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Agronomic and environmental causes of yield and nitrogen use efficiency gaps in Chinese rice farming systems

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ABSTRACT

Yield (YG) and nitrogen use efficiency (NUE) gap analysis is a key tool in addressing the sustainable intensification of agricultural systems. Distinguishing and quantifying the underlying agronomic and environmental causes of these gaps is as important as estimating their magnitude. We applied a field experimental framework that allowed us to partition YGs and NUE gaps due to crop management, climatic factors and/or inherent soil productivity. YG and NUE gaps were determined as the differences between yields and NUE under standard farm practices and the attainable yield and NUE using optimum management practices. In farmer's fields in China, the rice YG and NUE gap (expressed as the partial factor productivity of applied N, namely kg rice grain per kg fertilizer N applied, PFP_N) averaged 1900 kg ha^{-1} and 18 kg kg,$^{-1}$ respectively. However, both were subject to large variability within and across different rice farming systems in response to key agronomic and environmental variables, with larger gaps in moderate- and low-yielding fields and in single rice systems. Management practices such as optimizing N and water management and increasing rice transplanting density simultaneously narrowed the YG by 38% and the NUE gap by 39% on average. Climatic- (YG-C) and inherent soil productivity-based YGs (YG-S), which represented fractions of YG derived from climate and soil variability, accounted for on average 16% and 38% of the total YG across low- and moderate-yielding fields in single rice systems, and by 14% and 27% in early and 11% and 20% in late rice farming systems, respectively. Growing-degree days (GDD) for early rice and daily minimum temperature (T_{MIN}) for late rice were the best predictors of YG-C. For single rice in the Yangtze Delta, YG-C included multiple factors such as lower daily mean temperature and GDD, and higher daily maximum temperatures and precipitation during rice growing periods. Soil nutrient supplying capacity was partially responsible for YG-S in those under-performing fields. Significant and exploitable potential exists for increasing rice productivity with higher NUE, especially in moderate- and low-yielding fields. However, national and regional agricultural policies should place more emphasis on supporting good agronomy and soil management, thus moving towards a soil-climate smart management approach in rice farming systems.

1. Introduction

Rice (*Oryza sativa* L.) is the staple food of over three billion people and plays an important role in the national economy in many developing countries (Dat Van, 2001). China is the largest producer of rice, accounting for 19% of the global area sown and 29% of the total production of rice grain (FAO, 2013). Although rice consumption per capita may decline slightly in China as a result of overall economic development, further increases in rice production will be necessary to meet the demands of the growing population (Peng et al., 2009; Fan et al., 2012; Chen et al., 2014). This can only be achieved by increasing rice yields per unit area on the slowly declining planting area. Much effort has been spent in recent decades on genetic modification and the development of more effective management practices designed, to increase productivity through increasing the yield potential or decreasing the yield gap (YG), the difference between the yield under optimum

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management and the average yield achieved in normal agricultural practice by farmers (Yuan, 1996; Van Ittersum and Rabbinge, 1997; Evans, 1998; Cassman, 1999; Lobell et al., 2009; Chen et al., 2014).

Unfortunately, average national rice yields have stagnated in recent years (Ray et al., 2012; Grassini et al., 2013). Average rice yields in the intensive rice-growing regions of China may have reached 75–85% of the current genetic-climatic yield potential (Cassman, 1999; Van Wart et al., 2013), but there is likely to be huge variation among regions and farms, which can be further exploited. The assessment of mean yields and YGs on a national or regional scale may be masking wide heterogeneity of diverse smallholder rice farming systems. About 30 million ha of paddy soils are managed by more than 150 million farmers over a wide range of agroecological zones with very different climate and soil conditions and management practices (Chinese Ministry of Agriculture, 2006; Chinese National Bureau of Statistics, 2014; Maclean et al., 2002; Fan et al., 2012).

Substantial progress has recently been made in estimating rice YGs through crop modelling and field experiments, and by mapping YGs at national and regional scales (Zhu et al., 2004; Mueller et al., 2012; Van Ittersum et al., 2013; Van Wart et al., 2013; Chen et al., 2014; Zhang et al., 2014). However, there is still little information on the farm-scale heterogeneity of YGs. Moreover, distinguishing and quantifying the agronomic and environmental sources (e.g. climatic and edaphic) of YGs remains a considerable challenge, which is as important as estimating the magnitude of the YGs themselves (Lobell et al., 2009). Available evidence suggests that inappropriate crop management practices could be a major cause of YGs for Chinese rice production (Peng et al., 2009; Spiertz, 2012; Mueller et al., 2012; Georgen, 2014; Chen et al., 2014; An et al., 2015). Yield is highly dependent upon local climate and soil conditions (Van Ittersum and Rabbinge, 1997; Tao et al., 2013; Wu et al., 2013; Liu et al., 2014a, 2014b). However whether, and/or to what extent climatic and edaphic factors affects YGs in Chinese rice production remains to be determined. Such information is important in informing national and regional polices and helping land managers to develop practical solutions that narrow the YG.

Both on-farm experiments and crop modelling have also been proposed as ways of investigating the agronomic and/or environmental causes of YGs (IRRI, 1979; Casanova et al., 1999; Aggarwal and Kalra, 1994; Lobell et al., 2009; Van Ittersum et al., 2013; Bryan et al., 2014; Zhang et al., 2014; Zhang et al., 2016). With the former, the approach is to compare alternative management treatments side by side and/or environmental factors in a series of fields. A seminal previous study using this approach was conducted as part of the International Rice Agroeconomic Network (IRAEN) in the 1970s (IRRI, 1979; Lobell et al., 2009). However, follow-on experimental studies of causes in YGs with the same depth and breadth of the IRAEN are lacking (Lobell et al., 2009). We require a set of concepts and a framework that allow the assessment of agronomic and environmental controls of yield gaps at the farm scale.

Another major challenge in Chinese rice farming is to overcome the overuse and low use efficiency of nitrogen (N) fertilizer (Peng et al., 2010; Fan et al., 2012). The average fertilizer N application to rice of about 150 kg ha^{-1} is higher than in most countries and up to 67% above the global average; also the N use efficiency (NUE) of Chinese rice farming systems is much lower than that of most major rice production countries in Asia (Dobermann et al., 2002; Fan et al., 2007; Peng et al., 2010). However, there is a wide range in the total N application rates in commercial practice of from 50 to 400 kg ha^{-1} across the major rice production provinces, with no correlation found between grain yield and total N input (Fan et al., 2007; Peng et al., 2010). Increases in rice yields in the future are likely to be driven by increasing NUE and may be expected to reduce the environmental footprint in absolute terms and/or per unit of rice produced: the so-called sustainable intensification of rice farming systems (Fan et al., 2012). Closing the gap between actual and attainable NUE will therefore be as important as closing the YG itself. However, we do not fully understand the variation in, and sources of NUE gaps in farmer's fields or whether and to what extent future increases in rice production through decreasing the YG can also be accompanied by a narrowing of the NUE gap. Empirical evidence suggests that yield and efficiency gaps are partially independent, and both decreases and increases in efficiency gaps have been found in farming practice in current efforts to close yield gap (Van Noordwijk and Brussaard, 2014).

NUE can be defined as the yield produced per unit of N applied, taken up, or utilized by the plant to produce grain and straw (Cassman et al., 2002; Fageria and Baligar, 2005). Here we use the partial factor productivity of applied N (PFP_N, kg rice grain per kg fertilizer N applied) as the broadest measure of NUE because it integrates fertilizer input, inherent soil N supply capacity and the yield achieved (Cassman et al., 1996).

We conducted 403 on-farm experiments across major Chinese rice farming systems and developed an analytical framework with the aims of (i) analysing farm-scale heterogeneity in yield and PFP_N gaps within and across rice farming systems, (ii) determining the extent to which yield and PFP_N gaps can be narrowed by the adoption of a set of best management practices (BMPs) representing relatively low-cost and easily adoptable practices such as optimizing N and water management and increasing rice transplanting density, and (iii) distinguishing and quantifying the environmental (climatic and edaphic) sources of YGs.

2. Materials and methods

2.1. Data sources

2.1.1. Rice farming systems

The major rice farming systems in Chine are shown in Fig. 1, and we investigated the double-farming of early and late rice in south China and single rice farming in the Yangtze Delta (Fig. 1; Maclean et al., 2002; Wu et al., 2015), which together account for about 82% of Chinese rice production (Chinese National Bureau of Statistics, 2011). Early and late rice are grown in the same field each year (early rice from early April to July and late rice from July to late October), whereas single rice in the Yangtze Delta is grown over a longer period and rotated with wheat or rapeseed.

2.1.2. On-farm experiments

A description of the on-farm experiments used has been presented elsewhere (An et al., 2015). Briefly, the experiments (n = 403) were conducted with three treatments, namely conventional farm practice (FP), BMP and zero-N (to estimate inherent soil productivity) in the major rice production areas of Hunan (n = 205), Hubei (n = 32), Guangdong (n = 28), Anhui (n = 44), Jiangsu (n = 59) and Chongqing (n = 35) provinces from 2008 to 2011. About 80–115 experiments across the major rice production areas were involved each year. Of the 403 experiments, 98 represented early rice, 148 late rice and 157 single rice systems. The geographical distribution of the experimental sites is shown in Fig. 1.

In each production area, at the county or municipality scale, experimental sites with a range of soil fertility levels were selected based on the experiences of local farmers and the scientists who were responsible for the experiments. Average field size ranged from to 0.2 ha to 0.4 ha. The lay-out of treatments was established according to the guide for the on-farm demonstration project on Site Specific Nutrient Management (SSNM), initiated by IRRI (Dobermann et al., 2002; Peng et al., 2010). Each field was divided into two equal parts where FP and BMP treatments were established. Control plots ranging in size from 20 to 40 m^2 were located in BMP plots and separated from the surrounding field by bunds. Few experimental sites were used for more than one year.

For FP the farmers made all the management decisions. Based on the generally poor management practices used by farmers, BMPs were designed to represent feasible and practical measures which could be