A 4-year fixed field experiment was conducted to analyse the effect of introducing leguminous green manure (LGM) to different cropping systems on soil water, residual nitrate, soil quality and economic benefits to compare their sustainability using a comprehensive scoring system. The main treatments of the experiment were different cropping systems, leguminous green manure-winter wheat (LGM-WW) and leguminous green manure-spring maize-winter wheat (LGM-SM-WW) with summer fallow-winter wheat (SF-WW) as control. LGM late incorporation, early mulch and early incorporation were sub-treatments for LGM-WW while stalk mulch, incorporation and move-away were the sub-treatments for LGM-SM-WW to study the effects of different LGM managements. Compared with SF-WW, LGM-WW decreased average soil water storage before wheat seeding by 11% and increased residual nitrate storage after wheat harvest by 77% while they were not significantly changed for LGM-SM-WW. The soil organic carbon (SOC) content of LGM-WW and LGM-SM-WW in the 0–20-cm layer significantly increased when using legume as mulch. The economic benefits of LGM-SM-WW were 2 times greater than those of the other 2 cropping systems. The scoring system indicates that the total score of LGM-WW ranged from 11.85 to 12.78, which was even lower than that of SF-WW (13.07). On the contrary, the total score of LGM-SM-WW ranged from 16.46 to 18.49. In conclusion, the scoring system determined that the optimum cropping system for sustainable dryland agriculture is leguminous green manure-spring maize-winter wheat with legume stalk mulch.

1. Introduction

Agriculture faces great challenges to ensure global food security by increasing yields while reducing environmental costs. Although China has successfully fed more than 20% of the world population with only 8% of the total arable land (Zhang et al., 2012), the over-application of synthetic fertilizers (especially synthetic N) may related to a series of environmental consequences such as air pollution (Liu et al., 2013), soil acidification (Guo et al., 2010) and soil degradation (Yu et al., 2009; Piao et al., 2009). In addition, the extensive management such as inappropriate field operations also lead to the deteriorate of soil quality, especially depleted soil organic carbon (SOC) and total nitrogen (TN) pools. To minimize the shortcomings of the present production systems while keep increasing the crop yields to meet the demand for food in the future due to the projected peak population in 2030s (Cui et al., 2014), new incentives and policies for promoting the sustainability of agriculture and ecosystem services are required to ensure food security without compromising environmental integrity or public health (Valipour, 2015; Tilman et al., 2002).

Three key aspects are often incorporated into the concept of sustainable agriculture: environmental, economic and social aspects (Ludwig et al., 2011). Soil quality plays a key role in the sustainable development of environmental quality and agricultural productivity (Rasmussen et al., 1998). In general, SOC and TN are the two main indicators of soil quality due to their implications in both the environment and crop production (Malhi et al., 2006; Duan et al., 2016). On the other hand, synthetic nitrogen (N) application can cause the accumulation of residual nitrate in the soil profile and may cause

* Corresponding author at: College of Natural Resources and Environment, Northwest A & F University, Yangling, 712100, PR China.
E-mail addresses: yaozhiyuan298@foxmail.com (Z. Yao), yajungao@nwsuaf.edu.cn, yajungao2008@126.com (Y. Gao).

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environmental problems such as groundwater contamination (Dai et al., 2015). Maintaining the residual nitrate at a relatively low level can be regarded as a practical strategy to minimize the environmental impact. Therefore, both soil quality and residual nitrate can be chosen as indicators of the environmental effects of different cropping systems. However, increasing the yield should not be neglected because it can help to close the yield gap predicted for next 2 decades (Zhang et al., 2013a) and by increasing the economic output, farmers will be more likely to adopt the practice. The sustainable agricultural development for China therefore should integrate the performance of cropping systems both on environmental quality and economic output. For this purpose, a method that can quantitatively appraise the sustainability of cropping system at the field scale was developed.

Legumes can procure N through the symbiotic N_2 fixation and uptake soil mineral N like other plants, no synthetic N fertilizer is then required to grow legume crops. A study covered the main legume crops worldwide indicates that the amount of shoot N ranged from 48 to 129 kg N ha^{-1} while 39–75 kg N ha^{-1} was derived from the atmosphere via symbiotic N_2 fixation (Peoples et al., 2009). Therefore, growing legume as green manure (LGM) as an alternative N source to replace a part of synthetic N applied during crop growth can lower the carbon footprint of agricultural products (Gan et al., 2011). However, it should be noted that the carbon to nitrogen (C:N) ratio of LGM is generally much narrower than straw thus may result in faster N mineralization and increased nitrate accumulation in the soil profile (Li et al., 2015). Several strategies can be applied to solve it, such as reducing synthetic N accordingly when LGM is introduced, decreasing the amount of LGM return, or growing a high N-demanding crop (such as maize or wheat) after the legume to take up the excess N. Furthermore, the combination of legumes and cereal crop residues can also control residual nitrate by synchronizing its release with crop demand (Kampradit et al., 2009).

Dryland farming is important for crop production both in China and throughout the world since it accounts for 51% of the total arable land in China and 39% of that globally (Li et al., 2015). Irrigation is a highly effective means to improve crop yield (Zhang et al., 2013b), however, approximately 40% of the Chinese dryland is located on the Loess Plateau (Li et al., 2015) and part of the land lacks the equipment needed for irrigation. The precipitation from June to September accounts for 50–60% of the limited annual precipitation (Zhang et al., 2009), therefore summer fallow is widely used to store more water for the growth of wheat. However, high temperatures during the summer fallow period can induce large amounts of water loss through evaporation. Many studies have confirmed that only approximately 30% of the precipitation during summer fallow can be stored for use by the next crop (Nielsen and Vigil, 2005; Nielsen and Vigil, 2010; Farahani et al., 1998; Qin et al., 2013). In addition, this practice can also lead to soil erosion that is accompanied by decreased soil organic carbon content, especially when tillage is applied for weed control (Li et al., 2013). Growing LGM crops instead of summer fallow is a way to address the shortcomings of this traditional practice in dryland agriculture and provide an opportunity to develop more sustainable cropping systems.

Previous studies evaluated the effects of LGM on soil quality or economic performance separately (Sharama and Behera, 2009; Saseendran et al., 2013) because it's unlikely to compare the comprehensive effect of these 2 distinctive aspects quantitatively. Our previous study appraised the economic performance of 3 different LGMs in a LGM-winter wheat cropping system (Zhang et al., 2015). However, the sustainability of LGM in varied cropping systems with diversified management regimes is not yet studied. To close this knowledge gap, we chose soil quality (SOC, TN) and residual nitrate storage after 4 years to indicate the environment performance and examined gross revenue and output/input to show the economic performance based on the key aspects of sustainable agriculture and specific agricultural challenges mentioned above for China. A scoring system was then used to transform these parameters into scores, which enabled us to calculate the scores of different sections separately as well as the final score, thus making the sustainability of different cropping systems comparable. In this study, we introduced LGM and designed several LGM management regimes to alleviate the shortcomings of the widely applied local practices. The scoring system was then applied to all treatments to screen for the optimum cropping system(s) according to their final scores.

2. Materials and methods

2.1. Experimental site and soil type

This experiment was conducted at Shilipu village (35°13′14″N, 107°45′44″E, 1220 m above sea level), Changwu County, Shaanxi Province, China. This site receives 2994 °C of cumulative temperature and 171 frost-free days. The average annual precipitation is 588 mm, with approximately 50-70% occurring during the summer and early autumn.

The loess soil at the experimental site is classified as a Cumulic Haplustolls (USDA Soil Taxonomy) with a water field capacity of 22.4%. The properties of the 0–20-cm soil at the beginning of the experiment were as follows: organic carbon, 8.15 g kg^{-1}; total nitrogen, 0.90 g kg^{-1}; nitrate, 13.74 mg kg^{-1}; pH, 7.50; total phosphorus, 0.66 g kg^{-1}; Olsen phosphorus, 4.02 mg kg^{-1}; and available potassium, 131.95 mg kg^{-1}.

2.2. Experimental design and field management

The experiment included 3 cropping systems: leguminous green manure-winter wheat (LGM-WW), leguminous green manure-spring maize-winter wheat (LGM-SM-WW) and summer fallow-winter wheat (SF-WW), with the last serving as the control. Under LGM-WW, the LGM crop was managed in 3 different ways: 1) terminated at the full-bloom stage in early or mid-September followed by immediate incorporation by rotavator (early incorporation); 2) terminated at the full-bloom stage and mulched onto the surface of the ground, followed by incorporation 1–2 days before wheat seeding (early mulch); or 3) terminated followed by incorporated tillage 1–2 days before wheat seeding (late incorporation). The termination date for the last treatment was approximately 2 weeks later compared with that of the other 2 treatments. Under LGM-SM-WW, the LGM crop would grow until the mature stage, but after the grain was harvested, the stalk was managed differently: 1) mulched onto the surface during winter followed by incorporated tillage 1–2 days before spring maize seeding (stalk mulch); 2) incorporated immediately (stalk incorporation); or 3) removed the stalks of LGM (move-away), which also corresponded to local practice. There were 7 treatments in total and 4 replications, each plot was $36 \times 6\ m^2$. Both the rotation sequence for SF-WW and LGM-WW was 1 year; for LGM-SM-WW, a complete rotation sequence was 2 years. Therefore, the comparison between them in some sections was presented on a 2-year scale.

The experiment was initiated in June 2009 and finished in June 2013. Four rotation sequences were completed for SF-WW and LGM-WW and two for LGM-SM-WW. The monthly precipitation and growing period of different crops from 2009 to 2013 are shown in Fig. 1. The LGM was Huai bean (*Glycine ussuriensis* Regel et Maack) seeded at 75 kg ha^{-1} in late June or early July after wheat harvest. The winter wheat (*Triticum aestivum* L.) consisted of a widely used local cultivar called "Changwu 521" seeded at 180 kg ha^{-1} in late September. Considering the N provided by LGM, synthetic N for wheat was applied at a rate of 135 kg N ha^{-1} (18% lower than that of local practices, 162 kg N ha^{-1}) while 120 kg P_2O_5 ha^{-1} were applied before wheat seeding as basal fertilizer. The spring maize (*Zea mays* L.) cultivar "Shendan 16" seeded at 45 kg ha^{-1} in late April, with 180 kg N ha^{-1} and 90 kg P_2O_5 ha^{-1} applied before seeding as basal fertilizer. The N