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Ecological intensification management of maize in northeast China: Agronomic and environmental response

Rongrong Zhao[a,b], Ping He[a,b,*], Jiagui Xie[c], Adrian M. Johnston[d], Xinpeng Xu[a], Shaojun Qiu[a], Shicheng Zhao[a]

[a] Ministry of Agriculture Key Laboratory of Plant Nutrition and Fertilizer, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences (CAAS), Beijing 100081, PR China
[b] International Plant Nutrition Institute (IPNI) China Program, CAAS-IPNI Joint Lab for Plant Nutrition Innovation Research, Beijing 100081, PR China
[c] Jilin Academy of Agricultural Sciences, Changchun, Jilin 130124, PR China
[d] International Plant Nutrition Institute (IPNI), 104-110 Research Drive, Saskatoon SK S7N3R3, Canada

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ABSTRACT

Optimum field management practices need to be developed and improved to solve the challenge of increasing food production while retaining the ecological integrity of farming system underlying the goal of sustainable agriculture. In our study, the concept of ecological intensification (EI) was applied to a spring maize cropping system in Jilin province, China during 2009–2013. Results indicated that the average grain yield was 11.8 t ha^{-1} in the EI treatment; while the farmers' practice (FP) treatment had an average of 11.4 t ha^{-1} grain yield across five seasons. The Hybrid Maize Model was used to simulate the potential yield under water-limited condition, and the results showed that grain yield with 92.6% of the average potential yield (14.3 t ha^{-1}) in EI treatment was closer to the yield potential than FP treatment. Adjusted nitrogen (N) fertilizer rate, split-application of N at the right time and suitable recommended hybrid maize plant density were used for improving N use efficiency and decreasing the negative effects to the environment. Consequently, a total of 180 kg N ha^{-1} was enough for maize growth and resulted in equal plant N uptake as the 251 kg N ha^{-1} applied in FP. Higher agronomic efficiency of N (AE_N), recovery efficiency of N (RE_N) and partial factor productivity of N (PFP_N) in EI treatment (39.7 kg kg^{-1}, 66.1% and 66.2 kg kg^{-1}, respectively) were observed relative to those in FP treatments (26.9 kg kg^{-1}, 42.5% and 50.4 kg kg^{-1}, respectively). Improved N use efficiency contributed significantly less N loss to the environment. Our results showed that calculated residual N_{min}, the apparent N loss and total GHG emission was 37.5%, 34.3% and 29.8% lower in EI treatment when compared to FP treatment. This study helps quantify and understand the concept and practices of EI. Adoption of 4R Nutrient Stewardship (fertilizer right source, right rate, time and placement) and supporting agronomic practices (optimizing plant density and plant hybrid selection) in our study optimized crop production and minimized potential environmental impact.

1. Introduction

Global agriculture is facing the challenge of rising world-wide population and massive food demand. This occurs when issues like farmland decline, water resources depletion and insecurity and environmental degradation are gathering increased attention. China is facing the great challenges to feed one fifth of the world's population on less than one tenth of its arable land and limited freshwater resources.

Ecological intensification (EI) was first termed to describe a production system that satisfied the anticipated increase in food demand while meeting acceptable standards for environmental quality by Cassman (1999). Attaining high grain production while minimizing environmental cost by integrating the ecological management practices will be more likely to adopt in the future of China. The key points of EI have been associated with the eco-efficiency and focused on the debate around food production and environmental protection. EI aims to establish common practices based on ecological and evolutionary science (Dension, 2012). The use of EI practices represents a sustainable way of knowledge and

* Corresponding author at: Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, CAAS. No. 12, Zhongguancun South Street, Beijing 100081, PR China.
E-mail address: heping02@caas.cn (P. He).

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technologies in agriculture development which aims to address food security and environmental security. In the last decades, numerous field trials conducted in different sites have demonstrated the eco-efficiency ideas of EI. In recent studies, heterotic hybrids adoption plus the use of fertilizer and herbicide have helped US corn yield increased from 7.1 t ha^{-1} in 1990s to 9.4 t ha^{-1} in 2000s (Flavell 2010). Crop-legume intercropping system has been proved to be a useful component of EI in Mozambique, Africa (Rusinamhodzi et al., 2012). Optimized plant density, fertilizer N and water management could improve rice yield, N and water use efficiency in Amazonia (Gehring et al., 2013). According to these results, scientists and researchers have summarized that EI should be less dependent on non-renewable resources and should maintain soil fertility and biodiversity. To be specific, EI requires efficient use of input (fertilizer, pesticide), optimized practices (irrigation, cropping intensity) and minimal impact on global warming (greenhouse gas emission).

However, past agricultural intensification (e.g., Green Revolution) was mainly connected with negative impacts on natural resources and high environmental cost to solve the staple crop production. In China, the crop production systems have been performed as multiple crop rotation system (maize-wheat, rice-wheat, and rice-rice) since the 1950s. According to Zhang et al. (2011), the average maize yield was as high as 8.5 t ha^{-1} due to the adoption of new maize varieties in the field experiment conducted in northeast China, 37.6% higher than the average yield of 5.3 t ha^{-1} in farmers' field with old varieties. Moreover, the attainable maize yield in northeast China could be as large as 16.8 t ha^{-1} through high inputs of nutrients, water, labor and other additional improvements including crop straw return, no-tillage, and applications of organic manure (Fan et al., 2010). Due to this highly intensification in production systems, Chinese produced more than fourfold the grain production in 2010s compared to 1960s (Bishwajit et al., 2013). The cost for this yield increase is the high-input of fertilizer, pesticides and high environment risks including degradation of land and freshwater, emissions of greenhouse gases and loss of biodiversity (Chen et al., 2014; Davidson 2009; Christopher and Tilman, 2008; Diaz and Rosenberg, 2008; Guo et al., 2010). According to the statistics from China Agriculture Yearbook (2013), an estimated 74.3 Mt chemical fertilizer was consumed to produce 589.6 Mt crop productions in 2012. Fertilizer N application rate increased by 12.2%, 19.1% and 6.4% for wheat, rice and maize from 2000 to 2007 (Li et al., 2010). Meanwhile, low recovery efficiency of nitrogen (RE_N) values were found with values of 28.2%, 28.3% and 26.1% for wheat, rice and maize respectively when compared to the worldwide RE_N value which ranged from 40 to 60% (Zhang et al., 2008; Fan et al., 2012). High chemical fertilizer input, especially fertilizer N, caused great negative effects on environment quality, especially within and adjacent to farm fields and local fresh water. Over 50% of lakes were eutrophic in China, and soil acidification is becoming a major problem from fertilizer N cycling process (Guo et al., 2010).

Maize (*Zea mays* L.) is one of the important cereal crops which plays a significant role in expanding the overall grain production capacity in China. Sufficient yield information has been collected from a large number of farms, but producing higher yields under optimum management condition is far from clear. To date, how to narrow the yield gap between optimal treatment and farmers' practices and improve the attainable yield or achieving similar production levels with integrated management practices or reduced resources input and efficiency are still the challenges which the future of China agriculture is facing. According to Cui et al. (2008a,b), the average on-farm RE_N and partial factor productivity of nitrogen (PFP_N) for maize in the North China Plain were 16% and 37 kg kg^{-1} between 2002 and 2006. However, the average on-farm RE_N value in U.S. Corn Belt was 37%, which is more than twice than that in China (Cassman et al., 2002; Dobermann, 2005). The PFP_N value in some developed countries has been steadily maintained at 49 kg kg^{-1} since 1980s (Dobermann and Cassman, 2005). It was reported that current indigenous N supply was over 270 kg N ha^{-1} yr^{-1} in wheat-maize system in north China, and 90 kg N ha^{-1} of residual nitrate-N after harvest should be the maximum limit in the top 90 cm soil layer for achieving high maize yield (Cui et al., 2008a, 2008c; Cui et al., 2010). In our study, optimal nutrient management based on EI principles in the high-yielding maize cropping system was matched not only in fertilizer quantity and application timing, but was also dependent on improved agronomic practices (including variety, weather conditions and environment impact). Two main treatments were defined in our project. One was EI treatment with a fertilizer rate of 180 kg N ha^{-1} (N180), different N application methods and a higher plant population, which generally represents a trend of new Ecological Intensification of fertilizer N application. On the other hand, one traditional method of "Farmer's Practice (FP)" was defined as a higher fertilization rate in northeast China, average 251 kg N ha^{-1} (N251) with only basal dressing of all N, P and K fertilizer, and a lower plant population of 50,000/ha compared to the EI treatment. Therefore, the objectives of our study were to (1) compare the main differences in yield, N use efficiency and soil N loss from a 5-year period between EI and FP treatment, and (2) evaluate the agronomic and environmental effect of EI practices on grain yield, N efficiency parameters, and N losses and greenhouse gases (GHG) to provide scientific guidance to increase grain yield and N efficiency while minimizing adverse environmental effect.

2. Materials and methods

2.1. On-farm experiment

The long-term field experiment was conducted at Liufangzi County, Gongzhuling City, Jilin province which is located at 43°34.86′ N and 124°53.92′ E. The study area has a temperate and semi-humid continental monsoon climate. The mean annual air temperature is 18.2 °C. The average annual precipitation is 480–600 mm with average 140 days frost-free period. The basic baseline soil test parameters were pH of 6.06, organic matter of 20.4 g kg^{-1}, alkaline-extractable N of 118.2 mg kg^{-1}, Olsen-P_2O_5 75.7 mg kg^{-1} and NH_4OAC-extractable K_2O 122.4 mg kg^{-1}. The field experiments were initiated in the spring of 2009 with four treatments with four replications.

The Nutrient Expert (NE) for hybrid maize was used for fertilizer recommendations for the EI treatment (Pampolino et al., 2012). A series of information required based on five modules in the NE decision support tool, including current farmers' practice, plant density, site-specific nutrient management, and sources and splitting and profit analysis. According to Xu et al. (2014), expected yield response to fertilizer and agronomic efficiencies of applied N were the main determinant factors for fertilizer application rate. The fertilizer rate of 180 kg N ha^{-1}, 75 kg P_2O_5 ha^{-1} and 90 K_2O kg ha^{-1} in EI treatment, which is in accordance with the concept of ecological intensification system and represents a new trend of fertilizer application. Meanwhile, the FP treatment received fertilizer supply of 251 kg ha^{-1} N, 145 kg ha^{-1} P_2O_5 and 100 kg ha^{-1} K_2O from 2009 to 2013 which represent an average fertilizer rate applied in northeast China (Xu et al., 2014). An additional 30 kg S ha^{-1} and 5 kg Zn ha^{-1} was applied to EI based on soil test results to eliminate nutrient deficiencies in 2009. The N rate in the EI treatment with 180 kg ha^{-1} which were one quarter of N, all P_2O_5 and K_2O applied as basal and the remaining N applied for topdressing. FP treatment adopted 251 kg ha^{-1} with all N, P_2O_5 and K_2O applied as basal which was 28.3% higher N rate than in the EI treatment. The adjustment between EI and FP treatment also