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Overcoming nitrogen fertilizer over-use through technical and advisory approaches: A case study from Shaanxi Province, northwest China

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ABSTRACT

Over-application and inefficient use of nitrogen (N) fertilizer is a serious issue throughout China, with adverse environmental and economic impacts. In this paper we present evidence of this in the wheat/maize double cropping system in the Guanzhong Plain in Shaanxi Province, northwest China. Results show the economic benefits of overcoming this problem are greatest for the lowest income farmers. We also outline new advisory approaches that could aid delivery of information to farmers. Evidence of excessive N fertilizer applications, and opportunities to maintain or even increase crop yields with lower rates of N, are presented from several sources. A survey of N applications to maize by 80–100 farmers showed that 77% were applying N at rates in excess of those recommended by the local advisory agencies. Experiments with maize and wheat at 120 sites, testing a range of N application rates, show remarkably small yield responses to applied N and high yields even when no N is applied. This is mainly because of large nitrate residues accumulated in the soil from past N fertilizer applications. Trials were conducted in 30 farmers' fields comparing the farmer's usual N rate with a lower rate based on a combination of local recommendations and measurements of nitrate in soil. On average, N rates to maize and wheat could be decreased by 70% and 20%, respectively, with no loss of yield and sometimes small increases. Economic assessments and household surveys showed the economic benefits for farmers of moving to more rational use of N fertilizer. Even a 30% reduction in N use would increase household income by 2–9%, and a 50% reduction by 4–15%. In all cases the poorest farmers benefit the most because fertilizer represents a larger percentage of their expenditure, so policies and practices leading to more rational N use are clearly pro-poor. Advisory approaches based on an N budget approach are outlined as an alternative to traditional approaches where farmers are simply given a recommended application rate. Simple in-field measurements of nitrate concentration in soil, using commercially available nitrate-sensitive strips giving a color reaction, may be a useful supplement for field-specific advisory work if the logistics at village level can be organised.

1. Introduction

The winter wheat–summer maize double cropping rotation is the principal cropping system in northern China, occupying around 16 Mha and the output accounting for about a quarter of total national food production (Yang et al., 2014). Excessive application of mineral nitrogen (N) fertilizer is a common problem in this system, with average N application rate of 553 kg N ha^{-1} annually to this system in Shandong province (Kou et al., 2005) and an N surplus of up to 526 kg N ha^{-1} in some cases (Zhen et al., 2007). N applications 30% greater than required for maximum crop yield

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have been noted for wheat, maize and other crops in this region (Norse et al., 2012). The issue has received less attention in northwest China compared to other areas, but there is also evidence of excessive N fertilizer use in this region, especially in the relatively intensive cropping of the Guanzhong Plain of Shaanxi Province (Zhang et al., 2000; Tong et al., 2004,b; Zhao et al., 2010a,b; Chang et al., 2014).

Excessive N fertilization results in low N use efficiency (NUE), increased production costs for farmers, and unnecessarily large losses of N causing serious environmental problems such as groundwater nitrate contamination (Zhang et al., 1996; Zhang et al., 1996), greenhouse gas emissions (Zhang et al., 2013a,b,b) and soil acidification (Guo et al., 2010). In the North China Plain (NCP) high rates of N fertilizer application are closely associated with high nitrate concentrations in groundwater and nitrate accumulation in the soil profile (Gao et al., 1999; Chen et al., 2000; Liu et al., 2003a; Ju et al., 2004).

Due to the huge food demand in China, there is resistance to suggestions to decrease N fertilizer use as this is seen as risking loss of production, despite considerable evidence to the contrary (Ju et al., 2004; Sun et al., 2012). A major goal for Chinese agriculture is to identify rational practices for N fertilizer management that combine the imperative to increase food production whilst decreasing N-related environmental pollution to an acceptable level. An approach that has been successful elsewhere in the world over several decades is a strategy based on measuring the quantity of mineral N in soil before planting and using this to guide N fertilizer applications (Soper and Huang, 1962; Wehrmann and Scharpf, 1979). Such measurements, generally termed soil N_{min}, may include the total of nitrate- plus ammonium-N or just nitrate as this is usually dominant. In the NCP, an in-season N management strategy based on the soil N_{min} test was developed for the winter wheat–summer maize rotation system under experimental conditions (Liu et al., 2003b; Chen et al., 2006). In this method, N fertilizer is applied in two or three splits during the growing season, with an optimum application rate being determined by comparing measured soil nitrate content in the root layer with predetermined target values at different

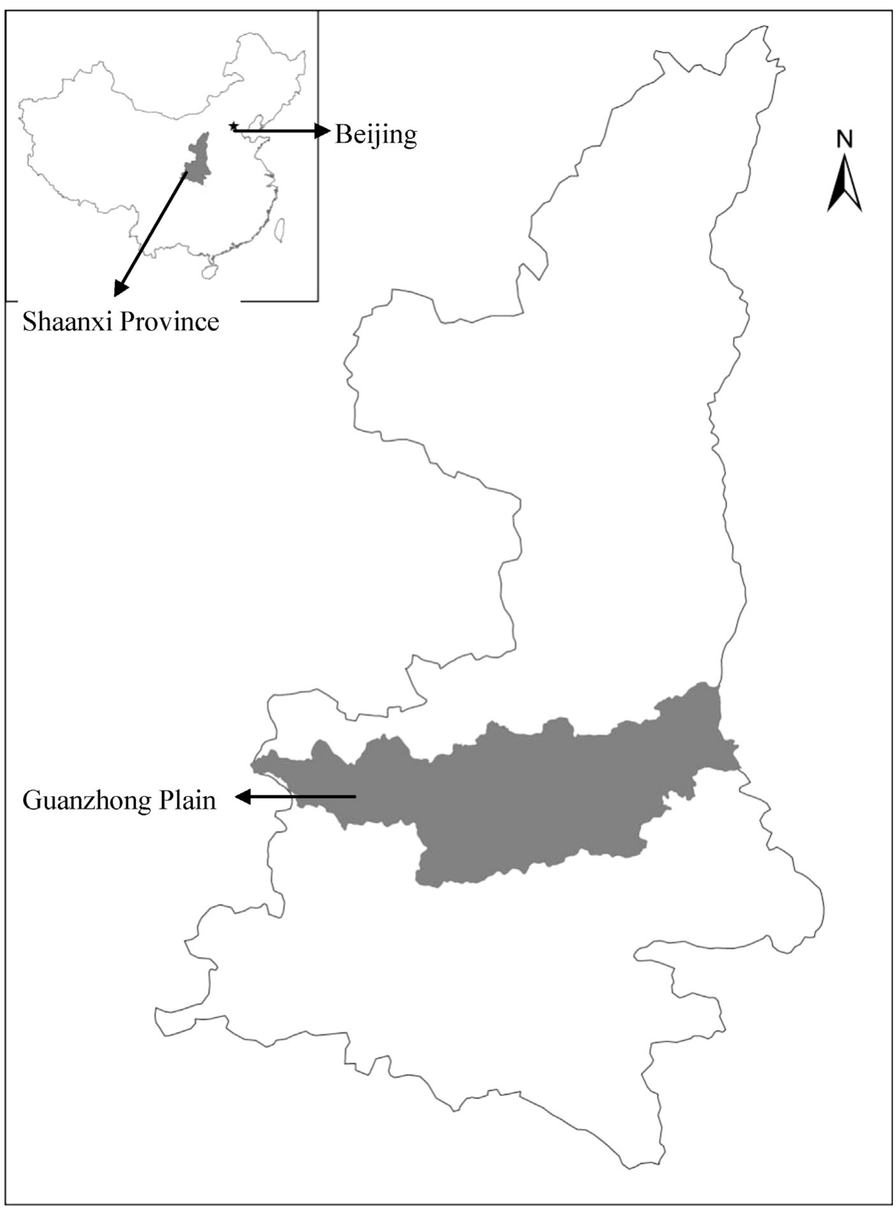

Fig. 1. Location of Guanzhong Plain in Shaanxi Province, northwest China.

Table 1
Experimental sites and soil test results on Lou soil in the Guanzhong Plain, Shaanxi Province, China.

Crop	Sites	pH		O.M. ($g\,kg^{-1}$)		Alkali-hydrolyzable N ($mg\,kg^{-1}$)		Olsen-P ($mg\,kg^{-1}$)		NH_4OAc-K ($mg\,kg^{-1}$)	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Wheat	120	7.9	7.0–8.6	15.2	7.1–27.8	80.1	31.5–156	25.5	7.8–67.1	163	77–386
Maize	120	7.9	7.2–8.7	15.7	7.8–30.1	66.1	23.6–137	25.5	7.3–50.7	158	77–367

growth stages. The results from eight successive cropping seasons with the winter wheat–summer maize rotation in the NCP showed that 79% of N fertilizer could be saved without any yield loss compared with farmer's N practice (Zhao et al., 2006). Subsequently this method has been tested in other parts of the NCP (Cui et al., 2008a,b,b). Moreover, long-term fertilizer experiments have shown that N applications can be reduced substantially for up to 15 years without lowering yields (Zhao et al., 2010a,b,b).

Shaanxi province in northwest China is a region that is less developed and less intensively studied than those in the east and south of China, yet there is evidence even here of excessive N fertilizer applications and increasing nitrate concentrations in groundwater (Zhang et al., 2000; Tong et al., 2004). Because farmers' incomes in this region are generally lower than in the more developed regions, it is likely that money wasted on unnecessary N fertilizer will have a disproportionate impact on their incomes. Thus there are environmental, economic and social reasons for investigating and addressing the issue in this region. There is also interest in the region in applying in-season N management strategies to overcome the problem. The objectives of this paper are to (1) quantify the extent of excessive N fertilizer use in the winter wheat–summer maize system in the Guanzhong Plain, northwest China; (2) quantify the negative economic impacts on farmers in different income groups and the economic benefits of more rational N fertilizer use; (3) evaluate an in-season N management strategy as a means of achieving more rational N fertilizer us; (4) propose an alternative advisory approach based on N budgeting.

We address these objectives by drawing on results from four independent sources: (a) On-farm field experiments testing different rates of N fertilizer and analyzed to obtain different types of yield response curves that are commonly used as a basis for N fertilizer advice. These experiments, part of a national network, were conducted at 120 sites in the region. (b) Nitrogen comparison experiments conducted on 30 farmers' fields in which the N_{min} approach was used to determine N fertilizer applications and results compared with farmers' practice. (c) A survey of 80–100 farmers to determine the N rates actually applied by farmers and compare these with local recommendations. (d) A separate survey of about 100 farm households with an emphasis on determining the cost of fertilizers as a proportion of total wheat and maize production costs to assess the economic benefits from reducing N applications to a rational value.

Finally we evaluate the practicalities and barriers affecting different advisory approaches and propose an N budget approach in which the N fertilizer application for a specific crop is determined by estimating the crop N removal (based on likely yield) and the sources of N using a combination of measurements, default values and local knowledge.

2. Materials and methods

The Guanzhong Plain (Fig. 1) is an important cereal production area supplying more than 50% of the grain for Shaanxi Province. It occupies about 34 km^2, and accounts for nearly 20% of the area of the province (Liu et al., 2014). The climate in the Guanzhong Plain is warm-temperate subhumid continental monsoon, with cold winters and hot summers. The annual precipitation is about 550 mm, with about 40% of the rainfall occurring during the winter wheat growth season (between the beginning of October and mid-June). The amount and distribution pattern of rainfall varies widely from year to year as affected by the continental monsoon climate. To achieve high grain yields, wheat is often irrigated, though availability of irrigation varies between areas within the region. In this study, most farmers irrigated wheat with about 100 mm on each of two occasions, before the freeze in winter and at the start of

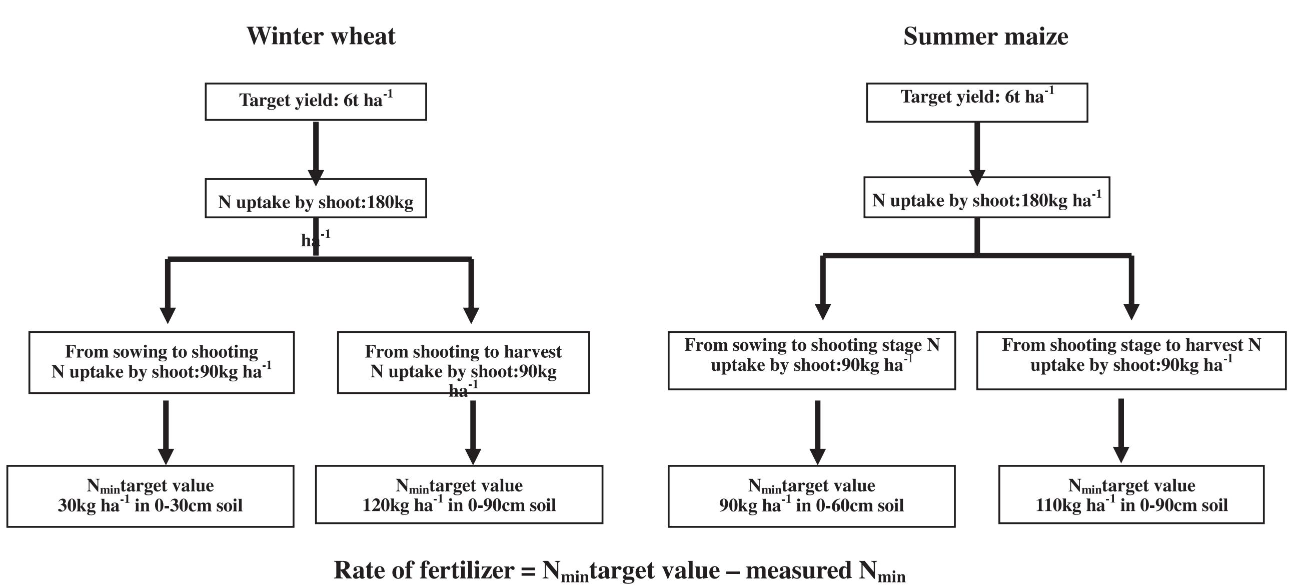

Fig. 2. Method of optimizing N fertilization for winter wheat (left) and summer maize (right) based on crop N demands and soil supply, at two growth rates.

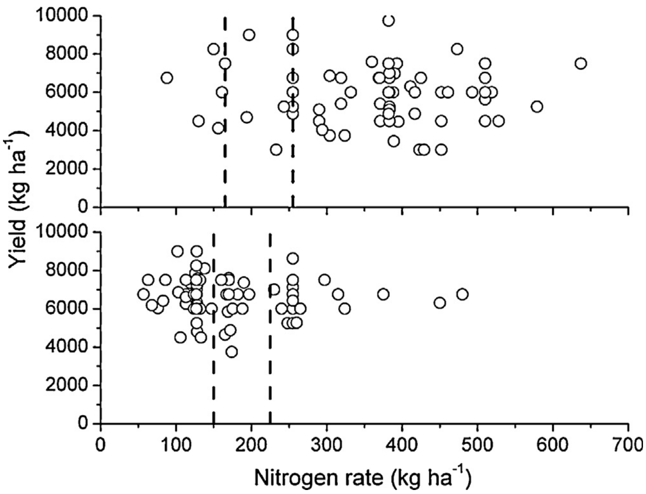

Fig. 3. Survey of fertilizer N rates applied by farmers to wheat (bottom panel) and maize (top panel) in the Guanzhong Plain, Shaanxi Province, and the resulting grain yields. (Dashed lines show range of fertilizer N rates recommended by local extension bureau based on expected crop yield).

the shooting stage next spring. At all experimental sites the soil is a silty clay loam derived from loess material with pH greater than 8.0 and calcium carbonate content around 8%, locally named Lou soil (Guo et al., 1992). Average soil organic matter content, alkali-hydrolyzable N, Olsen-P and NH_4OAc-K in the 120 locations used from the national network of sites are shown in Table 1.

2.1. Nitrogen rate experiment

On-farm experiments at 120 sites for winter wheat and summer maize were conducted from 2005 to 2009. At all sites a typical winter wheat–summer maize rotation system was practiced where winter wheat was sown immediately after harvest of summer maize in early October and harvested in the early or mid-June. The plot size was either 30 or 60 m^2, differing between sites.

To estimate the optimal rates of N fertilizer experiments with four N application rates were conducted at each site for both winter wheat and summer maize. The actual rates at each site were determined according to the soil type and an assessment of its fertility based on previous cropping or from results of previous experiments at the site, or nearby. In addition to N0 (control with no N application, rates were N1 (60–150 kg N ha^{-1}), N2 (120–300 kg N ha^{-1}) and N3 (180–450 kg N ha^{-1}). At each site the N2 rate was estimated to be the optimum for maximum yield. A larger number of N rates would have been preferable for more precisely calculating the optimum N rate at each site but this was not possible because the experiments were part of a national scheme deliberately designed to be simple. The treatments were unreplicated for the same reason so, for our analysis of the data, sites were treated as pseudo-replicates.

At all sites the wheat variety Xiaoyan 22 and maize variety Zhengdan 958 were grown, and sufficient P and K fertilizer were applied before sowing based on soil test results using local practice, but no manure was added. The quantities of P and K applied were in the range 0–150 kg P_2O_5 ha^{-1} as superphosphate and 0–120 kg K_2O ha^{-1} as potassium chloride. For winter wheat or summer maize, urea was incorporated at two times: before sowing and at the shooting stage (wheat) or before sowing and before tasselling stage (maize), before irrigation. Except for fertilizer application and harvest, the plots were managed in the same manner as the rest of the field by the individual farmer.

At harvest, wheat plants in an area of 3 m^2 and maize plants 15 m^2 in the middle of each plot were harvested manually; dry weights of grain was determined after separation and oven-dried at 60 °C

2.2. Nitrogen comparison experiment

On-farm comparison experiments were carried out for winter wheat and summer maize at three villages (Cui Donggou, Shangguan and Guancun) near Yangling in the Guanzhong Plain from 2008 to 2009, with ten farmers from each village giving a total of 30 farmer sites. There were two N treatments at each experimental household: in-season N management based on a soil nitrate test (Opt. N) and farmer's N practice (Con. N). There was no replication of N treatments as these were primarily demonstration sites, but the 10 sites per village were utilized as pseudo-replicates. In the Opt. N treatment, the growth of winter wheat or summer maize was divided into two periods: from planting to shooting stage, and from shooting to harvest. The optimum N rate in the two growth periods was determined by measuring soil nitrate content at the beginning of the period. The measured soil nitrate-N in root layers (0–30 cm and 0–90 cm for wheat and 0–90 cm for maize) was deducted from the target values as shown in Fig. 2 (adapted from Zhao et al., 2006). These target values represent the estimated plant uptake of N in shoots plus roots for different expected yield levels. The procedure is described in detail by Zhao et al. (2006). In the Con. N treatment, the amount of N fertilizer applied was according to the individual farmer's current practice, with all N applied before sowing. No manure was applied at any of the farmer sites and other management practices followed normal farmer practice as described for the experiments in Section 2.1.

2.3. Surveys of farmers' practices

To understand farmer's inputs to cereal production, two farm surveys were conducted. One comprised visits to randomly selected farmers in the region of Baoji City, Shaanxi Province, in 2007. In this region irrigation is commonly practiced; 80 farmers were growing wheat and 100 growing maize. The aim was to determine the range of N fertilizer applications being used. Another survey was conducted in Heyang County in 2008 on a rain-fed farming system to understand the financial cost of fertilizer use in crop production, and the impact on household income of reduced fertilizer use; information was obtained on 103 crops of both wheat and maize. Predesigned questionnaires were used in both surveys.

Table 2
Share of fertilizer in crop production costs of dryland wheat and maize systems.

Crops	Item	1st quartile	2nd quartile	3rd quartile	4th quartile	Average
Wheat (*N* = 103)	Fertilizer costs (Yuan ha^{-1})	1662	2092	2287	2124	2025
	Total production costs (Yuan ha^{-1})	3214	3849	4147	3932	3768
	% of fertilizer in total costs of production	50.6	51.2	52.4	49.3	50.8
Maize (*N* = 103)	Fertilizer costs (Yuan ha^{-1})	784	799	990	1367	985
	Total production costs (Yuan ha^{-1})	1410	1371	1673	2271	1861
	% of fertilizer in total costs of production	55.6	58.3	59.2	60.2	58.6

Yuan is the Chinese currency unit.

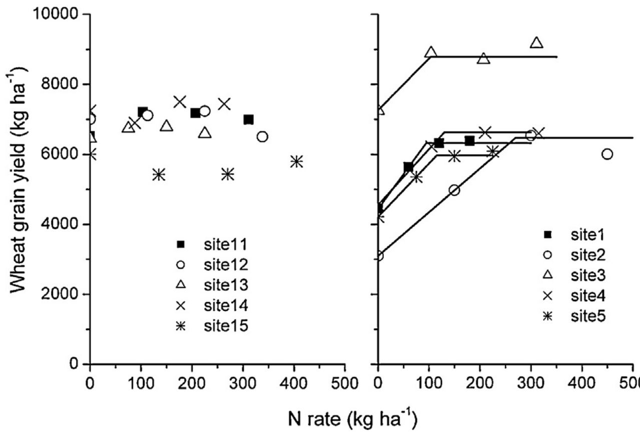

Fig. 4. Wheat yield response to nitrogen application rate in field experiments. Data shown is a selection of 5 sites taken from 68 experiments in the region where there was a yield response to N fertilizer (In there remainder of the 120 experiments there was no yield response).

2.4. Sampling and laboratory procedures

At the 120 sites of the nitrogen rate experiment (Section 2.1), a composite soil sample (0–20 cm) was collected before the start of each experiment with an "S" shape sampling strategy (approx. 15 auger samples). Soils were air-dried and sieved through a 0.2 mm mesh to remove undecomposed plant materials. The sieved samples were analyzed for organic matter content, total N content, Olsen-P and NH_4OAc-K referred to Bao (2008).

For the 30 sites of the nitrogen comparison experiments, at least five soil samples were randomly taken to a depth of 30 cm before sowing wheat, and to a depth of 100 cm after harvest. Soil samples, before planting and after harvest, were extracted with 0.01 mol L^{-1} $CaCl_2$, and analyzed for NO_3-N using nitrate-sensitive test strips (Nitrate Test RQeasy®, E. Merk, Germany); a reflectometer (RQeasy®, E. Merk, Germany) was used in the laboratory to measure color intensity and hence calculate soil NO_3-N concentration. Soil water content was measured by oven drying at 110 °C. Soil samples taken immediately prior to N fertilizer application were extracted with 1:1 ratio of soil to distilled water and nitrate analyzed in the same way. Soil nitrate content was then used to calculate the Opt. N rate at each site. For demonstration purposes for farmers, and to test the practicability of the procedure for advisory purposes, a hand-held reflectomer was also used for nitrate analyses in the field.

2.5. Statistical analysis

In order to examine the economic impacts of fertilizer-use among different income level households, the surveyed households in Heyang were divided into four quartiles based on total household income.

Crop yield response curves to N rate at the 120 sites of the N rate experiment were evaluated using quadratic, quadratic plus plateau and linear plus plateau models. In most cases, a linear plus plateau model fitted the data best and was chosen for all the sites. Significant relationships were found at 68 experimental sites for winter wheat and 60 sites for summer maize. Because the experimental treatments were not replicated we used sites as pseudo-replicates, and derived fitted parameters from the linear-plateau model using boxplots to give mean, median, the 25th and 75th percentile.

Data from 30 sites of the N comparison experiment were compared based on least significant difference (LSD) at 0.05 level of probability for means of N rate, crop yield, economic benefit and nitrate residue from all households by SPSS 16.0.

3. Results

3.1. Surveys of fertilizer use

The survey of farmers' practice in the Guanzhong Plain, based on 80 wheat and 100 maize crops, showed widespread over-use of N fertilizer. About 28% of the wheat crops had received a higher rate of N fertilizer than recommended by the local Extension Bureau (Fig. 3). With maize the extent of over-fertilization was

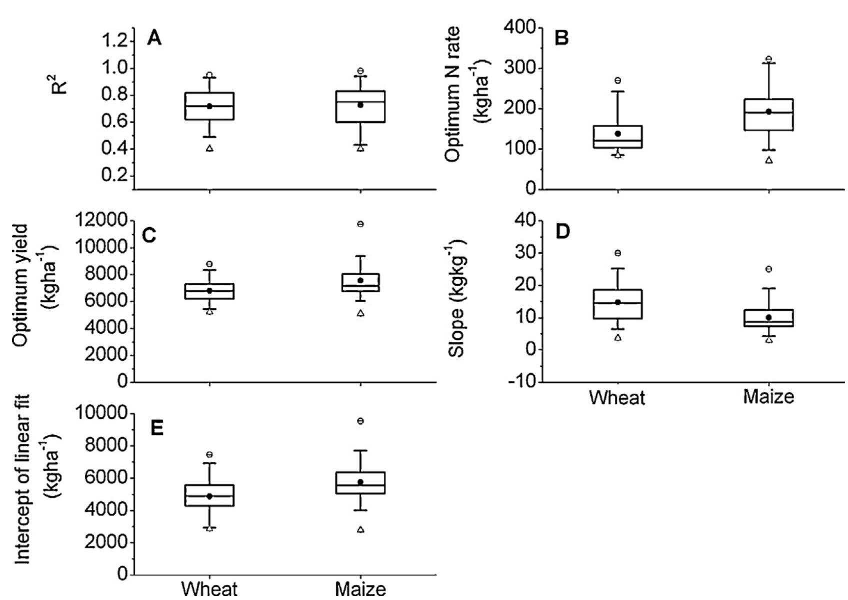

Fig. 5. Parameters (A, determination coefficient; B, optimum N rate; C, optimum yield; D, slope value; E, intercept of linear fit) from linear-plateau fit for N responsive experiments of winter wheat across 68 sites, and of summer maize across 60 sites in Guanzhong Plain of Shaanxi Province. The upper and lower limits of each box represent the 25th and 75th percentiles parameters' values. The horizontal line in the center of the box indicates the median. The solid circle indicates mean values, and open circle and open triangle indicate the max. and min. values.

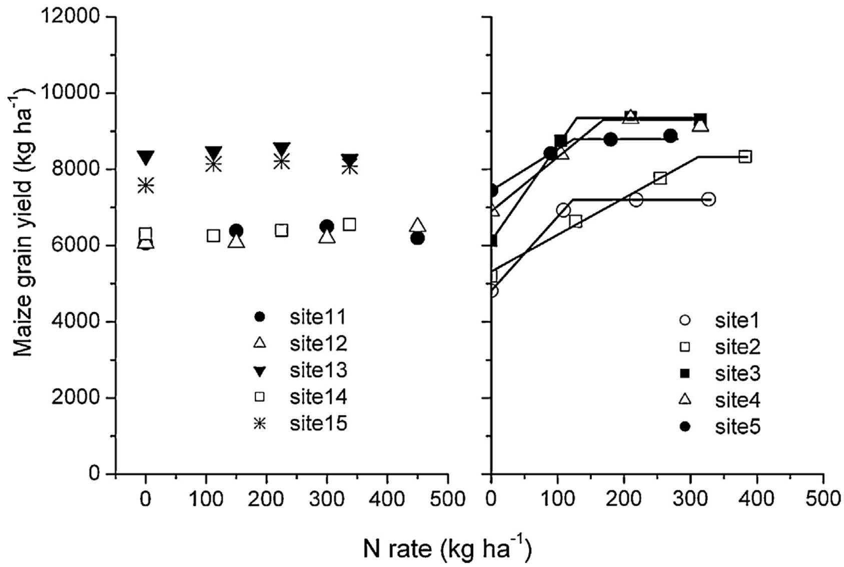

Fig. 6. Maize yield response to nitrogen application rate in field experiments. Data shown is a selection of 5 sites taken from 60 experiments in the region where there was a yield response to N fertilizer (In there remainder of the 120 experiments there was no yield response).

more extreme, with 77% of crops receiving more than the recommended rate (Fig. 3) and an average over-use of 58%. The survey showed a very wide range of N fertilizer application rates between different farmers and revealed some extremely high rates. For example, with maize 16% of farmers applied >500 kg N ha^{-1}, an astonishingly high rate when compared to the recommended rate of 170–260 kg N ha^{-1} and rates applied to maize crops elsewhere in the world giving similar or higher yields. The other remarkable finding from the survey was that there was no relationship between the quantity of N fertilizer applied and crop yield for either wheat or maize. For example, with maize, some farmers achieved grain yields of 6–8 t ha^{-1} with N applications of 250 kg N ha^{-1} or less (around the range of recommended rates, or even less) whilst yields for those applying 400–500 kg N ha^{-1} varied between 3 and 8 t ha^{-1} (Fig. 3). Clearly there are factors other N fertilizer input having a major influence on crop yields and these are not being addressed in current management practice. The results are also strong evidence that recommendations from the local advisory agency are widely ignored.

The survey of about 100 farmers in Heyang showed that, in their situation, the cost of fertilizer accounted for 49–60% of total production costs for both wheat and maize (Table 2). Although the rates of fertilizer applied, and hence the cost, were slightly higher for the higher income households, there was no difference between the different income groups in the cost of fertilizer when expressed as a proportion of production costs (Table 2). The implications of this for environmental policy and poverty alleviation are discussed later.

3.2. Wheat and maize response to N application rates

Wheat yield response to N application rate varied greatly among experimental sites. Yield showed no response to N rate for

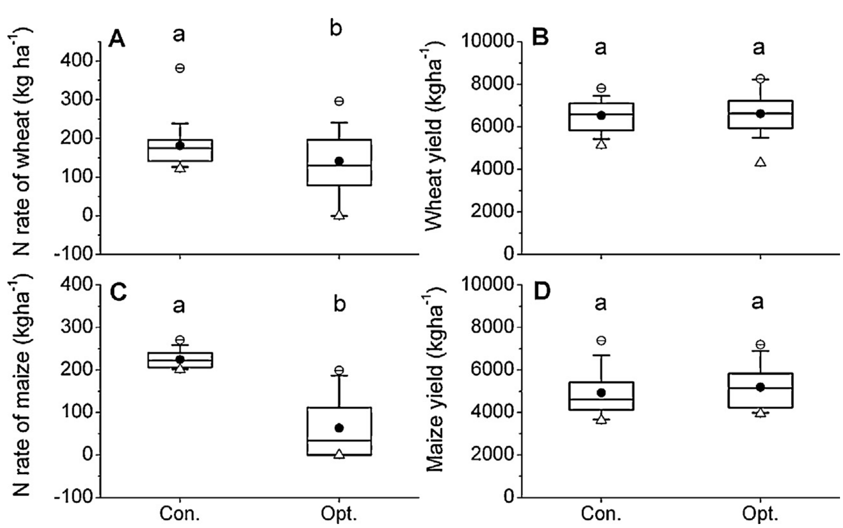

Fig. 7. Comparison of nitrogen application rates (A and C) and grain yields of wheat (B) and maize (D) between farmer's practice (Con.) and in-season N management (Opt.) across 30 households in Guanzhong, Shaanxi Province. The upper and lower limits of each box represent the 25th and 75th percentiles for N application rate. The horizontal line in the center of the box indicates the median. The solid circle indicates mean values, and open circle and open triangle indicate the max. and min. values. Different lowercase letters indicate significant difference between Con. and Opt. ($P < 0.05$).

Table 3
Nitrogen application reduction, grain yield increase and economic gains from in-season N management of wheat for three villages in the Guanzhong Plain.

Village	N reduction (kg N ha^{-1})	Fertilizer saving (Yuan ha^{-1})	Yield increase (kg ha^{-1})	Increase in crop value (Yuan ha^{-1})	Total profit increase (Yuan ha^{-1})
Cui Dong Gou	70	306	185	332	639
Shang Wan	18	79	117	211	290
Guancun	22	95	−39	−70	26
Average	36	155	88	158	318

Yuan is the Chinese currency unit.

Table 4
Nitrogen application reduction, grain yield increase and economic gains from in-season N management of maize for three villages in the Guanzhong Plain.

Village	N reduction (kg N ha^{-1})	Fertilizer saving (Yuan ha^{-1})	Yield increase (kg ha^{-1})	Increase in crop value (Yuan ha^{-1})	Total profit increase (Yuan ha^{-1})
Cui Dong Gou	167	728	208	312	1040
Shang Wan	155	674	298	447	1121
Guancun	160	694	261	392	1086
Average	161	699	256	384	1082

Yuan is the Chinese currency unit.

52 out of the 120 experiments, as shown by the example data from 6 sites in Fig. 4A. This data also illustrates the finding that remarkably large wheat yields of 6–7 t ha^{-1} were obtained with no addition of N fertilizer at a large number of sites, almost certainly due to large residues of nitrate in the soil profile accumulated from many years of excessive rates of N application, and in the case of some irrigated wheat high N levels in the irrigation water. For 68 experiments, a linear-plateau model successfully described the relationships between yields and N rates, as shown by examples from 6 sites (Fig. 4B). Fig. 5A shows the significant correlation coefficients derived from this model. The optimum N fertilizer rates derived from the linear-plateau model varied from 84 to 270 kg ha^{-1}, with a mean value of 138 kg ha^{-1} (Fig. 5B). The corresponding optimum yield varied from 5213 kg ha^{-1} to 8785 kg ha^{-1}, with a mean of 6789 kg ha^{-1} (Fig. 5C). The slope of the linear part of the relationship, representing agronomic efficiency of applied N (i.e., NUE expressed as kg of additional grain produced per kg N applied) varied 8-fold between sites from 3.7 to 29.9 kg grain kg^{-1} N (Fig 5D), indicating the wide range of agronomic conditions represented by the 68 sites and the scope for enormous improvement of N use efficiency in many cases. Most of the low values for NUE result from situations where N was over-supplied, giving only small increases in yield but a few cases may reflect situations where other factors are limiting crop growth; these are likely to include deficiency of other nutrients or lack of water. The values for the intercept of the linear part of the model with the y-axis (representing the modeled crop yield with no addition of N fertilizer; Fig. 5E) shows the wide range of grain yields with no applied N, between 2.8 and 4.9 t ha^{-1}. This is consistent with a wide range of values for residual nitrate in soil at the different locations.

Maize yield response to N rate also varied greatly among experimental sites, with yield showing no response to N rate for 60 out of 120 experiments, as shown by six examples (Fig. 6A). For the other 60 experiments, a linear-plateau model could well describe relationships between yields and N rates, as shown by the examples in Fig. 6B and significant correlation coefficient values (Fig. 5A). The optimum N rates varied from 71 kg ha^{-1} to 323 kg ha^{-1}, with a mean of 193 kg ha^{-1} (Fig. 5B). The

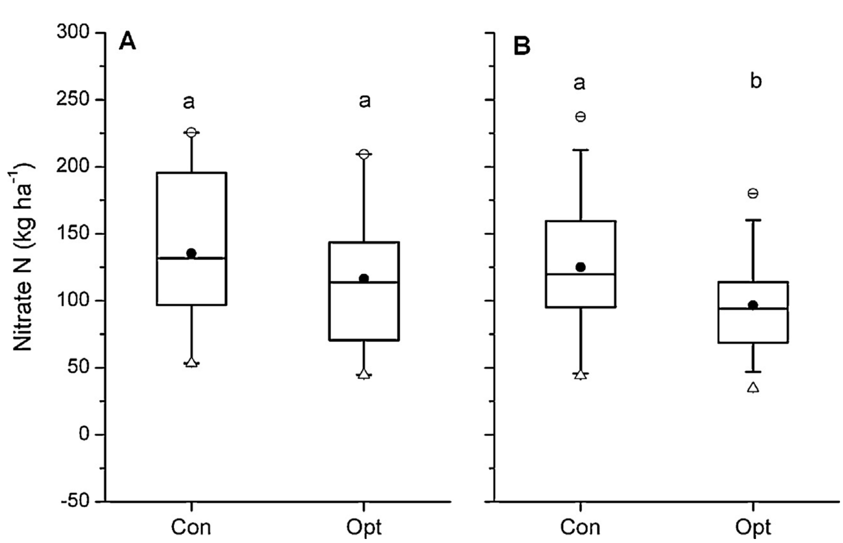

Fig. 8. Soil nitrate-N content (0–100 cm depth) under Con. N and Opt. N after harvest of winter wheat (A) and summer maize (B) across 30 households in Yangling, Shaanxi Province. The upper and lower limits of each box represent the 25th and 75th percentiles for N application rate. The horizontal line in the center of the box indicates the median. The horizontal line in the center of the box indicates the median. The solid circle indicates mean values, and open circle and open triangle indicate the max. and min. values. Different lowercase letters are significantly different between Con. and Opt. ($P < 0.05$).

Table 5
Impact of reduction in fertilizer N use on household income (dryland wheat).

Income level	Total household income (yuan)	Savings from 30% fertiliser use reduction		Savings from 50% fertiliser use reduction	
		Savings (Yuan)	% of household income	Savings (Yuan)	% of household income
1st quartile	1664	153	9	255	15
2nd quartile	6489	249	4	416	6
3rd quartile	10442	225	2	374	4
4th quartile	20260	221	1	369	2
Avg	9728	212	2	353	4

Yuan is the Chinese currency unit.

corresponding optimum yield varied from 5087 kg ha^{-1} to 11,744 kg ha^{-1}, with a mean of 7537 kg ha^{-1} (Fig. 5C). The agronomic efficiency varied from 3.0 kg kg^{-1} to 25.0 kg kg^{-1} with a mean of 10.0 kg kg^{-1} (Fig. 5D). The yield without N fertilizer application varied even more than for wheat, covering a 3-fold range between 2.8 and 9.5 t ha^{-1} (Fig. 5E).

3.3. Comparison between in-season N management and farmer's practice

Results from the comparison of farmers' N fertilizer practice with an in-season management approach based on measuring soil nitrate content showed that, in the locations tested, in-season management led to a wider range of N rates than was current practice by farmers. At virtually every site and for both wheat and maize, in-season management led to lower rates of N application than farmers' practice, maintained or slightly increased grain yields and increased income for the farmers (Fig. 7B and D, Tables 3 and 4). Increased income was due mainly to savings on the purchase of N fertilizer, though with some contribution from increased grain production especially for maize (Tables 3 and 4). With both crops, in-season management led to a recommended optimum N rate of zero in some cases (Fig. 7A and C). The impacts were particularly large for maize with the mean N application rate across all 30 sites decreasing from 232 to 60 kg N ha^{-1} (median decreased from 230 to 32 kg N ha^{-1}) whilst mean yield increased slightly from 4.9 to 5.2 t ha^{-1} (Fig. 7C and D). This represented a mean increase in NUE of over 3-fold from 25 to 83 kg grain kg^{-1} applied N. With wheat, results followed the same general trends but the effects were considerably smaller, indicating that the over-use of N fertilizer on wheat in these districts was substantially less than for maize. With in-season management the median value for recommended N rate for wheat was 125 kg N ha^{-1}, about 50 kg N ha^{-1} less than current farmers' practice, though the recommended rates did include some at zero (Fig. 7A). The mean and median grain yields for wheat were virtually unchanged though in-season management led to some farmers achieving increased yields: for example, with this strategy the maximum yield obtained was 8.3 t ha^{-1} compared to 7.8 t ha^{-1} with farmers' practice. Although the mean increase in profit for wheat was only about one third of that with maize, it was still helpful and contributed to an annual increase for the wheat–maize rotation of Yuan 1400 ha^{-1} (or 227 $ ha^{-1}) (Tables 3 and 4).

There was some tendency for the amount of residual nitrate in soil after both crops to be decreased where in-season N management had been practiced (Fig. 8A and B), but the quantitative change was less than might have been expected given the large decreases in N fertilizer application rates, especially to maize. After maize the mean decrease was only about 25 kg nitrate-N ha^{-1}, with the total amount present to a depth of 100 cm still about 100 kg nitrate-N ha^{-1}. This may well be due to the large amounts accumulated in soil over many years.

Table 6
Nitrogen budget sheet for use in farmer advisory work forwheat in the Guanzhong Plain, Shaanxi Province, China. Values refer to the wheat cropping season within the wheat–maize double cropping system.

Input/output items		Input/output rate (kg ha^{-1})	Target yield (kg ha^{-1})
Input	Deposition	15	
	Irrigation	15	
	Soil supply	105	
	Total	135	
Output	Soil residue	60	
	Losses	30	
	Wheat uptake	165	6000
		210	7500
N application	N rate	120	6000
		165	7500

Table 7
Nitrogen budget sheet for use in farmer advisory work formaize in the Guanzhong Plain, Shaanxi Province, China. Values refer to the maize cropping season within the wheat–maize double cropping system.

Input/output items		Input/output rate (kg ha^{-1})	Target yield (kg ha^{-1})
Input	Deposition	30	
	Irrigation	23	
	Soil supply	105	
	Total	158	
Output	Soil residue	60	
	Losses	45	
	Maize uptake	135	6000
		165	7500
N application	N rate	90	6000
		120	7500

4. General discussion and conclusions

4.1. Inappropriate N fertilization practices in the Guangzhong Plain, Shaanxi Province, and their economic consequences for farmers

This study is unusual because we attempt to synthesise information derived from diverse sources. These include large numbers of field trials on farmers' fields (including one series with a range of N rates and another in which soil nitrate testing was used to determine optimum N rate) and surveys of farmers practices that included economic information on household income that were used to assess the scope to improve farmers' incomes by moving to more rational N use.

Although the general situation of N fertilizer over-use and inefficient use in China is well documented, the majority of published data is for agricultural conditions in the most developed agricultural regions in the east and south of the country such as the North China Plain and the Yangtze River Basin (e.g., Ju et al., 2004, 2009; Zhao et al., 2006). The results from this study clearly demonstrate a similar problem in the wheat–maize system as practiced in northwest China, specifically the Guangzhong Plain in Shaanxi Province and are consistent with a small number of earlier reports from the region associating excessive N application rates with high concentrations of nitrate in groundwater (Gao et al., 1999; Tong et al., 2004).

Results from the field trials conducted at 120 sites for wheat and maize (Fig. 5) clearly demonstrated that the rates of fertilizer N used by farmers were frequently greater than required to achieve maximum grain yield. A remarkable finding was that, with maize, there was no yield response to applied fertilizer N at half of the sites (Fig. 6). Although the results showed that the degree of N over-use was less for wheat, 43% of the wheat sites showed no yield response to added N (Fig. 4). The very wide range of N application rates used by farmers, including some extremely high values, including many examples in excess of 300 kg N ha^{-1} for maize (Fig. 3) was also revealed by the survey of 103 farms in the Heyang area. This body of data represents the largest collected in this region. The results also demonstrate that recommendations for N use by the local extension agencies are widely ignored by farmers; this has also been observed in other regions and the reasons discussed together with the need for new and more effective approaches (Ju et al., 2009; Xiang, 2012; Jia et al., 2013). In addition to a lack of knowledge by farmers, there are often issues of conflicts with off-farm work and policies or strategies intended to overcome N fertilizer over-use will have to take these factors into account.

The economic results from two surveys of farmers show that excessive applications have a significant impact on framers' profitability and that there is considerable scope to increase profit by moving to rational rates of N fertilizer application – though this appears to be generally not recognised by farmers and thus far has not been acted on by policy makers. The survey of farmers in Heyang showed that fertilizer costs accounted for 49–60% of total production costs for wheat and maize (Table 2). Reducing N applications to a reasonable level caused no loss of grain yield (and small increases in some cases) but the total annual profit from the wheat–maize system could be increased by 1400 Yuan ha^{-1} (227 \$ ha^{-1}) (Tables 3 and 4). The other survey, of 103 farmers in a different area, showed that reducing N application rates to wheat by 30% produced cost savings in the range 150–250 Yuan per household, but the salient feature of the results was that the impact was greater for farm households with smaller total incomes because spending on N fertilizer was similar for all income groups. So the saving for the poorest farmers (the 1st quartile of income) was 9% of total income compared to only 1% for the highest income group (Table 5). Thus efforts to overcome the wasteful use of N fertilizer are clearly a pro-poor strategy. This point has not previously been noted and it has compelling policy implications.

4.2. Implications for N fertilizer advice systems

An approach currently used in China to determine optimum N fertilizer application rates as a basis for advice is to conduct N response trials and derive response functions relating grain production to N application. This was the reason for conducting the 120 on-farm trials in the Guangzhong Plain, the results of which are summarised in Figs. 4–6. The results revealed various serious problems with the approach. First, the great variability in response between sites in the region makes it extremely difficult to extrapolate findings to other sites with any confidence. Second, the fact that there was no yield response to N at about half of the sites makes it even more problematic to attempt the calculation of any average response function to use widely for advisory purposes. Thus recommendations based on this approach will be wildly inaccurate and very likely to result in excessive N application rates, low nitrogen use efficiency, decreased farmer incomes and an accumulation of nitrate in soil and groundwater. We conclude that the approach is not suitable as a basis for N fertilizer management in the studied region or in similar systems elsewhere in China, or elsewhere in the world in regions with a similar long-term history of excess N inputs such as the Indo-Gangetic Plains in India.

An in-season N management method, tested at 30 sites and based on measuring nitrate in the soil profile (Fig. 8) was highly effective for N management in the region. It led to lower N applications, increased profit and some decrease in residual nitrate in soil. The effect on soil nitrate was small after one year, but would presumably become gradually more beneficial if rational rates of N were used consistently over several years. Making measurements of nitrate in the soil is not difficult, being aided by the use of nitrate-sensitive test strips that can be read for color intensity in the field, either using a color chart or a reflectometer as in the current study. The procedure can be further speeded up by making the tests in the field, instead of taking soil samples to the laboratory as in this study. However, it is recognized that to put the approach into widespread practice would require a considerable degree of organization at local level, especially in view of the social and economic factors influencing farmers practice including the impact of off-farm work, as mentioned earlier. Even using simple and rapid in-field measurement of nitrate, the procedure still takes a significant amount of time and effort particularly to take the soil samples, whether this is done by the farmers, an adviser or by farmers co-operating as a group. It also requires a degree of organization that may be seen by farmers as not time-efficient, despite the clear saving of expenditure on unnecessary N fertilizer. In some situations we suggest that it would be possible and worthwhile to devote effort into organizing this type of soil testing as a simple strategy to improve N fertilizer management. The approach could be tested more widely and in a more structured way in order to measure farmers responses and could be incentivized by changes in government subsidies. One possibility would be a reorganization of subsidies to achieve improved N management with no overall increase in cost. But even if an increase in total cost was necessary, at least initially, this would be an example of public payment for environmental services in the form of lower GHG emissions and reduced nitrate contamination of groundwater. An alternative approach that avoids alterations to subsidy regimes and would be easier to implement, but inevitably less accurate, is outlined below.

The N budget approach is widely used in various forms worldwide and a version for use in this region of northwest China has been devised, using region-specific data. The principle is that the amount of N required to grow a crop is estimated on the basis of a realistic yield expectation for the area, using yields in the past few years as a guide. In addition to crop uptake, some N is inevitably lost, and an estimation of this is added to the requirement on the basis of expert knowledge by local scientists. After establishing the amount of N required, the different sources are considered and estimates made for each – although difficult to establish with precision, local agronomists can make reasonable estimates based on their experience of local farms and data from experiments.

The main sources of N for the wheat/maize rotation system are: (1) Residual nitrate in soil at the start of the growing season; (2) N mineralised from soil organic matter during the growing season; (3) N mineralized from additions of manure or other organic materials such as biogas residue; (4) Nitrate in irrigation water (where used); (5) N from rain and atmospheric deposition (dust + ammonia and oxides of nitrogen).

Using such a scheme, the amount of N fertilizer required is then the difference between total requirement and estimated supply from sources other than fertilizer. Tables 6 and 7 show examples of N budgets for wheat and maize, respectively, for situations that are typical for the Guangzhong Plain. Estimates of N derived from mineralization of soil organic matter, plus that from inputs such as atmospheric deposition and nitrate in irrigation water can be derived in various ways. One approach is to assume that the total of these inputs is equal to crop N removal in the 'no N fertilizer' treatments of agronomic experiments. An additional or complementary approach is to measure nitrate concentration in irrigation water, where this is used; this can easily be done using nitrate test strips, as used for soil analyses. Estimates of atmospheric N deposition can be obtained; in China data exists for Shaanxi as part of a national survey (Liu et al., 2013; Liang et al., 2014). The values in Tables 6 and 7 are based on measured local data and are regarded reasonable "default" values for the area. These could be improved if new data became available or for specific geographical areas within the Guanzhong Plain or for specific agronomic conditions.

Based on the N budget approach, N fertilizer application rates are 120 and 165 kg ha^{-1} for wheat and 90 and 120 kg ha^{-1} for maize depending on the expected yield (Tables 6 and 7). However, N supply from soil is known to vary greatly between fields, as shown in Fig. 8A and B, probably due to differences in past manure applications or to inherent soil variability. Hence, in the conditions of this region, it would be highly beneficial to complement the simple N budget approach with in-field soil nitrate testing as described earlier.

It should be noted that the imperative for improving N management for major grain crops in China is not only to improve farmer incomes, important as this is, but also for environmental protection and food security, both nationally and globally (Sutton et al., 2013). The impacts of N (together with P) from fertilizers and manures on water quality in China has been well documented, especially the increasing incidence of algal blooms (Sun et al., 2012). The manufacture and use of N fertilizer inevitably contributes to climate change through emissions of carbon dioxide and nitrous oxide; it has been estimated that a move to rational N fertilizer use in China could produce a decrease in national greenhouse emissions of between 2 and 6% compared to current trends by 2030 (Zhang et al., 2013a). N over-application affects food security in several ways, directly and indirectly. Crops given excessive rates of N tend to give slightly lower yields than optimally fertilized crops: this is shown by many of the results in this paper and from elsewhere in China (Norse et al., 2012) and is often due to lodging or the increased tendency of crops over-supplied with N to be affected by fungal diseases (Cu et al., 1996). High rates of N fertilizer have been shown to be causing serious acidification of soils in China (Guo et al., 2010) and, in the long-term, this will lead to decreased crop yields unless corrected by liming and thus imposing an additional cost on farmers. In addition to direct impacts on crop growth, increased nitrate in surface waters has an adverse impact on food security through decreased fish stocks and accumulation of toxins in shellfish (Zhang et al., 2013b).

Thus, for a wide range of reasons, it is imperative to design approaches for improved management of N fertilizer, even in regions such as northwest China which are generally less developed than the eastern and southern Provinces. These approaches must fully take account of the socio-economic conditions of farmers, including the impact of off-farm work on labor availability and time devoted to agriculture. Advisory approaches that ignore these factors are likely to have minimal impact on N fertilizer use.

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