Biogeosciences, 11, 2287–2294, 2014
www.biogeosciences.net/11/2287/2014/
doi:10.5194/bg-11-2287-2014

Biogeosciences
Open Access

Trade-offs between high yields and greenhouse gas emissions in irrigation wheat cropland in China

Z. L. Cui[1,*], L. Wu[1,*], Y. L. Ye[2], W. Q. Ma[3], X. P. Chen[1], and F. S. Zhang[1]

[1]Center for Resources, Environment and Food Security, China Agricultural University, Beijing 100193, China
[2]College of Resources and Environmental Science, Henan Agricultural University, Zhengzhou 450000, China
[3]College of Resources and Environmental Science, Hebei Agricultural University, Baoding 071001, China
[*]These authors contributed equally to this work.

Correspondence to: X. P. Chen (chenxp@cau.edu.cn)

Received: 20 September 2013 – Published in Biogeosciences Discuss.: 29 October 2013
Revised: 20 February 2014 – Accepted: 22 March 2014 – Published: 24 April 2014

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 high yields and GHG emissions in intensive agricultural production is not well understood. Here, we hypothesize that there exists a mechanistic relationship between wheat grain yield and GHG emission, and that could be transformed into better agronomic management. A total 33 sites of on-farm experiments were investigated to evaluate the relationship between grain yield and GHG emissions using two systems (conventional practice, CP; high-yielding systems, HY) of intensive winter 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. Compared to the CP system, grain yield was 39 % (2352 kg ha^{-1}) higher in the HY system, while GHG emissions increased by only 10 %, and GHG emission intensity was reduced by 21 %. The current intensive winter wheat system with farmers' practice had a median yield and maximum GHG emission rate of 6050 kg 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 26 % (6077 kg ha^{-1}, and 3555 kg CO$_2$ eq ha^{-1}). Further, the HY system was found to increase grain yield by 39 % with a simultaneous reduction in GHG emissions by 18 % (8429 kg ha^{-1}, and 3905 kg CO$_2$ eq ha^{-1}, respectively). In the future, we suggest moving the trade-off relationships and calculations from grain yield and GHG emissions to new measures of productivity and environmental protection using innovative management technologies.

1 Introduction

Increasing population and consumption are placing unprecedented pressure on agricultural and natural resources (Tilman et al., 2002; Burney et al., 2010; Foley et al., 2011). It has been projected that chemical nitrogen (N) fertilizer consumption will increase by 142–169 % to support a 100–110 % increase in global food crop yields from 2005 to 2050 (Tilman et al., 2011; IFA, 2012). Agricultural intensification of the "green revolution" improved crop productivity while simultaneously increasing environmental costs such as greenhouse gas (GHG) emissions (Tilman et al., 2002; Burney et al., 2010). Agriculture, including fertilizer production, directly contributes 10–12 % of 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., 2007). The Intergovernmental Panel on Climate Change (IPCC; 2007) reported that global GHG emissions would need to peak before 2015 and be reduced on the order of 50–85 % (from 2000 levels) by 2050 if dangerous climate change (i.e., a temperature rise $> 2.4\,^{\circ}$C) is to be avoided. 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 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 high grain yields. 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).

Wheat production in the North China Plain (NCP) involves some of the most intensive N applications in the world, and the enrichment of N in 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 NCP is often greater than 300 kg N ha^{-1} (Cui et al., 2010), even though results from region-wide experiments have demonstrated that the optimal N rate is 128 kg N ha^{-1} (Cui et al., 2008). This overuse of N fertilizer over the past 10 years has not increased wheat yield, with stagnation at $\sim$ 4573 kg ha^{-1} with national average (mean grain yield from 2003 to 2012, FAO, 2013). In contrast, in previous high-yield studies in this region, high wheat yield ($\geq$ 9000 kg ha^{-1}) was achieved by optimizing the wheat canopy and using favorable management practices to maximize both the quantity and quality of the wheat canopy (Meng et al., 2013).

Recent studies have shown great promise for increasing N-use efficiency and grain yield in maize production by integrating crop and N management (Chen et al., 2011; Grassini and Cassman, 2012). Here, we hypothesize that there exists a mechanistic relationship between wheat grain yield and GHG emission, and that could be transformed into better combining improved crop management technologies with optimal N management. Two groups of experiments with different on-farm N level management systems were conducted in the key winter wheat growing region of northern China. A conventional practice (CP) plot was managed based on farmers' current practices with a yield of approximately 6000 kg 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 8500 kg ha^{-1}. We evaluated the trade-off 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 to 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, Supplement Fig. S1 and 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 30–40 % of the rainfall occurring during the winter wheat growing season (from the beginning of October to middle of June). 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 site coordinates, average annual precipitation, soil texture, soil types and some soil properties are shown in Supplement 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 treatments. Five N treatments in 15 sites in Henan 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 median). The amount of N fertilizer for the median N treatment was recommended by local agricultural extension employees based on experience. Detailed information of N application rates for the 33 sites is shown in Table 1.

For both conventional practice (CP) and high-yield (HY) systems, one-third of granular urea ($CO(NH_2)_2$) is applied by broadcasting at the time of sowing, and the remainder is applied at the stem elongation stage prior to irrigation. Depending on the weather, winter wheat typically receives three irrigations (about 90 mm per time): one before winter, a second at the stem elongation stage, 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. For the CP system, experiments were managed using each individual farmer's current crop management practices, except for N fertilizer application rate. In the HY system, local agronomists recommended new varieties with resistance to disease, environmental stress, and lodging that also had the potential for high yields. These new varieties varied across experimental sites. In addition, the better combinations of planting date 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 farmers' fields used later sowing and used more seeds. Finally, in the HY system,

Table 1. N application rate and wheat grain yield for different N application rates and the two systems. N application rate including no N as a control (0 N), 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	CP										HY									
	N rate (kg N ha^{-1})					Grain yield (kg ha^{-1})					N rate (kg N ha^{-1})					Grain yield (kg ha^{-1})				
	0	50 %	100 %	150 %	200 %	0	50 %	100 %	150 %	200 %	0	50 %	100 %	150 %	200 %	0	50 %	100 %	150 %	200 %
S1	0	105	210	315	420	3993	5619	5757	5659	5822	0	105	210	315	420	6081	6962	7233	7390	7356
S2	0	105	210	315	420	3493	5619	5758	5659	5822	0	105	210	315	420	6008	8392	9389	9030	8429
S3	0	105	210	315	420	3794	5654	5759	6937	6673	0	105	210	315	420	6967	8476	9121	9163	8855
S4	0	105	210	315	420	4845	5387	5760	5672	5617	0	105	210	315	420	6495	7387	8379	8252	8263
S5	0	105	210	315	420	4875	5485	5761	6390	6240	0	105	210	315	420	4920	6510	8480	8795	8310
S6	0	105	210	315	420	3867	5205	5762	5167	4917	0	105	210	315	420	6168	7179	8215	8345	7484
S7	0	105	210	315	420	4059	5185	5763	6285	5869	0	105	210	315	420	4319	6710	7697	7627	7151
S8	0	105	210	315	420	3884	5122	5764	5746	5262	0	105	210	315	420	4546	5431	7680	8547	7775
S9	0	105	210	315	420	3904	4565	5765	5499	5465	0	105	210	315	420	6649	7989	8306	8783	8389
S10	0	105	210	315	420	3214	4504	5766	5781	5615	0	105	210	315	420	3914	6005	8218	8148	7595
S11	0	90	180	270	360	4876	5746	5767	5815	5770	0	90	180	270	360	6612	8308	8817	9644	9317
S12	0	90	180	270	360	4268	4908	5768	5127	4598	0	90	180	270	360	6016	7583	8216	8458	6992
S13	0	105	210	315	420	4035	5107	5769	5385	5120	0	105	210	315	420	5716	7320	8219	8011	7160
S14	0	105	210	315	420	4200	5256	5770	5989	5912	0	105	210	315	420	6556	7290	8923	8067	7812
S15	0	105	210	315	420	2667	4272	5771	5070	5208	0	105	210	315	420	5897	6972	8026	9212	8644
S16	0	90	180	270		5053	6768	7784	7078		0	90	180	270		5744	7747	8959	9057	
S17	0	90	180	270		4527	5664	6095	6068		0	113	225	338		6311	8176	9081	9206	
S18	0	90	180	270		4067	5415	5715	5889		0	90	180	270		5476	7398	8501	7743	
S19	0	113	225	338		5075	5839	6510	6162		0	113	225	338		6160	7537	9032	8531	
S20	0	90	180	270		5028	5494	5998	6038		0	113	225	338		6803	7718	8541	8029	
S21	0	105	210	315		5000	5997	6231	6251		0	105	210	315		7374	9025	9580	9628	
S22	0	105	210	315		5148	6175	6525	6225		0	105	210	315		7067	7632	9106	9138	
S23	0	90	180	270		4594	5531	5846	5972		0	105	210	315		6507	8400	9343	9324	
S24	0	90	180	270		4624	5378	6001	6134		0	105	210	315		7392	7982	8863	8901	
S25	0	105	210	315		4496	5367	6169	6002		0	105	210	315		6151	6449	8601	8235	
S26	0	113	225	338		4098	5004	5908	5699		0	113	225	338		6540	7454	8455	8423	
S27	0	105	210	315		4813	5456	6174	5853		0	113	225	338		6996	7781	8730	8482	
S28	0	105	210	315		4742	5402	5927	5754		0	113	225	338		7209	7576	9172	8420	
S29	0	90	180	270		4883	5383	5944	5509		0	113	225	338		6658	7617	8960	8236	
S30	0	105	210	315		4138	5086	5623	5094		0	105	210	315		7281	8006	8924	8955	
S31	0	105	210	315		4639	5465	6187	6357		0	105	210	315		6499	7355	8107	8104	
S32	0	90	180	270		5345	5507	6460	6435		0	90	180	270		7683	8039	9443	9395	
S33	0	90	180	270		4250	4420	6223	5839		0	90	180	270		5339	6774	9521	9147	
mean	0	101	201	302	412	4378	5363	5993	5895	5594	0	104	208	312	412	6244	7490	8662	8619	7969

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. 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 for both CP and HY system.

A randomized complete block design was employed in three replications with plots measuring $> 40\,\mathrm{m}^2$. All plots received approximately 90 kg P_2O_5 ha^{-1} as calcium 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.

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

2.2 Farmers' survey

With the key winter wheat growing region of northern China from 2004 to 2009, 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. Data required included fertilizer production, N content, fertilizer application rate and grain yield. For grain yield and N application, only a few observations ($< 5\,\%$) fell outside the normally expected ranges of the entire data set. However, considering the great variation in each parameter among fields, we treated the upper and lower 2.5 percentiles of the data as outliers (Fig. S2). By considering all of the survey data and removing the top and bottom 2.5 % of respondents, a total of 2938 (39 counties in 5 provinces) were evaluated in this study.

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, irrigation and harvesting (Supplement Table S2). The impact of the GHG emissions was calculated as CO_2 eq. The 100 yr global warming potential (GWP) of CH_4 and N_2O are 25 and 298 times the intensity of CO_2 on a mass basis, respectively (Forster et al., 2007). 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).

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 IPCC (IPCC, 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 Supplement Fig. S3:

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

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

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

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 Supplement 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.

The relationship between wheat grain yield and GHG emissions at each of the 33 sites in the two cropping systems with either four or five N treatments was determined using the IPNI Crop Nutrient Response Tool (http://nane.ipni.net/article/NANE-3068) and the NLIN procedure in SAS (SAS Institute, 1998). We evaluated five models: quadratic, quadratic with plateau, linear with plateau, square root, and spherical with plateau. In most cases, all five models significantly fit the data ($P < 0.01$), and had similar coefficients of determination (R^2). Considering the continuity and smooth simulation, we chose the spherical with plateau model for all of the sites (Cerrato and Blackmer, 1990). We determined the minimum GHG emissions needed to achieve maximum grain yield as the inflection point of the curve (Cerrato and Blackmer, 1990).

3 Results

Considering all 33 locations, wheat grain yield averaged 5993 kg ha^{-1} in the median N treatments (201 kg N ha^{-1}) of CP systems. For the HY system, grain yield averaged 8662 kg ha^{-1} (208 kg N ha^{-1}), which was 45 % ($\sim$ 2669 kg ha^{-1}) higher than that of the CP systems. Correspondingly, grain yield with no N control in the HY system averaged 6244 kg ha^{-1}, which was 43% ($\sim$ 1866 kg ha^{-1}) higher than a grain yield of 4378 kg 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 (Supplement Table S1).

3.1 Relationship between wheat yield and GHG emissions for different management systems

Pooling data from all 33 experimental sites receiving either four or five N treatments, the relationship between wheat grain yield and GHG emission fit a spherical-plateau model ($P < 0.001$; Fig. 1). The minimum GHG emissions needed to achieve maximum grain yield was 3555 and 3905 kg CO_2 eq Mg^{-1} for the CP and HY system. In contrast, the corresponding grain yield for the HY system was 8429 kg ha^{-1}, 39 % greater than the 6077 kg ha^{-1} for the CP system. The GHG emission intensity reduced by 21 % from 585 kg CO_2 eq Mg^{-1} for HY system to 463 kg CO_2 eq Mg^{-1} for CP system.

Large site-specific variations in GHG emission and grain yield were observed across the 33 experimental sites (Table 2). Calculated minimum GHG emissions needed to achieve maximum grain yield for the CP system by spherical with plateau model ranged from 2736 (S11) to 5475 kg CO_2 eq ha^{-1} (S9), similar to the HY system, which ranged from 3055 (S12) to 5476 kg CO_2 eq ha^{-1} (S15) (Table 2). The corresponding maximum yield for the CP system ranged from 5012 to 7421 kg ha^{-1}, whereas in the HY system, these values ranged from 7314 to 9598 Mg ha^{-1} (Table 2). As a result, GHG emission intensity ranged from 456 to 998 kg CO_2 eq Mg^{-1} for the CP system and from 343 to 652 kg CO_2 eq Mg^{-1} for the HY system (Table 2).

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 6050 kg ha^{-1} with a range from

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	CP system			HY system		
	Mini. GHG emission kg CO$_2$ eq ha^{-1}	Max. yield kg ha^{-1}	GHG emission intensity kg CO$_2$ eq Mg^{-1}	Mini. GHG emission kg CO$_2$ eq ha^{-1}	Max. yield kg ha^{-1}	GHG emission intensity kg CO$_2$ eq Mg^{-1}
S1	3117	5761	541	3322	7314	454
S2	3380	5771	586	3403	8961	380
S3	4295	6797	632	3338	9039	369
S4	3448	5875	587	3929	8286	474
S5	4398	6296	698	4556	8603	530
S6	2932	5277	556	3709	7988	464
S7	3801	6156	617	3920	7504	522
S8	3599	5660	636	5326	8170	652
S9	5475	5487	998	3444	8492	406
S10	4661	5715	816	4687	8003	586
S11	2736	5806	471	4799	9448	508
S12	2982	5012	595	3055	7888	387
S13	3249	5410	601	3280	7796	421
S14	3798	6119	621	3820	8210	465
S15	4610	5136	898	5476	8890	616
S16	3387	7421	456	3847	9059	425
S17	3143	6082	517	3742	9141	409
S18	3187	5814	548	3310	8106	408
S19	3650	6305	579	3992	8741	457
S20	3686	6033	611	3639	8259	441
S21	3026	6232	486	3295	9598	343
S22	2929	6367	460	4645	9189	505
S23	3050	5900	517	3537	9328	379
S24	3811	6127	622	4305	8917	483
S25	3763	6068	620	4520	8380	539
S26	3967	5781	686	4301	8459	508
S27	3591	5975	601	4000	8576	466
S28	3515	5815	604	4080	8685	470
S29	3084	5695	542	3851	8539	451
S30	3101	5348	580	4258	8977	474
S31	4315	6346	680	3966	8119	488
S32	4197	6475	648	4184	9459	442
S33	3986	5973	667	4341	9397	462

3.44 to 8.31 Mg ha^{-1} (Fig. 2, Supplement Fig. S2). The calculated GHG emissions averaged 4783 kg CO$_2$ eq ha^{-1} (Fig. 2), 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. Calculated GHG emission intensity averaged 807 kg CO$_2$ eq Mg^{-1}. The GHG emissions ranged from 2106 to 10757 kg CO$_2$ eq ha^{-1} with a variance of 38 %, whereas GHG emission intensity ranged from 382 to 1795 kg CO$_2$ eq ha^{-1} with a variance of 39 % (Fig. 2).

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 26 % from 4783 to 3555 kg CO$_2$ eq ha^{-1} without any losses in yield (pathway from A to B, Fig. 2). The GHG emission intensity of point B was 585 kg CO$_2$ eq ha^{-1}, which was only 74 % of current practices (point A). With the HY system, grain yield increased to 8429 kg ha^{-1} (or 39% compared to point A) with a GHG emission reduction of 18 % ($\sim$ 3905 kg CO$_2$ eq ha^{-1}) (pathway A to C, Fig. 2). As a result, the GHG emission intensity for point C reduced by 41 % from 807 kg CO$_2$ eq Mg^{-1} for point A to 463 kg CO$_2$ eq Mg^{-1}, for HY point C.

If food crop yields need to be increased by 100–110 % in the future (Tilman et al. 2011), a wheat yield of 12 Mg ha^{-1} will be necessary in China. This would require approximately 292 kg N ha^{-1} (Yue et al., 2012), close to the

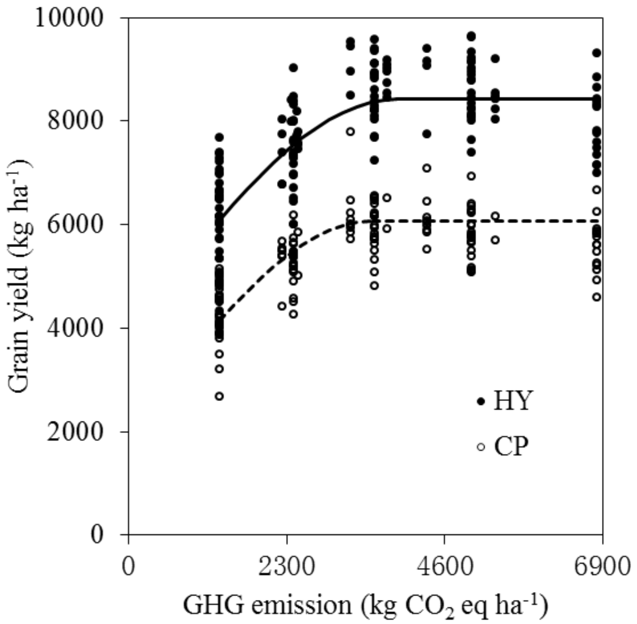

Fig. 1. The relationship between GHG emissions and grain yield for the CP (small circle and dashed line) and the HY (dot and solid line) system. Data were pooled from 33 sites of on-farm experiments for CP and HY systems. The relationship between GHG emissions and grain yield was $Y = 1940 + 4137(3X/7110 - 0.5(X/3555)^3)$, $X < 3555$; $Y = 6077$, $X > 3555$ ($R^2 = 0.75$, $P < 0.001$) for CP system, and $Y = 3845 + 4583(3X/7810 - 0.5(X/3905)^3)$, $X < 3905$; $Y = 8429$, $X > 3905$ ($R^2 = 0.68$, $P < 0.001$) for HY system.

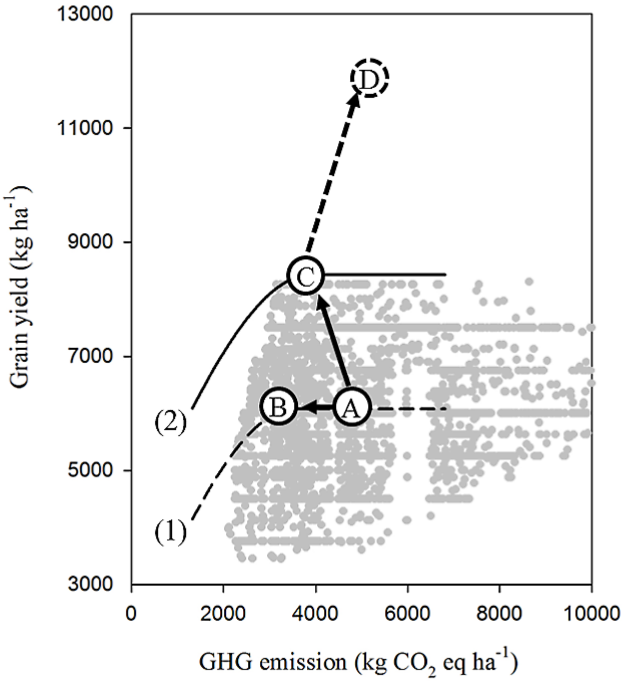

Fig. 2. A stylized grain yield–GHG emission framework demonstrating three pathways to produce higher yields with less GHG emissions. The gray dots represent grain yields and GHG emissions for the 2938 farmers surveyed. The line of dashed line (1) and solid line (2) mean relationship between grain yield and 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.

284 kg N ha^{-1} total N rate used under current practices. This indicates that the target yield of 12 Mg ha^{-1} could be achieved using current N application rates if N losses can be controlled. Thus, GHG emissions from N fertilizer would be similar to or less than the level 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 been notably disconnected in the past (Tilman et al., 2002; Burney et al., 2010; Carberry et al., 2013). Generally, 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; Hoben et al., 2011; Van Groenigen et al., 2010; Cui et al., 2013ab). Previous studies have focused 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 et al., 2010; Cui et al., 2013a, b). For winter 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 Nha^{-1} compared to current practices, resulting in an large decrease in GHG emissions from N fertilizer 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. 2. Although these practices represent a large step forward, increasing rather than merely maintaining grain yield, they also present a fundamental challenge.

In intensive cropping systems, the more efficient cycling of N 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).

In the HY system of the present study, the better 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 39 %, and GHG emission intensity was reduced by 41 %, 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).

To the best of our knowledge, this is the first on-farm study to report the relationship between wheat grain yields and total GHG emissions. Grain yield increased with increasing GHG emissions before reaching the maximum yield, with the lowest GHG emissions achieved when emission intensity decreased, indicating a trade-off relationship between high yields and GHG emissions (Figs. 2 and 4S). In this study, grain yield in the HY system increased by 39 % while GHG emissions increased by only 10 %, and GHG emission intensity was reduced by 21 %, compared to the CP system. This 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). 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. 2). Most see this pathway being met by genetically modified crops (Phillips, 2010). Yet obtaining substantially higher yields without further depleting soils, destroying natural habitats, and polluting air and water will demand a comprehensive approach. (Zhang et al., 2013). 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 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

The current relationship between wheat yield and GHG emissions due to farmers' practices 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 39 % and reduced GHG emission intensity by 41 %, 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.net/11/2287/2014/bg-11-2287-2014-supplement.pdf.

Acknowledgements. This work was funded by the Special Fund for the Agricultural Profession (201103003), the Program for New Century Excellent Talents in University (NCET-11-0478), and the Innovation Group Grant of the National Natural Science Foundation of China (31121062).

Edited by: Z. Jia

References

Berry, P. M., Kindred, D. R., and Paveley, N. D.: Quantifying the effects of fungicides and disease resistance on greenhouse gas emissions associated with wheat production, Plant Pathol., 57, 1000–1008, 2008.

Burney, J. A., Davis, S. J., and Lobell, D. B.: Greenhouse gas mitigation by agricultural intensification, P. Natl. Acad. Sci. USA, 107, 12052–12057, 2010.

Carberry, P. S., Liang, W. L., Twomlow, S., Holzworth, D. P., Dimes, J. P., McClelland, T., Huth, N. I., Chen, F., Hochman, Z., and Keating, B. A.: Scope for improved eco-efficiency varies among diverse cropping systems, P. Natl. Acad. Sci. USA, 110, 8381–83866, 2013.

Cassman, K. G.: Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture, P. Natl. Acad. Sci. USA, 96, 5952–5959, 1999.

Cassman, K. G., Dobermann, A., Walters, D. T., and Yang, H.: Meeting cereal demand while protecting natural resources and improving environmental quality, Annu. Rev. Environ. Resour., 28, 315–358, 20023.

Cerrato, M. E. and Blackmer, A. M.: Comparison of models for describing corn yield response to nitrogen fertilizer, Agron. J., 82, 138–143, 1990.

Chen, X. P., Cui, Z. L., Vitousek, P. M., Cassman, K. G., Matson, P. A., Bai, J. S., Meng, Q. F., and Hou, P.: Integrated soil–crop system management for food security, P. Natl. Acad. Sci. USA, 108, 6399–6404, 2011.

Conant, R. T., Ogle, S. M., Paul, E. A., and Paustian, K.: Measuring and monitoring soil organic carbon stocks in agricultural lands for climate mitigation, Front. Ecol. Environ., 9, 169–173, 2010.

Cui, Z. L., Zhang, F. S., Chen, X. P., Miao, Y. X., Li, J. L., Shi, L. W., Xu, J. F., Ye, Y. L., Liu, C., Yang, Z., Zhang, Q., and Huang, S.: On-farm evaluation of an in-season nitrogen management strategy based on soil N_{min} test, Field Crop Res., 105, 48–55, 2008.

Cui, Z. L., Chen, X. P., and Zhang, F. S.: Current nitrogen management status and measures to improve the intensive wheat-maize system in China, Ambio, 39, 376–384, 2010.

Cui, Z. L., Yue, S. C., Wang, G. L., Meng, Q. F., Wu, L., Yang, Z. P., Zhang, Q., Li, S. Q., Zhang, F. S., and Chen, X. P.: Closing the yield gap could reduce projected greenhouse gas emissions: a case study of maize production in China, Glob. Change Biol., 19, 2467–2477, 2013a.

Cui, Z. L., Yue, S. C.,Wang, G. L., Zhang, F. S., and Chen X. P.: In-season root-zone n management for mitigating greenhouse gas emission and reactive N losses in intensive wheat production, Environ. Sci. Technol., 47, 6015–6022, 2013b.

FAO: FAOSTAT Database, http://faostat3.fao.org/faostat-gateway/go/to/download/Q/QC/E (last access: 15 May 2013), 2013.

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., and O' Connell, C.: Solutions for a cultivated planet, Nature, 478, 337–342, 2011.

Grassini, P. and Cassman, K. G.: High-yield maize with large net energy yield and small global warming intensity, P. Natl. Acad. Sci. USA, 109, 1074–1079, 2012.

Hoben, J. P., Gehl, R. J., Millar, N., Grace, P. R., and Robertson, G. P.: Nonlinear nitrous oxide (N_2O) response to nitrogen fertilizer in on-farm corn crops of the US Midwest, Glob. Change Biol., 17, 1140–1152, 2011.

IFA: International Fertilizer Industry Association, http://www.fertilizer.org/ (last access: 1 May 2012), 2012.

IPCC (Intergovernmental Panel on Climate Change): Agriculture, forestry and other land use, in: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme edited by: Eggelston, S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K., IGES, Japan, 2006.

IPCC (Intergovernmental Panel on Climate Change): Mitigation of Climate Change. Summary for Policy Makers. Working Group 3 – 4th Assessment Report, Geneva, Switzerland, 36 pp., 2007.

IPNI Crop Nutrient Response Tool http://nane.ipni.net/article/NANE-3068 (last access: 20 April 2014), 2014.

Keating, B. A., Peter S., Carberry, P. S., Prem, S., Bindraban, P. S., Senthold Asseng, S., Meinkee, H., and Dixon, J.: Eco-efficient agriculture: concepts, challenges, and opportunities, Crop Sci., 50, 109–117, 2010.

Matson, P. A., Parton, W. J., Power, A. G., and Swift, M. J. Agricultural intensification and ecosystem properties, Science, 277, 504–509, 1997.

McSwiney, C. P. and Robertson, G. P.: Nonlinear response of N_2O flux to incremental fertilizer addition in a continuous maize (*Zea mays* L.) cropping system, Glob. Change Biol., 11, 1712–1719, 2005.

Meng, Q., Yue, S., Chen, X., Cui, Z., Ye, Y., Ma, W., Tong, Y., and Zhang, F.: Understanding dry matter and nitrogen accumulation with time-course for high-yielding wheat production in China, Plos One, 8, e68783, doi:10.1371/journal.pone.0068783, 2013.

Millar, N., Robertson, G., Grace, P., Gehl, R., and Hoben, J.: Nitrogen fertilizer management for nitrous oxide (N_2O) mitigation in intensive corn (Maize) production: an emissions reduction protocol for US Midwest agriculture, Mitig. Adapt. Strateg. Glob. Change, 15, 185–204, 2010.

Phillips, R. L.: Mobilizing science to break yield barriers, Crop Sci., 50, 99–108, 2010.

Robertson, G. P. and Vitousek, P. M.: Nitrogen in agriculture: Balancing the cost of an essential resource, Annu. Rev. Environ. Resourc., 34, 97–125, 2009.

S.A.S Institute: SAS user's guide: Statistics, SAS Institute, Cary, NC, 1998.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., Mccarl, B., and Ogle, S.: Agriculture, in: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Metz, B., Davidson, O. R., Bosch, P. R., Dave, R., and Meyer, L. A., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

Snyder, C. S., Bruulsema, T. W., Jensen, T. L., and Fixen, P. E.: Review of greenhouse gas emissions from crop production systems and fertilizer management effects, Agr. Ecosys. Environ., 133, 247–266, 2009.

Swaminathan, M. S.: An evergreen revolution, Biologist, 47, 85–89, 2000.

Tilman, D., Cassman, K. G., and Matson, P. A.: Agricultural sustainability and intensive production practices, Nature, 418, 671–678, 2002.

Tilman, D., Balzer, C., Hill, J., and Befort, B. L.: Global food demand and the sustainable intensification of agriculture, P. Natl. Acad. Sci. USA, 108, 2026–20264, 2011.

Van Groenigen, J. W., Velthof, G. L., Oenema, O., Van Groenigen, K. J., and Van Kessel, C.: Towards an agronomic assessment of N_2O emissions: a case study for arable crops, Eur. J. Soil Sci., 61, 903–913, 2010.

Xu, Z. Z., Yu, Z. W. and Zhao, J. Y.: Theory and application for the promotion of wheat production in China: past, present and future, J. Sci. Food Agr., 93, 2339–2350, 2013.

Yue, S. C., Meng, Q. F., Zhao, R. F., Ye, Y. L., Zhang, F. S., Cui, Z. L., and Chen, X. P.: Change in nitrogen requirement with increasing grain yield for winter wheat, Agron. J., 104, 1–7, 2012.

Zhang, F. S., Cui, Z. L., Chen, X. P., Ju, X. Y., Shen, J. B., Chen, Q., and Liu, X. J.: Integrated nutrient management for food security and environmental quality in China, Adv. Agron., 116, 1–40, 2012.

Zhang, F. S., Chen, X. P., and Vitousek, P.: An experiment for the world, Nature, 497, 33–35, 2013.