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Eco-efficient agriculture for producing higher yields with lower greenhouse gas emissions: a case study of intensive irrigation wheat production in China

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Abstract

Although the concept of producing higher yields with reduced greenhouse gas (GHG) emissions is a goal that attracts increasing public and scientific attention, the trade-off between crop productivity and GHG emissions in intensive agricultural production is not well understood. In this study, we investigated 33 sites of on-farm experiments to evaluate the tradeoff between grain yield and GHG emissions using two systems (conventional practice, CP; high-yielding systems, HY) of intensive irrigation wheat (*Triticum aestivum* L.) in China. Furthermore, we discussed the potential to produce higher yields with lower GHG emissions based on a survey of 2938 farmers. However, in both the HY and CP systems, wheat grain yield response to GHG emissions fit a linear-plateau model, whereas the curve for grain yield from the HY system was always higher than that from the CP system. Compared to the CP system, grain yield was 44 % (2.6 Mg ha^{-1}) higher in the HY system, while GHG emissions increased by only 2.5 %, and GHG emission intensity was reduced by 29 %. The current intensive irrigation wheat system with farmers' practice had a median yield and maximum GHG emission rate of 6.05 Mg ha^{-1} and 4783 kg CO_2 eq ha^{-1}, respectively; however, this system can be transformed to maintain yields while reducing GHG emissions by 40 % (5.96 Mg ha^{-1}, and 2890 kg CO_2 eq ha^{-1}). Further, the HY system was found to increase grain yield by 41 % with a simultaneous reduction in GHG emissions by 38 % (8.55 Mg ha^{-1}, and 2961 kg CO_2 eq ha^{-1}, respectively). In the future, we suggest moving the tradeoff relationships and calculations from grain yield and GHG emissions, to new measures of productivity and environmental protection using innovative management technologies. This shift in focus is critical to achieve food and environmental security.

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1 Introduction

Increasing populations and consumption are placing unprecedented pressure on agriculture and natural resources (Tilman et al., 2002; Burney et al., 2010; Foley et al., 2011). It was projected that chemical nitrogen (N) fertilizer consumption would increase by 116–140 % to support a 100–110 % increase in global food crop yields from 2010 to 2050 (Tilman et al., 2011; IFA, 2012). This increase is expected to substantially intensify reactive N losses to the environment and to negatively affect ecosystems, including a loss of ecosystem services and an increase in species extinctions (Tilman et al., 2011). These intertwined challenges necessitate a new imperative for global agriculture, where higher grain yields are produced with more efficient use of N fertilizer and a reduction in both reactive N losses and greenhouse gas (GHG) emissions.

Several conceptual frameworks have been proposed to guide efforts that could produce higher yields with reduced input or environmental costs. These frameworks include ecological intensification (Cassman, 1999), an evergreen revolution (Swaminathan, 2000), and eco-efficient agriculture (Keating et al., 2010), and they share a view of cropping systems as ecosystems that should be designed to maximize the use of fixed resources (land, light, favorable growing conditions) and optimize the use of agricultural inputs (particularly N and P fertilization) to produce useful products. Such systems can draw upon features of traditional agricultural knowledge and add new ecological information to the intensification process (Matson et al., 1997; Chen et al., 2011). While there is agreement regarding the need for such improvements, there are only a few examples of how they can be developed and adapted on a large scale and across hundreds of millions of farmers' fields (Carberry et al., 2013).

The agricultural intensification of the "green revolution" improved crop productively while simultaneously increasing environmental costs such as GHG emissions (Tilman et al., 2002; Burney et al., 2010). Agriculture, including fertilizer production, directly contributes 10–12 % of the global GHG emissions; and this figure rises to 30 % or more when land conversion and emissions beyond the farm gate are included (Smith et al.,

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2007). The International Panel on Climate Change (IPCC) (2007) reported that global GHG emissions would need to peak before 2015 and be reduced by something on the order of 50–85 % (from 2000 levels) by 2050 if dangerous climate change (i.e., a temperature rise $> 2.4\,^{\circ}\mathrm{C}$) is to be avoided. However, integrated assessments of tradeoff relationships between crop productivity and GHG emissions and management alternatives are lacking in terms of their ability to produce higher yields in combination with GHG emission reductions.

Decreases in GHG emissions per unit of grain yield have been reported in association with agricultural intensification, as a result of impressive gains in N and energy use efficiency in crop production (Burney et al., 2010); however, decreases in absolute GHG emissions have been given less attention (Cavigelli et al., 2012). We hypothesize that combining plant variety innovation with agronomic management technologies could transform the tradeoff relationship between wheat grain yield and GHG emissions to reach new levels of crop productivity and environmental protection while producing higher yields with reduced GHG emissions. The Chinese irrigated wheat production system is an exemplary case to test this hypothesis. This is not only because this system has some of the most intensive N applications in the world, but also because the enrichment of N in the soil, water, and air has created serious environmental problems (Cui et al., 2010; Zhang et al., 2012). For example, the N applied by farmers of winter wheat in the North China Plain (NCP) is often at a rate of greater than $300\,\mathrm{kg\,N\,ha^{-1}}$ (Cui et al., 2010), whereas results from region-wide experiments have demonstrated the optimal N rate to be $128\,\mathrm{kg\,N\,ha^{-1}}$ (Cui et al., 2008). Furthermore, food production in China must increase by $> 40\,\%$ by 2030 to meet projected demand, while current wheat production has stagnated since 1998 (Zhang et al., 2012).

Here, we conducted two groups of experiments with different on-farm N level management systems in the key irrigated wheat growing region of northern China. A conventional practice (CP) plot was managed based on farmers' current practices with a yield of approximately $6\,\mathrm{Mg\,ha^{-1}}$; on a high-yield (HY) plot, an integrated soil-crop system management approach was applied to close the yield gap and maintain the grain yield at approximately 9 Mg ha^{-1}. We evaluated the tradeoff relationships between crop productively and GHG emission for the CP and HY systems. We discuss the potential for shifting the focus of the current farming system to new productivity and environmental protection values to produce higher yields with reduced GHG emissions.

2 Methods and materials

All experiments were conducted on farm fields at 33 sites in 31 counties from 2007–2008, including 15 sites in Henan province (S1 to S15), 4 sites in Hebei province (S16 to S19), 12 sites in Shandong province (S20 to S31), and 2 sites in Shaanxi province (S32 to S33, Fig. 1; Table S1). The climate in the experimental region is a warm, temperate, sub-humid, continental monsoon climate with cold winters and hot summers. The annual cumulative mean temperature for days with mean temperatures above 10 °C is 4000–5000 °C, and the annual frost-free period is 175 to 220 days. Annual precipitation is 500 to 700 mm, with approximately 70 % of the rainfall occurring during the summer maize growing season. The amount and distribution of rainfall vary widely from year to year, and are affected by the continental monsoon climate. The soil types were mainly calcareous fluvo-aquic, yellow brown, cinnamon, yellow cinnamon, meadow sanne, and yellow soils. Details of these soil types and some soil properties are shown in Table S1.

2.1 On-farm field experiments: design, crop management, and sampling procedures

Both systems (CP and HY) were tested at each of the 33 sites under four or five N fertilizer levels. Five N treatments in 15 sites in Hennan province included no N as a control (CK), and low (50 % of median), median, high (150 % of median), and very high (200 % of median) treatments. Four N treatments at the other 18 sites included no N as a control (CK), and low (50 % of median), median, and high (150 % of me-

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dian). The median N application rates for the 33 sites are shown in Table 1. For the CP system, experiments were managed using each individual farmer's current crop management practices, except for N fertilizer application. For the HY system, we adopted new varieties with resistance to disease, environmental stress, and lodging and that had the potential to produce high yields based on information from local agronomists. In addition, the right combinations of planting data and plant populations based on local weather (e.g., mean temperatures) were used to optimize the crop canopy, and make maximum use of regional environmental resources (e.g., light and temperature). Compared to the HY system, most farmer's fields used late sowing and overused seeds. Finally, in the HY system, we improved sowing quality by careful management to foster strong individual plants and make them uniform, creating a lodging-resistant architecture in the crop canopy.

Depending on the weather, winter wheat typically receives three irrigations: one before winter, a second at the shooting stage during which stem elongation occurs, and another around the anthesis stage. Although the volume of irrigation was not precisely measured for every plot and site, the values were similar for each system at every site. Weeds were well controlled with the use of spray herbicides and manual pulling. Pest and disease stress were controlled using spray insecticide and fungicide before the stem elongation stage and after anthesis. No obvious water, weed, pest, or disease stress was observed during the wheat-growing season.

A randomized complete block design was employed in three replications with plots measuring $> 40\,m^2$. All plots received approximately $90\,kg\,P_2O_5\,ha^{-1}$ as triple superphosphate ($Ca(H_2PO_4)_2 \cdot H_2O$) and about $60\,kg\,K_2O\,ha^{-1}$ as potassium chloride (K_2SO_4) before planting. Urea ($CO(NH_2)_2$) applications were made prior to winter wheat planting and again at the shooting stage.

At maturity, three separate areas (each $2–3\,m^2$) were harvested manually. All plant samples were oven dried at $70\,^{\circ}C$ in a forced-draft oven to a constant weight, weighed, and yields were adjusted to $125\,g\,kg^{-1}$ moisture content.

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2.2 Farmers' survey

With the key irrigation wheat growing region of northern China, a multistage sampling technique was used to select representative farmers' practices for wheat production from wheat–maize rotation systems. First, approximately 2–8 typical townships were randomly selected in each county, and 4–6 typical villages were randomly selected in each township. Out of these, 8–10 farmers were randomly questioned regarding their choice of fertilizer, application rate, and grain yield in the past year.

The data were required to include fertilizer production, N content, fertilizer application rate and grain yield. Grain yield was measured by farmers and adjusted to a standard 12.5 % moisture. For grain yield and N application, only a few observations (< 5 %) fell outside the normally expected ranges of the entire dataset. However, considering the great variation in each parameter among fields, we treated the upper and lower 2.5 percentiles of the data as outliers. In this study, a total of 2938 (39 counties in 5 provinces) were investigated from 2004 to 2009.

2.3 Data analysis

For each experiment, the total GHG emissions, including CO_2, CH_4, and N_2O during the whole life cycle of wheat production, were divided into three components: (1) those emitted during N fertilizer application, including direct and indirect N_2O emissions, which can be calculated based on the empirical N loss model (see below); (2) those released during N fertilizer production and transportation; and (3) those emitted during the production and transportation of pesticides to the farm gate and diesel fuel use in farming operations such as sowing, tilling, and harvesting (Table S1). The soil CO_2 flux as a contributor to global warming potential was not included in our analysis, because net flux has been estimated to contribute < 1 % of the GHG emissions from agriculture on a global scale (Smith et al., 2007). The change in soil organic carbon content was also not included in our analysis because it was difficult to detect such a small magnitude of change over a short time (Conant et al., 2010).

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We used values in the published literature to simulate the relationship between N loss and N application rate and to estimate GHG emissions from N fertilization. Total N_2O emissions included both direct and indirect emissions. Indirect emissions were estimated using a method of the ICPP (ICPP, 2006), where 1 % and 0.75 % of ammonia (NH_3) volatilization and nitrate (NO_3^-) leaching are lost as N_2O, respectively. The N losses were calculated based on an empirical model that employs the following equations from Cui et al. (2013b):

$$\text{Direct } N_2O \text{ emissions } (\text{kg N ha}^{-1}) = 0.33\exp(0.0054\text{Nrate}) \quad (1)$$

$$NH_3 \text{ volatilization } (\text{kg N ha}^{-1}) = 0.17\text{Nrate} - 4.95 \quad (2)$$

$$\text{N leaching } (\text{kg N ha}^{-1}) = 2.7\exp(0.0088\text{Nrate}) \quad (3)$$

The system boundaries were set using scales in the life cycle from production inputs (such as fertilizers and pesticides), delivery of inputs to the farm gates, farming operations, and wheat harvesting. Using the emission factors for all agricultural inputs given in Table S2, we calculated total GHG per unit area, expressed as kg CO_2 eq ha^{-1}, and the GHG intensity, expressed as kg CO_2 eq Mg^{-1} grain.

Response curves of wheat grain yield to GHG emissions at each of the 33 sites, and the two systems, with either four or five N treatments, were generated using the NLIN procedure in SAS (SAS Institute, 1998). Three response models were evaluated: quadratic, quadratic with plateau, and linear with plateau. In most cases, the linear with plateau model fit the data best, and was chosen for all of the sites (Cerrato and Blackmer, 1990).

3 Results

Considering all 33 locations, wheat grain yield averaged 5.99 Mg ha^{-1} in the median N treatments (201 kg N ha^{-1}) of CP systems. This grain yield is typical in northern China and similar to those reported elsewhere (Cui et al., 2008, 2010).

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For the HY system, grain yield averaged 8.66 $Mg\,ha^{-1}$ (208 $kg\,N\,ha^{-1}$), which was 45 % (~ 2.67 $Mg\,ha^{-1}$) higher than that of the CP systems. Correspondingly, grain yield with no N control in the HY system averaged 6.24 $Mg\,ha^{-1}$, which was 43 % (~ 1.87 $Mg\,ha^{-1}$) higher than a grain yield of 4.38 $Mg\,ha^{-1}$ from the CP system (Table 1). Although a large difference in grain yield was observed between the CP and HY systems, there were no differences in soil properties and soil type. Soil organic matter, total N content, Olsen-P, exchanged K, and pH for the HY system averaged 14.7 $kg\,kg^{-1}$, 0.92 $kg\,kg^{-1}$, 29 $mg\,kg^{-1}$, 119 $mg\,kg^{-1}$ and 7.4 $mg\,kg^{-1}$, which are similar to the14.7 $kg\,kg^{-1}$, 0.89 $kg\,kg^{-1}$, 29 $mg\,kg^{-1}$, 135 $mg\,kg^{-1}$ and 7.5 $mg\,kg^{-1}$ observed for the CP system (Table S1).

3.1 A trade-off relationship between crop productivity and GHG emissions

Considering all 33 experimental sites, wheat grain yield response to GHG emissions fit a linear-plateau model ($P < 0.001$; Fig. 2) for both the CP and HY systems. For the CP system, minimum GHG emissions occurred at an average maximum grain yield of 3031 $kg\,CO_2\,eq\,ha^{-1}$, and ranged from 1977 (S11) to 4317 $kg\,CO_2\,eq\,ha^{-1}$ (S9) (Table 2). The corresponding maximum yield averaged 5.36 $Mg\,ha^{-1}$ with a range from 5.02 to 7.43 $Mg\,ha^{-1}$ (Table 2). In contrast, a minimum of 3276 $kg\,CO_2\,eq\,ha^{-1}$ GHG emissions were needed to achieve the maximum grain yield in the HY system, with a range from 2427 in S12 to 4527 $kg\,CO_2\,eq\,ha^{-1}$ in S15 (Table 2). The HY system had a corresponding grain yield of 8.58 $kg\,ha^{-1}$with a range from 7.33 to 9.60 $Mg\,ha^{-1}$ (Table 2).

Pooling data from all 33 experimental sites receiving either four or five N treatments, the wheat grain yield response to the N rate also fit a linear-plateau model ($P < 0.001$; Fig. 3). The minimum GHG emissions needed to achieve maximum grain yield in the HY system was 2961 $kg\,CO_2\,eq\,ha^{-1}$, which is similar to 2890 $kg\,CO_2\,eq\,ha^{-1}$ for the CP system. In contrast, the corresponding grain yield for the HY system was 8.55 $Mg\,ha^{-1}$, 44 % greater than the 5.96 $Mg\,ha^{-1}$ for the CP system. Prior to achieving

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maximum grain yield, GHG emission intensity for the CP system increased by 300 to 485 kg CO_2 eq Mg^{-1} with an increased grain yield from 4.41 Mg ha^{-1} to 5.96 Mg ha^{-1}. In contrast, GHG emission intensity for the HY system increased 311 kg CO_2 eq Mg^{-1} to 346 kg CO_2 eq Mg^{-1} with an increased grain yield from 6.28 Mg ha^{-1} to 8.55 Mg ha^{-1}.

3.2 Opportunity to produce higher yields with reduced GHG emissions

Based on a survey of farmers' practices for 2938 farmers, the N application rate averaged 284 kg N ha^{-1} and ranged from 77 to 573 kg N ha^{-1}; the corresponding grain yield averaged 6.05 Mg ha^{-1} with a range from 3.44 to 8.31 Mg ha^{-1} (Fig. 4). This grain yield and N application rate are higher than the reported global averages but are similar to results reported for typical research trials in China (Cui et al., 2008, 2010; FAO, 2012). There was no relationship between N application rate and grain yield, indicating inefficient N management.

The calculated GHG emissions averaged 4783 kg CO_2 eq ha^{-1} (Fig. 4), of which 1183 kg CO_2 eq ha^{-1} was attributable to field management (e.g., irrigation, tillage, and harvesting), 1270 kg CO_2 eq ha^{-1} was from N fertilization, and 2330 originated from N production and transport. GHG emissions intensity averaged 807 kg CO_2 eq Mg^{-1}, with large variation among farmers' practices. The GHG emissions ranged from 2106 to 10 757 kg CO_2 eq ha^{-1} with a variance of 38 %, whereas GHG emission intensity ranged from 382 to 1795 kg CO_2 eq Mg^{-1} with a variance of 39 % (Fig. 4).

Compared to average farmers' practices (point A), the minimum GHG emissions needed to achieve a maximum grain yield for CP systems (point B) was reduced by 40 % from 4783 to 2890 kg CO_2 eq ha^{-1} without any losses in yield (pathway from A to B, Fig. 4). The GHG emission intensity of point B was 485 kg CO_2 eq Mg^{-1}, which was only 60 % of current practices (point A). With the HY system, grain yield increased to 8.55 Mg ha^{-1} (or 41 % compared to point A) with a GHG emissions reduction of 38 % ($\sim$ 2961 kg CO_2 eq ha^{-1}) (pathway A to C, Fig. 4). The GHG emissions intensity was 356 kg CO_2 eq Mg^{-1} for point C, which was only 44 % of that under current practices.

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If food crop yields need to be increased 100–110 % in the future (Tilman et al., 2011), a wheat yield of 12 $Mg\,ha^{-1}$ will be necessary in China. The N requirement of 12 $Mg\,ha^{-1}$ is for a wheat yield of approximately 292 $kg\,N\,ha^{-1}$ (Yue et al., 2012), similar to the 284 $kg\,N\,ha^{-1}$ total average N rate used in current practice. This indicates that an N application rate of 12 $Mg\,ha^{-1}$ should produce a wheat yield similar to that achieved using the current N application rate if N losses can be controlled well; therefore, GHG emissions from N fertilization should be less than the total average associated with current practices. A new level for productivity and environmental sustainability should be created for the pathway from point C to D in Fig. 4.

4 Discussions

While the concept of producing higher yields with less GHG emissions as a goal has been widely debated, studies on crop productively and GHG emission have notable disconnected in the past (Tilman et al., 2002; Burney et al., 2010; Carberry et al., 2013). Generally, grain yields and GHG emissions are reported separately as a function of N application rate (Cassman et al., 2003; McSwiney and Robertson, 2005). The increasing of N application rate cannot promise a substantial increase in crop productivity because of diminishing returns (Cassman et al., 2003), but increase GHG emission (McSwiney and Robertson, 2005; Cui et al., 2013a, b). Some research has assumed a linear relationship between GHG emissions from N_2O and N rate (ICPP, 2006), while a growing body of evidence indicates the occurrence of nonlinear, exponential responses in N_2O emissions or N leaching to the N application rate (Goulding, 2000; McSwiney and Robertson, 2005; Hoben et al., 2011; Cui et al., 2013a, b). Recently, some studies have suggested that GHG emissions of N_2O depend on more than just the amount of N input (Van Groenigen et al., 2010; Cui et al., 2013b). Appropriate source, timing, placement or product (slow and controlled-released fertilizer) of fertilizer N, and related practice which tend to enhance crop recovery of applied N, increased crop yield, and could also contribute to lower reactive N losses and GHG emission (Snyder et al., 2009). Within irrigation wheat production, GHG emission also included field management practices such as irrigation and tillage (Röös et al., 2011). In the present study, GHG emissions from field management contributed 25 % of the total GHG emissions due to farmers' practices. These interdependent and contradictory results underscore the need for additional hypothesis-driven studies to enhance our current understanding of how to produce higher yields with less GHG emissions in the current intensive cropping system.

To the best of our knowledge, this is the first on-farm study to report grain yields in response to GHG emissions. Grain yield increased linearly with increasing GHG emissions before reaching the maximum yield, with the lowest GHG emissions achieved when emission intensity decreased, indicating a tradeoff relationship between crop productivity–GHG emissions and grain yield/GHG intensity (Figs. 2 and 3). This tradeoff relationship could be optimized using the new cropping system described herein. In this study, grain yield in the HY system increased by 44 % while GHG emissions increased by only 23 % and GHG emission intensity was reduced by 15 %, compared CP system.

In intensive cropping systems, the N cycle depends on environmental management interactions that influence the balance and rate of microbial processes (e.g., nitrification and denitrification) and transport among plant, soil and environments (e.g., air and water) (Robertson and Vitousek, 2009). When a high-yield system was adopted in a previous study, crop health, insect and weed management, moisture and temperature regimes, supplies of nutrients other than N, and use of the best-adapted cultivar or hybrid all contributed to more efficient uptake of available N and greater conversion of plant N to grain yield, therefore reducing reactive N losses and GHG emissions (Cassman et al., 2003; Cui et al., 2013b).

Studies often focus on how to optimize N management (e.g., appropriate source, timing, placement, or product) to enhance crop recovery of applied N and reduce N losses and GHG emissions (Snyder et al., 2009; Millaret al., 2010; Cui et al., 2013a, b). For irrigation wheat systems in China, an in-season root-zone N management strategy can reduce the N application rate by 61 % from 325 $kg N ha^{-1}$ to 128 $kg N ha^{-1}$

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compared to current practices, resulting in an 80 % decrease in GHG emission intensity of N fertilization from 201 to 47 kg CO_2 eq Mg^{-1}, with no loss in wheat grain yield (Cui et al., 2013b). This result is represented by the pathway from point A to B in Fig. 4. Although these practices represent a large step forward, increasing rather than merely maintaining grain yield, they also present a fundamental challenge.

In the HY system of the present study, the right combination of adopted varieties, planting data, and planting quality was determined to optimize the crop canopy, and this maximized the use of regional environmental resources (e.g., light, temperature). Yields were increased by 41 %, and GHG emissions were reduced by 38 %, compared to current practices. Within the CP system, late sowing and the use of too many seeds often results in excessively large canopies and weak individuals, which lead to high susceptibility to lodging, low efficiency of light capture, small spikes, small grains, and consequently low yields (Xu et al., 2013).

The new paradigm for productivity and environmental sustainability is currently being extended to farmers throughout the cereal crop production area in China, but it also appears to be relevant for other high-yield cropping systems outside China. For example, in UK wheat production, GHG emission intensity is 313 kg CO_2 eq Mg^{-1} of grain and grain yield is about 10 Mg ha^{-1} (Berry et al., 2008). Irrigated maize in central Nebraska achieves higher grain yields (13.2 Mg ha^{-1}) with lower GHG emission intensity (231 kg CO_2 eq Mg^{-1} of grain) (Grassini and Cassman, 2012).

In the future, yields must be doubled to meet the growing food demands of an ever-increasing population, without further compromising environmental integrity; therefore, new frontiers for food and environmental sustainability must be created (from point C to D in Fig. 4). Most see this pathway being met by genetically modified crops (Phillips, 2010). Yet obtaining drastically higher yields without further depleting soils, destroying natural habitats, and polluting air and water will demand a comprehensive approach (Zhang et al., 2003). In reality, pushing the boundaries of productivity will likely evolve from the synergies between novel plant genetics, innovative management technologies, and increasing soil fertility (Keating et al., 2010). Moving millions of smallholder

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farmers to new productivity and environmental protection paradigms will require research into, and the delivery of, new technologies that increase production at much the same level of investment.

5 Conclusions

Previous trade-off analyses of crop productivity and GHG emissions have found high yields and reduced GHG emissions to be in conflict with one another, using similar cropping systems. However, this tradeoff can be reversed for high-yielding systems using innovative management technologies, and a new paradigm of productivity and environmental sustainability can be created to produce higher yields while reducing GHG emissions. In this study, we increased yield by 41 % and reduced GHG emission intensity by 57 %, compared to current practices. In the future, there will need to be an eco-efficiency agricultural revolution, with large increases in grain yields complemented with reduced GHG emissions. A win–win outcome for agriculture and emissions will require eco-efficient solutions that create new productivity and environmental frontiers to achieve food and GHG security.

Supplementary material related to this article is available online at http://www.biogeosciences-discuss.net/10/16879/2013/bgd-10-16879-2013-supplement.pdf.

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Table 1. N application rate of median N treatment and wheat grain yield for different N application rates and the two systems. N application rate including no N as a control (0N), 50 % of median N rate (50 % N), 100 % of median N rate (100 % N), 150 % of median N rate (150 % N), and 200 % of median N rate (50 % N). The systems included a conventional practice (CP) and a high-yielding system (HY).

Sites	Median N rate	Grain yield for FP (Mg ha^{-1})					Median N rate	Grain yield for HY (Mg ha^{-1})				
	(kg N ha^{-1})	0N	50 % N	100 % N	150 % N	200 % N	(kg N ha^{-1})	0N	50 % N	100 % N	150 % N	200 % N
S1	210	3.99	5.62	5.76	5.66	5.82	210	6.08	6.96	7.23	7.39	7.36
S2	210	3.49	5.62	5.76	5.66	5.82	210	6.01	8.39	9.39	9.03	8.43
S3	210	3.79	5.65	5.76	6.94	6.67	210	6.97	8.48	9.12	9.16	8.86
S4	210	4.84	5.39	5.76	5.67	5.62	210	6.50	7.39	8.38	8.25	8.26
S5	210	4.88	5.49	5.76	6.39	6.24	210	4.92	6.51	8.48	8.80	8.31
S6	210	3.87	5.20	5.76	5.17	4.92	210	6.17	7.18	8.22	8.35	7.48
S7	210	4.06	5.18	5.76	6.28	5.87	210	4.32	6.71	7.70	7.63	7.15
S8	210	3.88	5.12	5.76	5.75	5.26	210	4.55	5.43	7.68	8.55	7.78
S9	210	3.90	4.56	5.77	5.50	5.46	210	6.65	7.99	8.31	8.78	8.39
S10	210	3.21	4.50	5.77	5.78	5.62	210	3.91	6.01	8.22	8.15	7.60
S11	180	4.88	5.75	5.77	5.82	5.77	180	6.61	8.31	8.82	9.64	9.32
S12	180	4.27	4.91	5.77	5.13	4.60	180	6.02	7.58	8.22	8.46	6.99
S13	210	4.03	5.11	5.77	5.38	5.12	210	5.72	7.32	8.22	8.01	7.16
S14	210	4.20	5.26	5.77	5.99	5.91	210	6.56	7.29	8.92	8.07	7.81
S15	210	2.67	4.27	5.77	5.07	5.21	210	5.90	6.97	8.03	9.21	8.64
S16	180	5.05	6.77	7.78	7.08	–	180	5.74	7.75	8.96	9.06	–
S17	180	4.53	5.66	6.09	6.07	–	225	6.31	8.18	9.08	9.21	–
S18	180	4.07	5.41	5.72	5.89	–	180	5.48	7.40	8.50	7.74	–
S19	225	5.07	5.84	6.51	6.16	–	225	6.16	7.54	9.03	8.53	–
S20	180	5.03	5.49	6.00	6.04	–	225	6.80	7.72	8.54	8.03	–
S21	210	5.00	6.00	6.23	6.25	–	210	7.37	9.02	9.58	9.63	–
S22	210	5.15	6.17	6.53	6.22	–	210	7.07	7.63	9.11	9.14	–
S23	180	4.59	5.53	5.85	5.97	–	210	6.51	8.40	9.34	9.32	–
S24	180	4.62	5.38	6.00	6.13	–	210	7.39	7.98	8.86	8.90	–
S25	210	4.50	5.37	6.17	6.00	–	210	6.15	6.45	8.60	8.24	–
S26	225	4.10	5.00	5.91	5.70	–	225	6.54	7.45	8.46	8.42	–
S27	210	4.81	5.46	6.17	5.85	–	225	7.00	7.78	8.73	8.48	–
S28	210	4.74	5.40	5.93	5.75	–	225	7.21	7.58	9.17	8.42	–
S29	180	4.88	5.38	5.94	5.51	–	225	6.66	7.62	8.96	8.24	–
S30	210	4.14	5.09	5.62	5.09	–	210	7.28	8.01	8.92	8.96	–
S31	210	4.64	5.47	6.19	6.36	–	210	6.50	7.35	8.11	8.10	–
S32	180	5.35	5.51	6.46	6.44	–	180	7.68	8.04	9.44	9.40	–
S33	180	4.25	4.42	6.22	5.84	–	180	5.34	6.77	9.52	9.15	–
mean	**201**	**4.38**	**5.36**	**5.99**	**5.89**	**–**	**208**	**6.24**	**7.49**	**8.66**	**8.62**	**–**

Table 2. The minimum GHG emissions needed to achieve maximum grain yield and the corresponding yields for a conventional practice (CP) and a high-yielding system (HY).

Sites	FP system		HY system	
	Mini. GHG emission $kg\,CO_2\,eq\,ha^{-1}$	Max. yield $Mg\,ha^{-1}$	Mini. GHG emission $kg\,CO_2\,eq\,ha^{-1}$	Max. yield $Mg\,ha^{-1}$
S1	2477	5.75	2837	7.33
S2	2457	5.75	2647	8.95
S3	3677	6.81	2797	9.05
S4	3457	5.92	3487	8.30
S5	3857	6.32	3657	8.55
S6	2447	5.27	3287	8.02
S7	3347	6.18	2747	7.49
S8	2857	5.66	4067	8.16
S9	4317	5.48	2797	8.49
S10	3727	5.70	3407	7.99
S11	1977	5.79	3637	9.48
S12	2397	5.02	2427	7.89
S13	2697	5.41	2717	7.80
S14	3307	6.15	3587	8.25
S15	2897	5.03	4527	8.93
S16	2607	7.43	2827	9.01
S17	2587	6.08	3087	9.14
S18	2517	5.80	2597	8.12
S19	3247	6.34	3537	8.78
S20	3317	6.04	3207	8.29
S21	2657	6.24	2777	9.60
S22	2607	6.38	3757	9.14
S23	2617	5.91	2927	9.33
S24	3087	6.07	3697	8.90
S25	3277	6.09	3587	8.24
S26	3507	5.80	3737	8.44
S27	3327	6.01	3707	8.61
S28	3107	5.84	3777	8.69
S29	2877	5.73	3677	8.60
S30	2707	5.36	2657	8.96
S31	3437	6.27	3337	8.11
S32	3397	6.44	3357	9.40
S33	3237	5.84	3237	9.11
mean	**3031**	**5.94**	**3276**	**8.58**

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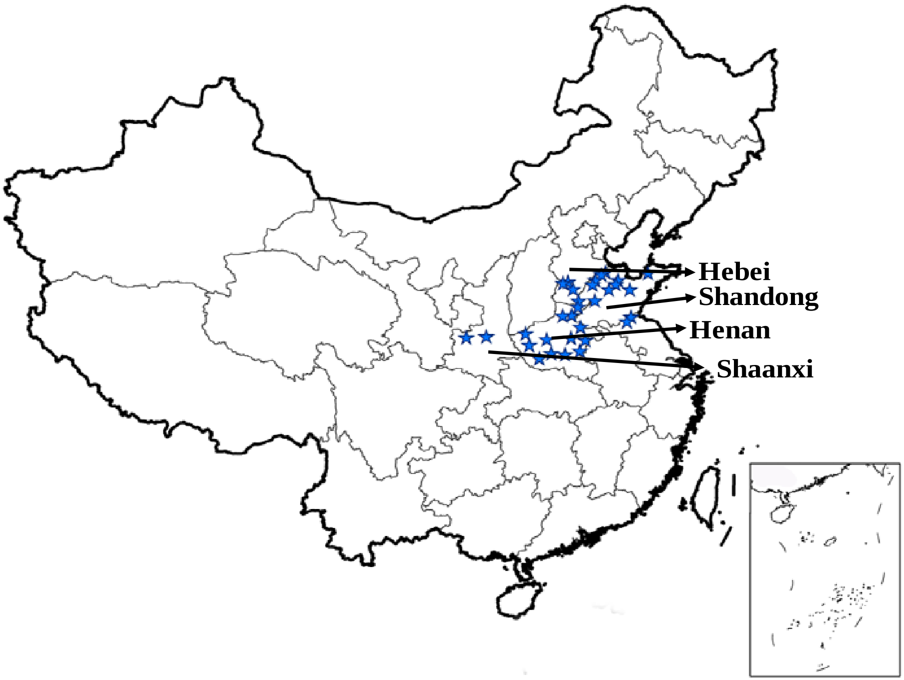

Fig. 1. The sites of the on-farm experiments used for this study. There are 15 sites in Henan province, 4 sites in Hebei province, 12 sites in Shandong province, and 2 sites in Shaanxi province. These four provinces represent 59 % of wheat production in China in 2012 (FAO, 2012).

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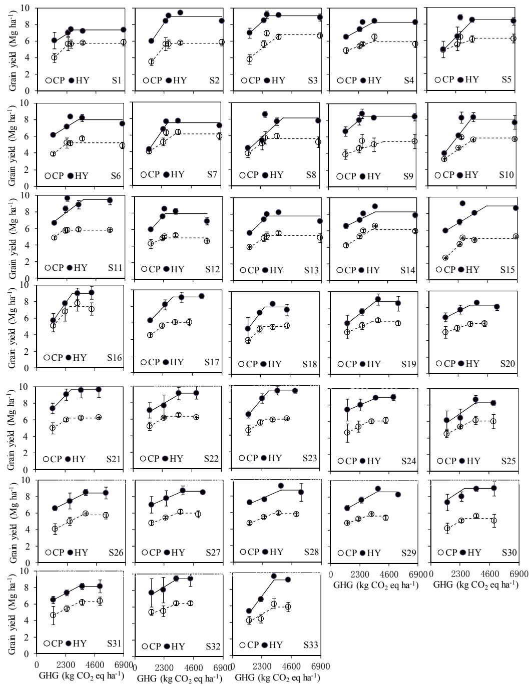

Fig. 2. Grain yield as a function of increasing total GHG emissions for the CP (small circle) and the HY (dot) system. The total GHG emissions include CO_2, CH_4, and N_2O during the whole life cycle of wheat production for N fertilization, N fertilizer production and transportation, and crop management. Response curves of wheat grain yield to GHG emissions at each of the 33 sites are generated linear with plateau model ($P < 0.001$). The minimum GHG emissions needed to achieve maximum grain yield and the corresponding yields for these two systems are shown in Table 2. There are 15 sites in Henan province (S1 to S15), 4 sites in Hebei province (S16 to S19), 12 sites in Shandong province (S20 to S31), and 2 sites in Shannxi province (S32 to S33).

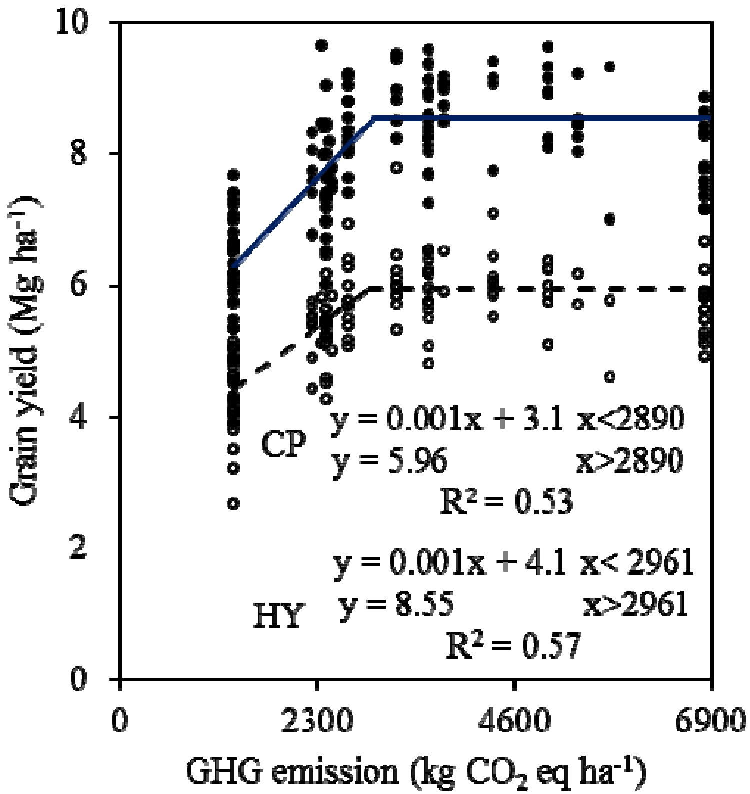

Fig. 3. The tradeoff relationship between GHG emissions and grain yield for the CP (small circle and dashed line) and the HY (dot and solid line) system. Data were pooled from 33 sites of on-farm experiments for CP and HY systems.

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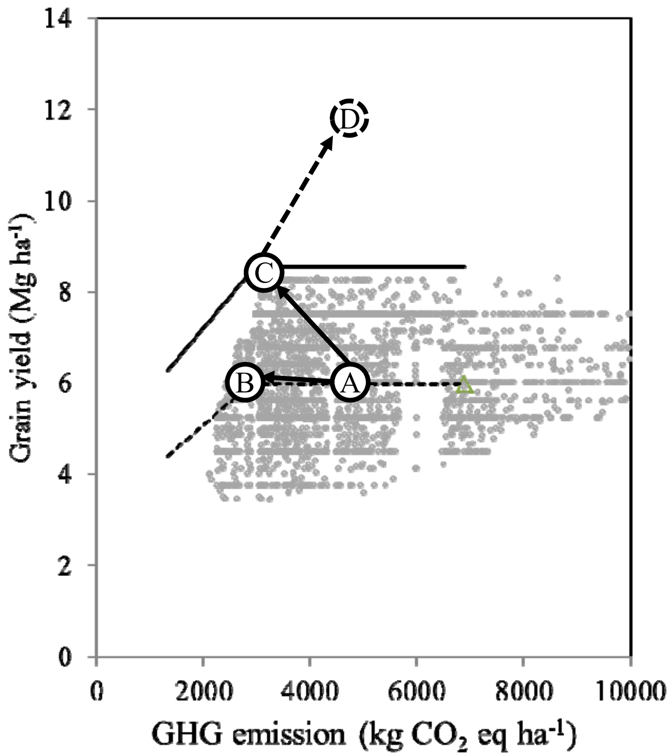

Fig. 4. A stylized grain yield–GHG emission framework demonstrating three pathways to produce higher yields with less GHG emissions. The gray dots represent grain yields and GHG emissions for the 2938 farmers surveyed. The line of dashed line and solid line mean grain yield responses to GHG emission for CP and HY system, respectively. Point A is the average for all farmers; Points B and C are the minimum GHG emissions for maximum grain yield with the CP and HY system, respectively (the details are shown in Fig. 3); and Point D represents the target of 12 Mg ha^{-1} of wheat grain yield in the future.