Pedosphere **26**(2): 137–147, 2016
doi:10.1016/S1002-0160(15)60030-3
ISSN 1002-0160/CN 32-1315/P

Published by Elsevier B.V. and Science Press

PEDOSPHERE

www.elsevier.com/locate/pedosphere

Improving Yield and Nitrogen Use Efficiency Simultaneously for Maize and Wheat in China: A Review

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(Received October 19, 2015; revised January 16, 2016)

ABSTRACT

Achieving both high yield and high nitrogen use efficiency (NUE) simultaneously has become a major challenge with increased global demand for food, depletion of natural resources, and deterioration of environment. As the greatest consumers of N fertilizer in the world, Chinese farmers have overused N, and there has been poor synchrony between crop N demand and N supply because of limited understanding of the N uptake-yield relationship. To address this problem, this study evaluated the total and dynamic N requirement for different yield ranges of two major crops (maize and wheat), and suggested improvements to N management strategies. Whole-plant N aboveground uptake requirement per grain yield (N_{req}) initially deceased with grain yield improvement and then stagnated, and yet most farmers still believed that more fertilizer and higher grain yield were synonymous. When maize yield increased from < 7.5 to > 12.0 Mg ha^{-1}, N_{req} decreased from 19.8 to 17.0 kg Mg^{-1} grain. For wheat, it decreased from 27.1 kg Mg^{-1} grain for grain yield < 4.5 Mg ha^{-1} to 22.7 kg Mg^{-1} grain for yield > 9.0 Mg ha^{-1}. Meanwhile, the percentage of dry matter and N accumulation in the middle-late growing season increased significantly with grain yield, which indicated that N fertilization should be concentrated in the middle-late stage to match crop demand while farmers often applied the majority of N fertilizer either before sowing or during early growth stages. We accordingly developed an integrated soil-crop system management strategy that simultaneously increases both grain yield and NUE.

Key Words: crop N requirement, high yield, integrated soil-crop system management, N application timing, N demand

Citation: Meng Q F, Yue S C, Hou P, Cui Z L, Chen X P. 2016. Improving yield and nitrogen use efficiency simultaneously for maize and wheat in China: A review. *Pedosphere*. **26**(2): 137–147.

INTRODUCTION

By 2050, the global population is predicted to reach 8.0–10.4 thousand million, with a median value of 9.1 thousand million, and food supplies are projected to increase by 70%–110% (World Summit, 2009; Tilman *et al.*, 2011). Given limited capacity for arable land expansion, it requires sustaining yield improvement (*e.g.*, vegetable and grain) in existing land to meet the increasing food demand (Cassman, 1999). High grain yield means more carbohydrate accumulation and higher crop nitrogen (N) requirement in total (Cassman *et al.*, 2002). Tilman *et al.* (2001, 2002) forecasted that global N fertilizer consumption would need to increase by 2.7 times by 2050 to meet food demand. However, without significant N use efficiency (NUE) improvement, this increase in N fertilization would lead to eutrophication in terrestrial, freshwater, and near-shore marine ecosystems, which would cause unprecedented environmental and ecological degradation and threaten human survival (Galloway and Cowling, 2002; Ju *et al.*, 2009). Thus, it is crucial to simultaneously increase grain yield and NUE, and it is a key challenge for agricultural development in the next few decades (Cassman *et al.*, 2002; Ciampitti and Vyn, 2011, 2012, 2013).

Recent studies on improving NUE in crop production have emphasized the need for greater synchrony between crop N demand and N supply from various sources throughout the growing season (Cui *et al.*, 2010; Ciampitti and Vyn, 2012; Zhang *et al.*, 2012). This approach has been extremely successful in contemporary cropping systems with middle levels of grain yield. However, attempts to manage N supplies to achieve significant increases in yield have been constrained by knowledge in the relationship between N requirements of a high-yielding system and management practices (Cassman *et al.*, 2002; Setiyono *et al.*, 2010; Ciampitti and Vyn, 2011, 2012). For example, global N consumption increased more than 9-fold, from

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11 to 106 Mt, while grain yield only increased by 164% from 1960 to 2009 (FAO, 2012). To solve this problem, the development of robust N fertilization strategies for high-yielding crop systems is a crucial step toward achieving food security and environmental protection (Cassman *et al.*, 2002).

With the largest population in the world, China consumed over 57 Mt of N fertilizers in 2010, approximately 32% of the total global consumption (FAO, 2012). Despite of a 55% increase in N fertilizer consumption from 37 Mt in 1990 to 57 Mt in 2010, grain yield only improved by 28% (FAO, 2012). During the last decade, 54% of the global increase in N fertilizer consumption (about 11 Mt) was attributed to China. Increased N fertilizer application did not improve grain yield but did cause a series of environmental problems, including the eutrophication of surface waters (Le *et al.*, 2010), soil acidification (Guo *et al.*, 2010), various air-pollution problems (Liu *et al.*, 2011), and increased greenhouse gas emissions (Zheng *et al.*, 2004).

In this paper, we briefly review the current chemical N management status in China and then suggest improvements to N management strategies by clarifying N requirements in intensive maize (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.) cropping systems. Finally, we developed an integrated soil-crop system management (ISSM) to simultaneously improve crop productivity and NUE.

CURRENT N MANAGEMENT IN CHINA

Since the 1990s, China's agricultural production has encountered an unprecedented challenge: a decrease in NUE with stagnated grain yields (Zhang *et al.*, 2011). The recovery efficiency of N fertilizer in cereal production decreased from 30%–35% in the 1980s (Zhu, 1998) to < 20% in the 2000s (Cui *et al.*, 2010), which was much lower than the global values of 33%–37% (Raun and Johnson, 1999; Smil, 1999; Cassman *et al.*, 2002). This decrease in China's NUE was caused by poor N management. Under these conditions, we need to understand the current farmers' and researchers' N fertilization practices in order to improve NUE.

Current N management practices

Overuse of chemical N fertilizers. N fertilizer is often overused by Chinese farmers in intensive crop production, with large variation in application rates (Cui *et al.*, 2010). For example, based on numerous on-farm investigations, the N rate in maize production is typically about 257 kg ha^{-1}, varying from < 100 to nearly 400 kg ha^{-1}. Meanwhile, the average maize yield is around 6.8 Mg ha^{-1} and N uptake is only 132 kg ha^{-1} (Chen *et al.*, 2011). For wheat, the N rate is as high as 325 kg ha^{-1} on average (ranging from 120 to 729 kg ha^{-1}), with 5.8 Mg ha^{-1} grain yield. Yet, wheat N uptake was estimated to be only 160 kg ha^{-1} (Cui *et al.*, 2010). According to the field results from region-wide experiments, the economically optimal N rate averages 150 kg ha^{-1} (ranging from 130 to 160 kg ha^{-1}) for both wheat (about 6 Mg ha^{-1} grain yield) and maize (about 9 Mg ha^{-1} grain yield) (Cui *et al.*, 2008a, b).

In a winter wheat-summer maize rotation system in the North China Plain, N surplus (N fertilizer input – crop N uptake) was calculated to be as high as 227 kg ha^{-1} year^{-1}, which is substantially higher than 10 kg ha^{-1} year^{-1} in the corn-soybean rotation in USA (Vitousek *et al.*, 2009). Accordingly, some studies have shown that additions of N fertilizer could be cut in half without a loss of yield, which would reduce N loss by > 50%, when N sources from the environment and soil are also taken into account (Ju *et al.*, 2009). Clearly, N fertilizer application has far exceeded crop requirements for achieving the highest potential in wheat and maize yield in China.

Though affected by the Green Revolution, most farmers still believe that more fertilizer and higher grain yield are synonymous. In addition, small-scale farming, with high variability between fields and poor infrastructure in the extension service, has resulted in the duplication of effort and low efficiency for current N management practices in China. High off-farm incomes and relatively low retail prices for N fertilizers have also encouraged farmers to continuously increase their application of N.

Poor synchrony of N supply with crop N demand. In typical farm practices, fertilizer applications are often based on experience rather than real-time nutrient requirements of crops and/or site-specific knowledge of soil nutrient status (Zhang *et al.*, 2012). For example, in wheat production, a single large N fertilizer application is used by one-fifth of farmers, with > 300 kg ha^{-1} N being applied (Cui *et al.*, 2008b). The remaining farmers applied N fertilizer at two times, with > 130 kg ha^{-1} of N fertilizer being applied before sowing, representing more than a 2-fold increase in N uptake during the period from sowing to the next N application (at stem elongation stage). Early in the growing season, young crops do not yet have extensive root systems in the soil and their overall mass is low, and therefore, they do not have the capacity to store N. Thus, N uptake capacities are inherently low and these large quantities of early N fertilizer applications are prone to