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Assessing the contribution of nitrogen fertilizer and soil quality to yield gaps: A study for irrigated and rainfed maize in China

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ABSTRACT

Yield gap (Yg) analysis is useful to map the scope for sustainable intensification of agriculture, but explaining and quantifying the underlying causes of yield gaps remains a considerable challenge. The objective of this study was to decompose maize yield gaps under different nitrogen (N) application rates and soil quality conditions across irrigated and rainfed cropping systems in China. A comprehensive database consisting of 5228 on-farm trials located in three major maize production regions of China was used for this purpose. The on-farm trials contained detailed information for four different treatments: fertilizer omission (control), optimal N rate (optimal N), 50% of optimal N rate (low N) and 150% of optimal N rate (high N). These were combined with biophysical and yield potential data from the Global Yield Gap Atlas (http://yieldgap.org). An analytical framework integrating stochastic frontier analysis and principles of production ecology was applied to decompose the overall maize yield gap into components of efficiency (and respective management and soil quality effects, Yg-M and Yg-S), resource (Yg-R), and technology Yg (Yg-T). The potential yield (Yp) of irrigated maize averaged 14.5 Mg/ha in Northeast China (NE) and 11.9 Mg/ha for North China Plain (NCP), and the water-limited potential yield (Yw) of rainfed maize averaged 12.0 Mg/ha in NE and 10.5 Mg/ha in Southwest China (SW), respectively. Maize yield gaps were highly variable across N treatments and cropping systems and ranged between 27–56% of Yp or Yw. Larger absolute yield gaps were observed in irrigated cropping systems in NE (4.8–8.1 Mg/ha) than in NCP (3.8–6.1 Mg/ha) and in rainfed cropping systems in NE (3.6–6.7 Mg/ha) and SW (2.8–5.9 Mg/ha). The components of the yield gap differed in size across cropping systems and N treatments. Yg-T was fairly small and consistent across N treatments ranging between 7.0% and 12.0% of Yp for irrigated maize and only ca. 2.0% of Yw for rainfed maize in NE. Yg-R was strongly associated with the N treatment explaining between 16.0–26.0% of Yp (or Yw) for control and low N treatments and being close to negligible for the optimal and high N treatments. Yg-M due to inefficient crop management accounted for 6.0–14.0% of Yp (or Yw) across cropping systems and N treatments, which is equivalent to 0.7–1.8 Mg/ha. The Yg-S explained the largest proportion of the total yield gap, especially in trials with low and medium soil quality levels, accounting for 11.0–24.0% of Yp or Yw (1.3–3.1 Mg/ha). The Yg-S was linked to partly manageable soil properties, such as low soil organic matter contents and low available P and/or K. This study is one of the first to incorporate the effects of soil quality in yield gap analysis and provides a basis to target management practices that can improve soil quality and N use efficiency while narrowing maize yield gaps in China.

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1. Introduction

Maize (*Zea mays* L.) is the main food staple in the world contributing to 24% of the world's agricultural calories (Tilman et al., 2011). China is one of the largest maize producers accounting for 21% of the global cultivated area and 23% of the total grain maize production (FAO, 2019). With the projected economic and population growth by 2030, demand for maize in China is expected to increase by 47% compared with maize production of 2012 (Chen et al., 2014). Further increases in cereal production must come from increased yields per unit area rather than from area expansion (Fan et al., 2012). This can be achieved through genetic improvement of crop yield potential (Godfray et al., 2010) or through narrowing yield gaps (Yg), the difference between the potential yield (Yp) and the actual yield observed in farmers' fields (van Ittersum and Rabbinge, 1997; van Ittersum et al., 2013; Fischer, 2015; Lobell et al., 2009).

Substantial progress has been made to estimate the magnitude and variability of the yield gaps for the major cereal crops in China using crop modeling and field experiments (Liu et al., 2017; Meng et al., 2013; Liu et al., 2012; An et al., 2018). The Global Yield Gap Atlas (GYGA; http://yieldgap.org) developed a standard approach to estimate yield gaps from local to regional scale (van Ittersum et al., 2013; Van Wart et al., 2013). Currently, yield gaps of irrigated and rainfed maize are estimated 35–42% of Yp (Liu et al., 2017; http://yieldgap.org). Yet, explaining and quantifying the underlying causes behind yield gaps remains a challenge as it requires many on-farm trials and associated data and the use of different methodologies (Lobell et al., 2009; Beza et al., 2017).

Suboptimal crop management practices (e.g., sowing date, plant density, tillage, fertilization, irrigation) were identified as major causes of yield gaps in cereal production systems (van Ittersum et al., 2013; Hochman and Horan, 2018; Mueller et al., 2012; Chen et al., 2014; An et al., 2015; Silva et al., 2017a, 2017b). Nitrogen (N) is one of most important yield-limiting factors in cereal cropping systems around the world (Cassman et al., 2003). Chinese agriculture has serious problems of over-application and low use efficiency of N fertilizer (Zhang et al., 2012; Fan et al., 2012; Chen et al., 2014). For example, the N rate applied to summer maize by farmers in North China Plain (NCP) was on average 260 kg N/ha, which was more than 100 kg N/ha greater than the estimated economically optimal N rate (ca. 160 kg N/ha) in this region (Cui et al., 2008). However, there is an enormous variation in the total N application rates in farmers' fields, ranging from 50 to 500 kg N/ha across maize cropping systems in China (Zhang et al., 2016; Cui et al., 2018). Thus, it is essential to assess the linkages between existing yield gaps and sub-optimal N management.

It is recognized that soil quality could be a key cause of yield gaps (Fermont et al., 2009; Tittonell and Giller, 2013; Beza et al., 2017; An et al., 2018; Di Mauro et al., 2018). However, there is little quantitative understanding on how soil quality may interact with or constrain yield gap closure. Crop productivity is a net result of complex interactions between genotype, environment (climate and soil), and crop management (van Ittersum and Rabbinge, 1997; Cassman, 1999), and it is difficult to isolate the relative importance of soil properties from other factors. Secondly, many soil properties, including native fixed attributes (e.g., soil type and soil texture) and more dynamic soil fertility factors (e.g., soil organic matter (SOM) and soil nutrients), interact with each other and impact crop growth and yield with both trade-offs and compensating effects. Previous studies proposed a quantification of a soil quality yield gap (An et al., 2018), however, linking soil quality-derived yield gaps to easily manageable and key soil properties is critical to move towards identifying concrete management practices to narrow yield gaps. Thus, there remains a need for an integrated conceptual and analysis framework accommodating the contributions of sub-optimal crop management and soil quality to yield gaps.

The objective of this study was to assess the contribution of N management and soil quality to yield gaps of irrigated and rainfed maize in China. We build upon an existing framework (Silva et al., 2017a, 2017b) for decomposing yield gaps into their efficiency (Yg-E), resource (Yg-R) and technology (Yg-T) components. That framework was expanded to further disentangle the efficiency yield gap into its crop management (Yg-M) and soil quality components (Yg-S). Here, soil quality is defined as the capacity of the soil to provide nutrients and water and the capacity of the crop to access these and support crop productivity (Bünemann et al., 2018). Yield gaps and their intermediate components, including soil quality, were quantified for specific climate zones (CZ) and soil types. It is hypothesized that maize yield gaps in China can be mostly attributed to the Yg-S, in view of the intensive crop management practices and soils with low quality properties across the major maize cropping systems in the country. A large database of on-farm trials (n = 5228) with four different N treatments conducted in different soil quality levels during the period 2006–2012 was analyzed for this purpose.

2. Materials and methods

2.1. Theoretical framework to disentangle yield gaps

A theoretical framework considering five different yield levels and four intermediate yield gaps was used to disentangle maize yield gaps in China (Fig. 1). In this approach, yield gaps are specific for a well-defined biophysical environment (i.e., unique year, climate zone and soil textural class) and explained by sub-optimal management of N and of other inputs referring to limiting (water and other nutrients) and reducing factors (pests, diseases, and weeds), and/or soil conditions. The Yp is defined as the maximum theoretical yield of a specific crop genotype when grown in a well-defined biophysical environment under non-limiting water and nutrient supply and biotic stresses effectively

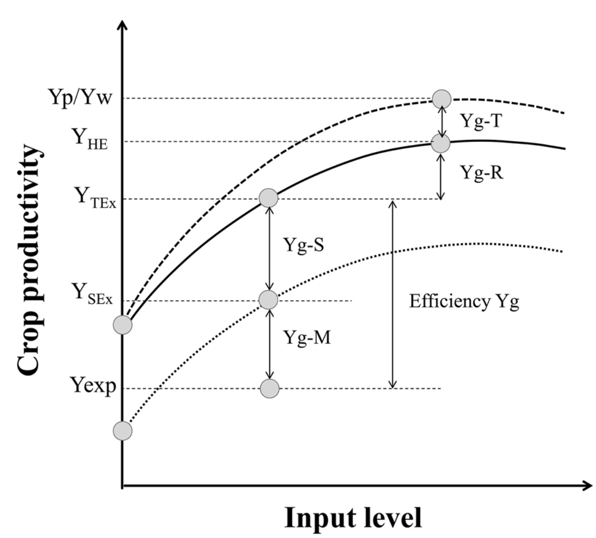

Fig. 1. Theoretical framework to decompose yield gaps in a well-defined biophysical environment (i.e., unique climate zone and soil textural class). The potential yield (Yp) and water-limited yield (Yw) are the biophysical benchmarks for irrigated and rainfed crop production systems, respectively. The highest experimental yield (Y_{HE}) refers to the highest yield achieved with optimal inputs and crop management under favorable soil quality. The technical efficient yield (Y_{TEx}) refers to the maximum experimental yield for a given input level and under favorable soil quality. The soil efficient yield (Y_{SEx}) refers to the maximum yield for a given input and soil quality level. The experimental yield (Yexp) reflects the productivity recorded in on-farm trials. It is assumed that the observed yield gap could be attributed to low soil quality, crop management imperfections and/or sub-optimal amount of inputs applied. Yg-M stands for management yield gap, Yg-S for soil quality yield gap, Yg-R for resource yield gap and Yg-T for technology yield gap. The efficiency yield gap refers to the sum of Yg-M and Yg-S.

controlled (van Ittersum and Rabbinge, 1997). Yw is defined similarly to Yp with the difference that crop growth is limited by water supply. Yp and Yw are the benchmarks for irrigated and rainfed cropping systems, respectively. The highest experimental yield (Y_{HE}) refers to the yields achieved with optimum N input and with very high soil quality (see definition below) within a given year × climate zone × soil type combination. The technical efficient yield (Y_{TEx}) reflects the maximum yield that can be achieved with a given observed amount of inputs and in trials with very high soil quality levels. The soil-efficient yield (Y_{SEx}) refer to the highest possible yields obtained with a given amount of N and a given soil quality level. The experimental yield (Yexp) reflects the productivity measured in the on-farm trials for different N treatments.

Four intermediate yield gaps can be computed based on the aforementioned yield levels.The efficiency yield gap (Yg-E) is defined as the difference between Y_{TEx} and Yexp and indicates sub-optimal timing, spacing and form of crop management practices and low soil quality in the on-farm trials (Silva et al., 2017a, 2017b). This yield gap is, in this study, attributed to crop management imperfections (Yg-M) and/or low soil quality (Yg-S).

The experimental yield in nutrient omission plots was treated as an indicator of soil quality (Fan et al., 2013;Tittonell and Giller, 2013). For soil properties, intrinsic properties (e.g., soil texture) were used to define specific climate-soil zones (see below Section 2.3.1.) and manageable soil fertility factors were considered as explanatory factors of the Yg-S. As a result, Yg-S in the current study is attributed to differences in soil properties that can be managed by farmers mostly through long-term soil management practices that can ensure adequate soil pH, soil organic matter and soil nutrients for nutrient uptake and plant growth.

The resource yield gap (Yg-R) is defined as the difference between Y_{HE} and Y_{TEx} and indicates the potential to increase yields in the short-term due to increases in the amount of N inputs applied in fields with very high soil quality in a given growing season (Fig. 1). Yg-R is expected to decrease with increasing N fertilizer rates and thus to be smaller in the N treatments with optimal N rates tested in on-farm trials. The technology yield gap (Yg-T) refers to the difference between Yp or Yw and Y_{HE} and it can be explained by a lack of technologies able to reach Yp or Yw (e.g., precision farming or full pest and disease control). Yg-T can also be attributed to sub-optimal input use if the amount of inputs observed in the on-farm trials underlying Y_{HE} are smaller than that needed for Yp or Yw.

On-farm trials tested different N application rates and followed best crop management practices at local level. Hence, our analysis does not fully capture actual yields and farmers' management practices. As a result, the Yg-M and Yg-R reflect yield gaps caused mostly by inefficient N management practices.

2.2. Database of on-farm fertilizer trials

2.2.1. Maize-based cropping systems

Maize-based cropping systems in China were classified as irrigated and rainfed based on climatic and hydrological conditions. Field trials of irrigated maize were located in two main agroecological zones, namely Northeast China (NE) and NCP. For rainfed maize, field trials were located in NE and Southwest China (SW). Irrigated and rainfed maize in NE were grown as a single crop in a year from April to October. Irrigated maize in NCP was grown from June to October and rotated with winter wheat in the same year. Rainfed maize in SW was grown from March to July either as single crop or rotated with wheat, oilseed rape or potato in

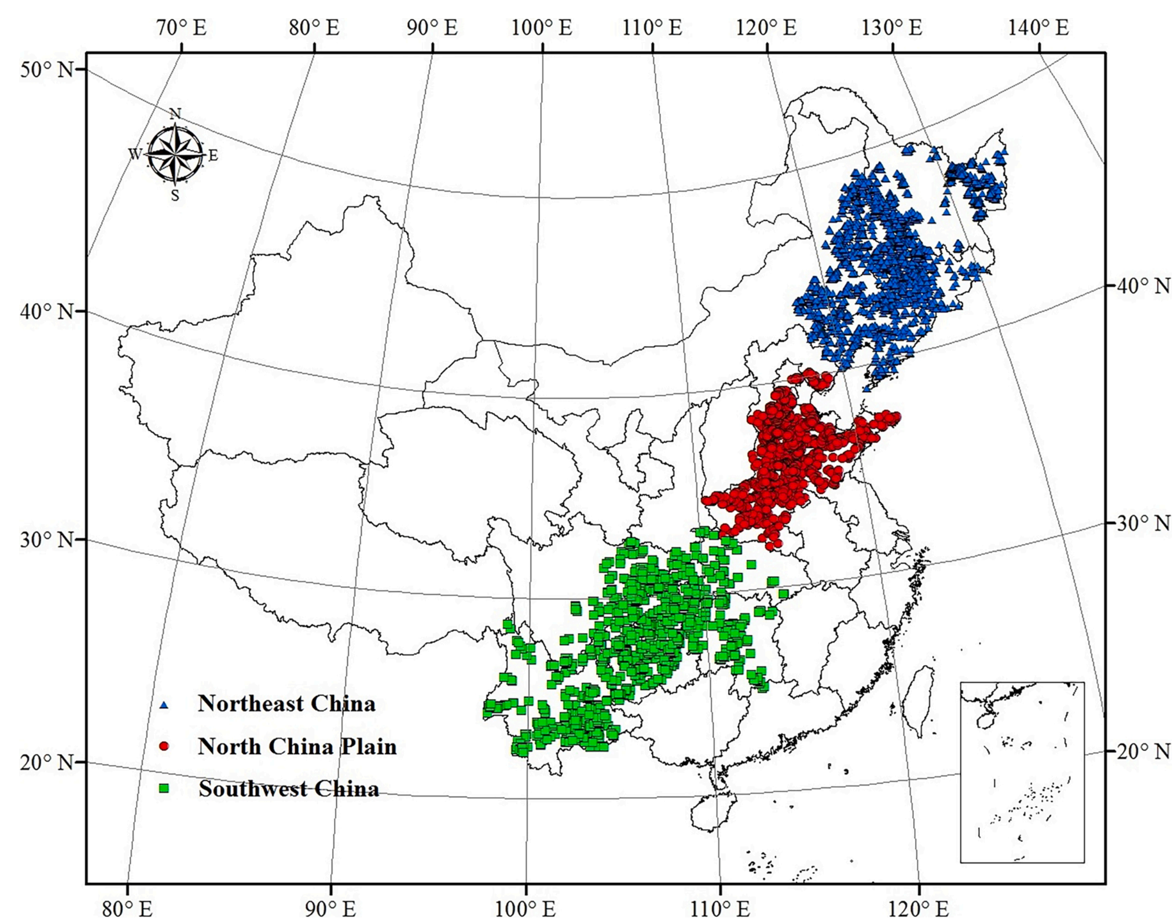

Fig. 2. Geographical distribution of on-farm trials in maize cropping systems of China. Maize is cultivated under irrigated conditions in North China Plain (NCP), under rainfed conditions in Southwest China (SW), and under both irrigated and rainfed conditions in Northeast China (NE).

the same year. In total, these regions and cropping systems account for more than 90% of total harvested area and production of maize in China (National Bureau of Statistics of China, 2017). An overview of the cropping systems, geographical location and provinces covered is shown in Fig. 2.

2.2.2. Crop data and fertilizer treatments

Data on maize yield, fertilizer application and soil properties for each cropping system were obtained from on-farm trials conducted under the auspices of national soil test and fertilizer recommendation projects during the period 2006−2012. The on-farm trials included four treatments: fertilizer omission (control), optimal nitrogen (N) rate (optimal N), 50% of optimal N rate (low N) and 150% of optimal N rate (high N). Plots with fertilizer omission received neither organic amendments (i.e., manure and crop residues) nor mineral fertilizer. The optimal N rates were recommended by agricultural scientists or local agricultural extension officers based on economic criteria and the soil nutrient conditions. The optimal amounts of P_2O_5 and K_2O were applied and kept constant in all treatments, except control plots which did not receive P and K. Best management practices in relation to cultivar, sowing date and density and supplementary irrigation (in irrigated cropping systems) were used in the trials. The final database contained data for 3115 on-farm trials in irrigated (n = 1609 in NE and n = 1506 in NCP), and 2113 trials in rainfed (n = 1022 in NE and n = 1091 in SW) maize-based cropping systems in China.

2.2.3. Biophysical conditions

An overview of the weather and soil data available in the database is provided in Table 1. Weather data during the growing season were obtained for each on-farm trial in the county or municipality where the trial was conducted from the Chinese Meteorological Administration (http://data.cma.cn). These included daily mean temperature (Tave), maximum (Tmax) and minimum temperatures (Tmin), precipitation (PRE) and sunshine duration (SSD). Sunshine duration was converted into daily solar radiation (RAD) using the WeatherAid module in the Hybrid-Maize model (Yang et al., 2004; http://www.hybridmaize.unl.edu/). The growing degree days (GDD) were calculated as an annual sum of daily mean temperatures over a base temperature of 10 °C during the crop growing period (Ramankutty et al., 2002).

Soil data included soil texture, soil organic matter (SOM), soil total nitrogen (TN), soil available phosphorus (Olsen-P) and potassium (Avail-K) and pH. All soil parameters were measured from topsoil samples taken at a depth of 0–20 cm. SOM was analyzed with the potassium dichromate volumetric method (digested by $K_2Cr_2O_7$-sulfuric acid (H_2SO_4)) and TN with the Kjeldahl method (digested by H_2SO_4 and cupric sulfate-sodium sulfate ($CuSO_4$-Na_2SO_4) as the catalyst agent). Olsen-P was determined with the Olsen method, and Avail-K was analyzed with a flame photometer following extraction with 1 M ammonium acetate (NH_4OAc). Soil pH was measured using a glass electrode in a 1:2.5 soil/water (H_2O) suspension. Soil texture was expressed in three levels, namely sandy soil, loamy soil and clay soil determined by the relative proportion of clay, sand and silt particles.

2.3. Yield gap analysis

2.3.1. Climate-soil zones

Spatially explicit data from the Global Yield Gap Atlas (GYGA, www.yieldgap.org) were linked to the database of on-farm trials based on the GPS coordinates of each trial. These data included simulated potential and water-limited yields (as explained in Section 2.3.2), climate zones (van Wart et al., 2013) and other biophysical information (e.g., soil type). The climate zones consist of a matrix of three climate variables namely GDD with base temperature of 0℃, temperature seasonality, quantified as the standard deviation of monthly average temperatures, and annual aridity index (AI), calculated as the annual total precipitation divided by annual total potential evapotranspiration (van Wart et al., 2013). Irrigated maize trials were located in nine climate zones in NE and seven climate zones in NCP, rainfed maize trials were located in nine climate zones in NE and eight climate zones in SW. Within each climate zone, arable land was further divided into three climate-soil

Table 1
Descriptive statistics (mean ± standard deviation) of climatic, soil and agronomic variables for irrigated and rainfed maize cropping systems in China. Agronomic variables N, P_2O_5, K_2O and yield refer to the optimal N treatment.

Type of variables	Variable description	Abbreviation	Irrigated maize		Rainfed maize		Source
			Northeast China	North China Plain	Northeast China	Southwest China	
Climate	Growing degree days during growing period (℃ d)	GDD	1465 (±181)	1591 (±102)	1399 (±199)	1696 (±266)	Chinese Meteorological Administration
	Accumulated precipitation during growing period (mm)	PRE	336 (±115)	408 (±117)	417 (±120)	725 (±218)	
	Accumulated solar radiation during growing period (MJ/m^2)	RAD	2666 (±257)	1666 (±195)	2568 (±322)	1955 (±289)	
	Climate zones (number)	CZ	9	7	9	8	Global Yield Gap Atlas
Soil	Soil texture in topsoil (Sandy soil, loamy soil and clay soil)	Soil texture	Sandy, loamy and clay soil	Sandy, loamy and clay soil	Sandy, loamy and clay soil	Sandy, loamy and clay soil	Soil test in on-farm experiments and Harmonized World Soil Database
	Content of soil organic matter in topsoil (g/kg)	SOM	25.8 (±13.3)	15.2 (±3.9)	30.2 (±13.2)	27.8 (±11.8)	
	Content of total nitrogen in topsoil (g/kg)	TN	1.4 (±0.7)	1.0 (±0.3)	1.6 (±0.7)	1.6 (±0.6)	
	Content of available phosphorus in topsoil (mg/kg)	Olsen-P	20.2 (±13.3)	22.1 (±13.0)	25.7 (±14.6)	18.0 (±12.9)	
	Content of available potassium in topsoil (mg/kg)	Avail-K	147.4 (±55.6)	113.4 (±41.9)	144.5 (±65.3)	117.6 (±59.7)	
	pH in topsoil	pH	7.2 (±1.0)	7.8 (±0.6)	6.4 (±0.9)	6.2 (±1.0)	
Agronomy	Application rate of nitrogen (kg N/ha)	N	149 (±35)	199 (±31)	152 (±44)	220 (±53)	Crop survey in on-farm trails
	Application rate of phosphorus (kg P_2O_5/ha)	P_2O_5	90 (±27)	72 (±25)	83 (±26)	107 (±34)	
	Application rate of potassium (kg K_2O/ha)	K_2O	68 (±23)	106 (±31)	74 (±32)	141 (±66)	
	Grain yield (kg/ha)	Yield	9837 (±2059)	8103 (±1291)	9328 (±1811)	7768 (±1538)	

zones based on soil texture types (sandy soil, loamy soil, and clay soil). In total, irrigated maize trials were located in 27 and 21 climate-soil zones in, respectively, NE and NCP and, rainfed maize trials were located in 27 and 21 climate-soil zones in NE and SW, respectively.

2.3.2. Yield potential

Yp and Yw were simulated with the Hybrid-Maize model following the protocols of GYGA (Liu et al., 2017). As an exception, Yw was expressed as Y_{HE} for rainfed maize cropping systems of SW because Y_{HE} in this region was consistently greater than the simulated Yw. The reasons for the low Yw in this region are discussed in the Supplementary Material (Fig S1; Table S1) but mostly refer to the fact that the on-farm trials analyzed in this study are only representative of the high yielding areas in SW while the simulations of Yw in GYGA cover a wider range of biophysical and management conditions.

2.3.3. Technical efficiency yields and efficiency yield gap

Stochastic frontier analysis (Kumbhakar and Lovell, 2000) was used to estimate the production frontier and the efficiency yield gap. Quantitative input-output data for unique combinations of field × climate zone × year × soil type × cropping system were used for this purpose. The production frontier was assumed to follow a translog functional form, which mathematical formulation is as follows:

$$\ln y_{it} = \alpha_0 + \sum_k^K \beta_k \ln x_{kit} + \frac{1}{2}\sum_k^K \sum_j^K \theta_{kj} \ln x_{kit} \times \ln x_{jit} + \sum_k^K \delta_k\, SQ_{kit} + \frac{1}{2}\sum_k^K \sum_j^J \lambda_{kj} SQ_{kit} \times \ln N_{jit} + v_{it} - u_{it} \quad (1)$$

$$v_{it} \sim \mathrm{N}(0, \mathrm{sigma}_v^2) \quad (2)$$

$$u_{it} \sim \mathrm{N}^+(\mathrm{mu}, \mathrm{sigma}_u^2) \quad (3)$$

$$\text{Yg-M}_{it} = 1 - \exp(-u_{it}) \quad (4)$$

$$Y_{SEit} = \mathrm{Yexp}_{it} \times \exp(-u_{it})^{-1} \quad (5)$$

where the y_{it} is the maize yield from on-farm trials in climate-soil zone i and year t. The vector of biophysical and management variables, x_k, and N (N fertiliser rate), is designed to capture growth-defining and -limiting factors (van Ittersum and Rabbinge, 1997). SQ_{it} is a categorical variable expressing different soil quality levels and was constructed based on the experimental yields in the control treatment (see further explanation below). The continuous variables y, x_k and N were mean-scaled and log-transformed prior to the analysis. The random errors v_{it} capture the influence of random noise and are assumed to be independently and identically distributed (i.i.d.) according to a normal distribution with mean 0 and variance sigma_v^2 (Eq. 2). The non-negative random errors u_{it} capture the technical inefficiency due to sub-optimal crop management or soil quality and are assumed to be identically distributed but according to a half-normal distribution truncated at 0 with mean mu and variance sigma $_u^2$ (Eq. 3). Finally, α_0, β_k, θ_{kj}, δ_k and λ_k are parameters to be estimated using maximum likelihood as implemented in the *sfa()* function of the "frontier" package in R (Coelli and Henningsen, 2013).

The growth-defining factors considered in x_k were growing-degree days (°C) and solar radiation (MJ/m^2) during the growing season and two dummy variables for climate zones and year. The variables considered as growth-limiting factors were the rainfall in the growing season (mm), the amount of N fertilizer applied, soil type expressed as a categorical variable with three levels (sandy soil, loamy soil, and clay soil) and soil quality of each on-farm trial. The soil quality level of each trial was constructed based on the experimental yields of the fertilizer omission plots (control treatment) and had four levels (very high, high, medium, and low). On-farm trials with very high soil quality level were identified as the ones with the top 10th percentile experimental yields in the control treatment in a given climate zone × year × soil type × region combination. A similar approach was followed to identify on-farm trials with high (experimental yields in the control treatment between 60th and 90th percentiles), medium (experimental yields in the control treatment between 30th and 60th percentiles) and low soil quality level (experimental yields in the control treatment below the 30th percentile). Therefore, and by definition, we expect Yg-S to be greater in on-farm trials with low, medium and high soil quality levels than in on-farm trials with very high soil quality levels, where Yg-S is negligible.

Y_{TEx} was estimated by fitting the stochastic frontier model (Eq. 1–3) to on-farm trials with very high soil quality level to predict the maximum yields that could be achieved with the various N inputs. This was done with the *fitted()* function in R by using the estimated production frontiers for each maize cropping system (cf. Table 2), rather than using Eq. 5 as in Silva et al. (2017a, 2017b). For the fitting procedure, the soil quality dummy was set to very high soil quality and all other variables were kept as in the original database. This allows us to quantify the yield differences between different soil quality levels, for a given N treatment and maize cropping system (cf. Fig. 1). Y_{SEx} and the Yg-M were estimated with Eq. 4 and 5. Yg-S was the difference between Y_{TEx} (i.e., the frontier yield under very high soil quality level) and the Y_{SEx} predicted for high, medium and low soil quality level.

2.3.4. Highest experimental yields, resource yield gap and technology yield gap

The resource yield gap (Yg-R) was quantified as the difference between Y_{HE} and Y_{TEx} for unique combinations of individual years and climate-soil zones. Therefore, the Y_{HE} was estimated by averaging the Y_{TEx} with optimal N fertilizer rate and very high soil quality level (cf. Fig. 1). Yg-T was thus calculated as the difference between Yp (or Yw) and Y_{HE} for irrigated (rainfed) cropping systems, while controlling for individual years and climate-soil zones. Crop model simulations were used for maize cropping systems in NE and NCP. It was not possible to quantify Yg-T in the SW because Y_{HE} was consistently greater than the simulated Yw (see Section 2.3.2 and further information about the reasons behind this in the Supplementary Material).

2.4. Soil properties for different soil quality levels

Differences in soil chemical properties namely SOM, TN, Olsen-P,

Table 2
Parameter estimates of the stochastic frontier models estimated for irrigated and rainfed maize cropping systems in China. The default soil type and soil quality (SQ) level are "Sand" and "Very high", respectively. 'TE scores' refer to the average of the field-specific Technical Efficiency scores (i.e., 100 minus the efficiency yield gap expressed in %) obtained for each stochastic frontier model. R^2 was estimated by fitting the same model specification with ordinary least squares (OLS). Significance codes: '***' 0.1% '**' 1% '*' 5%.

Variables	Irrigated maize		Rainfed maize	
	NE	NCP	NE	SW
Intercept	0.503 ***	0.233 ***	0.226 ***	0.338 ***
Growing Degree Day	0.095	−0.078	−0.054	−0.039
Precipitation	0.095 ***	0.023	−0.203 ***	0.014
Solar radiation	−0.005	0.220 *	−0.01	0.021
Growing Degree Day^2	0.186	−2.912 **	−0.323	0.135
Precipitation^2	0.280 ***	−0.131 ***	−0.157 **	−0.008
Solar radiation^2	0.477	0.679 *	0.576	−0.097
Nitrogen	0.060 ***	0.075 ***	0.085 ***	0.051 ***
Nitrogen^2	0.007 ***	0.010 ***	0.010 ***	0.005 ***
Soil type_Loam	−0.033 ***	0.004	0.037 ***	0.006
Soil type_Clay	−0.069 ***	0.013	0.035 *	0.021.
SQ level_High	−0.119 ***	−0.099 ***	−0.210 ***	−0.125 ***
SQ level_Middle	−0.240 ***	−0.172 ***	−0.122 ***	−0.208 ***
SQ level_Low	−0.333 ***	−0.287 ***	−0.263 ***	−0.332 ***
Year_2007	−0.007	0.043 ***	0.031 ***	0.007
Year_2008	0.036 ***	0.053 ***	0.075 ***	0.085 ***
Year_2009	0.011	0.041 ***	0.022	0.054 ***
Year_2010	0.045 ***	0.005	0.012	0.071 ***
Year_2011	−0.011		−0.075 ***	
Year_2012	−0.007		−0.048 ***	
CZ_2303	−0.099 ***			
CZ_2403	−0.124 ***		0.033 *	
CZ_2503	0.004		0.252 ***	
CZ_2603			0.272 ***	
CZ_2703			0.308 ***	
CZ_3103	0.220 ***			
CZ_3203	0.084 ***			
CZ_3303	−0.014		0.098 ***	
CZ_3403	0.040 ***		0.137 ***	
CZ_3503	0.025		0.266 ***	
CZ_4403		0.009.	0.198 ***	
CZ_5103		0.019 *		
CZ_5203		0.030 ***		
CZ_5303		0.020 **		
CZ_5403		−0.065 ***		
CZ_5503		−0.115 ***		
CZ_5602				0.032.
CZ_5702				−0.044 *
CZ_5802				−0.047 **
CZ_5902				−0.071 ***
CZ_6701				−0.054 *
CZ_6702				−0.166 ***
CZ_6802				−0.157 ***
Growing Degree Day x Precipitation	0.091	0.197	−0.522 ***	−0.006
Growing Degree Day x Solar radiation	−0.335	0.406	−0.656 *	0.012
Growing Degree Day x Nitrogen	−0.008 *	−0.015 **	0.004	0.002
Precipitation x Solar radiation	0.033	0.119.	0.266 **	−0.038
Precipitation x Nitrogen	0	0.003 **	0.002	0.002.
Solar radiation x Nitrogen	0.004	−0.003	0.005	−0.007 *
Nitrogen x High soil quality	0.007 ***	0.006 ***	0.005 ***	0.010 ***
Nitrogen x Moderate soil quality	0.014 ***	0.014 ***	0.014 ***	0.021 ***
Nitrogen x Low soil quality	0.028 ***	0.022 ***	0.030 ***	0.035 ***
sigmaSq	0.056 ***	0.033 ***	0.063 ***	0.064 ***
gamma	0.765 ***	0.756 ***	0.825 ***	0.800 ***
TE scores (%)	85.53	88.58	84.39	84.47
Sample size (n)	6378	5824	3992	4151
R^2	0.71	0.71	0.71	0.74

Avail-K and pH were assessed across fields with different soil quality levels in order to link manageable soil fertility factors to Yg-S as a means to identify concrete management practices to narrow soil quality yield gaps. For this purpose, linear mixed-effects models were estimated considering soil factors in their absolute values as the dependent variables, soil quality as a fixed effect and climate zone and year treated as random effects. The linear mixed-effects models were fitted using the R function *lme()* in the package "nlme" (Pinheiro et al., 2015). Differences between groups were considered statistically significant at 5% significance level.

3. Results

3.1. Magnitude and variability of maize yield gaps

The Yp of irrigated maize in NE averaged 14.5 Mg/ha and was greater than in NCP (11.9 Mg/ha, Fig. 3). The Yw of rainfed maize in NE (12.0 Mg/ha) was greater than Y_{HE}, a proxy for Yw, in SW (10.5 Mg/ha). Yexp were highly heterogeneous across and within cropping systems, with ranges of 2.0–16.6 Mg/ha (Fig. 3). Across N treatments, Yexp were on average 6.4–9.8 Mg/ha, 5.8–8.1 Mg/ha, 6.1–9.3 Mg/ha and 4.7–7.8 Mg/ha for irrigated maize in NE and NCP, and rainfed maize in NE and SW, respectively.

There were large variations in maize yield gaps across N fertilizer treatments (Fig. 3) with a coefficient of variation of 46.8% in NE and 38.0% in NCP for irrigated maize systems, and 55.3% in NE and 51.4% in SW for rainfed maize systems (Fig. 3). Across the four maize cropping systems, yield gaps were on average 5.9 to 8.1 Mg/ha, 3.6–5.8 Mg/ha, 2.8–4.8 Mg/ha and 3.1–5.1 Mg/ha for control, low N, optimal N and high N treatments, respectively (Fig. 3). Experimental yields, Yexp, were 44.0–68.0%, 59.0–65.0%, 68.0–73.0% and 65.0–72.0% of Yp or Yw for control, low N, optimal N and high N treatments, respectively (Fig. 3). The yield gap in the optimal N treatment was on average 4.6 Mg/ha and 3.8 Mg/ha in irrigated maize cropping systems for NE and NCP, and 2.7 Mg/ha and 2.8 Mg/ha in rainfed maize cropping systems for NE and SW (Fig. 4), which was less than that in the treatments with no, low, and high N. This shows N rates in the optimal fertilizer treatment are generally sufficient to narrow yield gaps in the cropping systems studied.

Yexp variability across all N treatments was associated with biophysical conditions and crop management practices and ca. 70% of the variation observed in Yexp could be explained by the biophysical and management variables included in the stochastic frontier model (Table 2). The dummy "CZ"and"year" were both statistically significant in all maize cropping systems, indicating that climate zone and the year-specific weather have a considerable effect on Yexp. However, climatic variables showed different effects on Yexp across the different cropping systems. For example, the effect of precipitation on Yexp was positive for irrigated maize of NE, but negative for irrigated maize in NCP and rainfed maize in NE. Soil type significantly affected Yexp in both irrigated and rainfed maize cropping systems of NE, in which Yexp was significantly greater in sandy soils than in clay and loamy soils for irrigated maize while the opposite was true for rainfed maize. The positive significant effect of N rates and soil quality on Yexp indicates that Yexp was greater in treatments with greater amounts of N applied and in plots with higher soil quality (i.e., greatest yields in the control treatment). For all maize cropping systems, yield responses to N decreased with increasing levels of soil quality as indicated by statistically significant interaction between N fertilizer rates and soil quality (Table 2). The significant positive effects of N rates and soil quality on Yexp were also observed when the stochastic frontier models were fitted to a subset of the data excluding the nutrient omission plots (see Supplementary Material, Table S3). Yet, yield responses to N in soils with high soil quality became not significantly different from yield responses to N in soils with very high soil quality for all cropping systems. Similarly, yield responses to N in soils with moderate soil quality were not significantly different

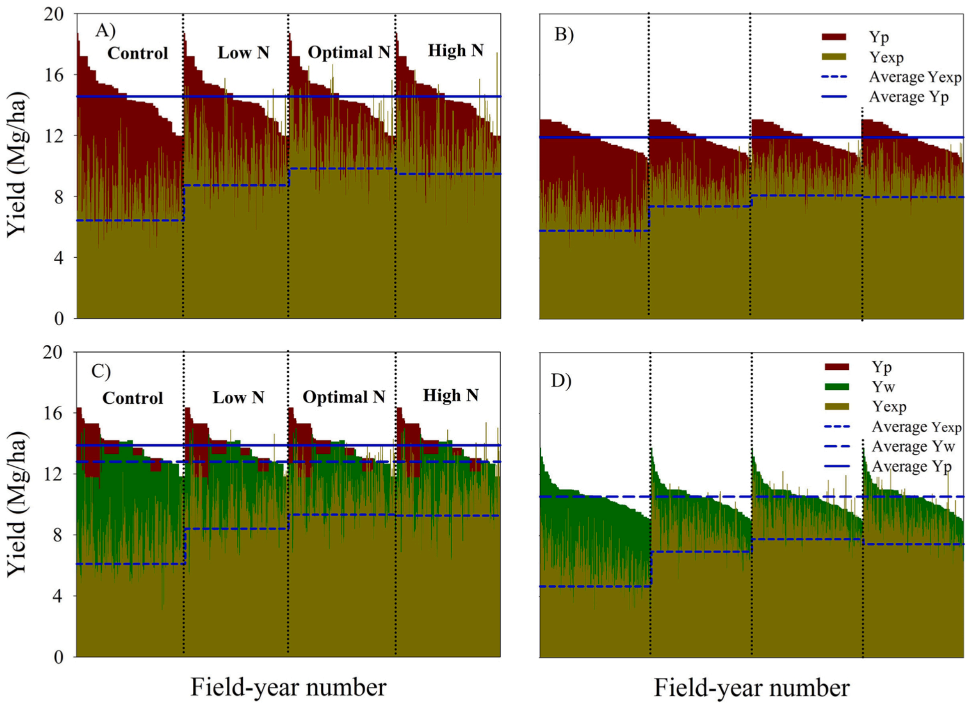

Fig. 3. Yield potential (Yp), water-limited yield (Yw) and experimental yield (Yexp) for four N treatments in a large network of on-farm trials conducted across the main maize cropping systems of China. A) and B) represent irrigated maize cropping systems in Northeast China (NE) and North China Plain (NCP), respectively; C) and D) represent rainfed maize cropping systems in Northeast China (NE) and Southwest China (SW), respectively. Yp of rainfed maize in SW is not shown in figure, as explained in the Supplementary Material. Each bar corresponds to an individual field-year combination. The red, dark green and light green portions of the bars indicate Yp, Yw and Yexp, respectively. Yexp indicates experimental yield achieved in plots with fertilizer omission (control), optimal nitrogen rate (optimal N), 50 % of optimal N rate (low N) and 150 % of optimal N rate (high N) treatments. Horizontal lines indicate average Yp (solid lines), Yw (long-dashed lines), and Yexp (short-dashed lines) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

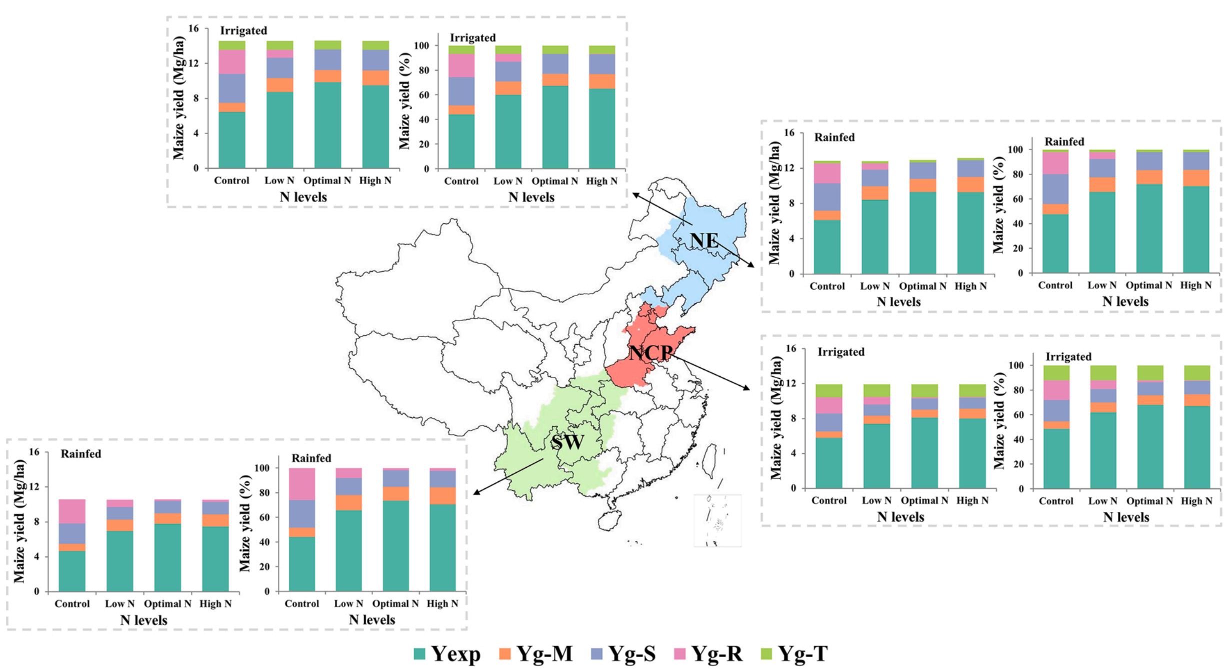

Fig. 4. Experimental yield and yield gap (expressed as Mg/ha and % of Yp or Yw), decomposed into management efficiency (Yg-M), soil efficiency (Yg-S), resource (Yg-R) and technology (Yg-T) yield gaps for different N treatments of irrigated maize cropping systems in Northeast China (NE) and North China Plain (NCP), and rainfed maize cropping systems in Northeast China (NE) and Southwest China (SW). Data are averaged across soil quality levels.

from yield responses to N in soils with very high soil quality for rainfed maize in NE and SW, while for the irrigated maize in NE yield responses to N in soils with low soil quality were not significantly different from yield responses to N in soils with very high soil quality.

3.2. *Decomposition of maize yield gaps across N fertilizer rates*

The parameter estimates of maize production frontiers in Table 2 show that the inclusion of two random errors (v_{it} and u_{it}, see Eq 1) is appropriate for all cropping systems. This is indicated by the gamma (γ) values which were relatively close to 1 (Table 2), meaning that most of the unexplained variability in Yexp can be attributed to the efficiency yield gap (u_{it}) rather than to statistical noise (v_{it}).

The components of the yield gap differed in size across cropping systems and N treatments (Fig. 4). Yg-T was fairly small across N treatments ranging between 7.0% and 12.0% of Yp for irrigated maize in NE and NCP, and ca. 2.0% of Yw for rainfed maize in NE. This translates into 0.3–1.5 Mg/ha across maize cropping systems and N treatments.

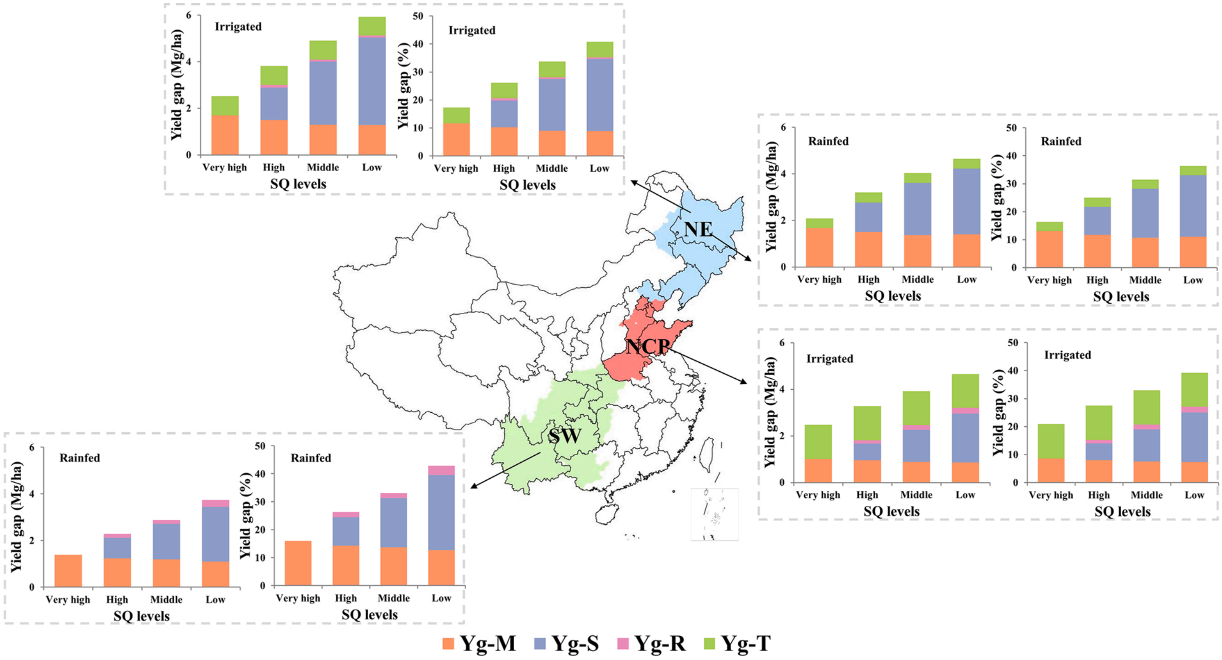

Fig. 5. Management efficiency (Yg-M), soil efficiency (Yg-S), resource (Yg-R) and technology (Yg-T) yield gaps (expressed as Mg/ha and % of Yp or Yw) at optimal N application level for different soil quality levels of irrigated maize cropping systems in Northeast China (NE) and North China Plain (NCP), and rainfed maize cropping systems in Northeast China (NE) and Southwest China (SW). Data for the other N treatments are provided in Supplementary Material.

Yg-R was, evidently, related to N treatments. For instance, it accounted for 17.4–27.0% (1.9–2.8 Mg/ha) and 5.6–9.8% (0.7 – 0.9 Mg/ha) of Yp (or Yw) for control and low N treatments, respectively. However, Yg-R was very small to nil for optimized N and high N treatments in the different cropping systems. Yg-S was substantial in all cropping systems: 17.4–24.1%, 10.7–14.7%, 10.5–16.1% and 10.8–16.2% of Yp (or Yw) for control, low N, optimal N and high N treatments, respectively (Fig. 4; Table S2). This is equivalent to 1.3–3.3 Mg/ha in absolute terms. Yg-S was 16.1–22.8%, 10.5–17.4%, 14.7–24.1% and 13.3–22.2% of Yp (or Yw) for irrigated maize in NE and NCP, and rainfed maize in NE and SW, respectively (Fig. 4). Yg-M was still large but consistent across cropping systems and N treatments (6.0–14.0% of Yp or Yw, which is equivalent to 0.7–1.8 Mg/ha).

3.3. *Soil quality contribution to maize yield gaps*

The yield gap decomposition in the optimal N treatment across different soil quality levels is presented in Fig. 5. The total yield gap decreased from about 40% of Yp (or Yw) to less than 20% from low to very high soil quality levels (Fig. 5). Yg-S varied from 17.7 to 26.9% of Yp (or Yw) in low soil quality level to 11.5–18.5% in medium soil quality level and 6.0–10.2% in high soil quality level across maize cropping systems (Fig. 5). Based on our framework, Yg-S in on-farm trials with very high soil quality levels was nil by definition. The relative values of Yg-S are equivalent to 2.1–3.7 Mg/ha, 1.4–2.7 Mg/ha and 0.7–1.4 Mg/ha for low, medium, and high soil quality levels, respectively. Conversely, Yg-M, Yg-R and Yg-T were similar for the different soil quality levels, accounting for 7.8–14.1%, 0–3.3% and 3.3–12.3% of Yp (or Yw) across maize cropping systems, respectively. Results for other N rates are provided in the Supplementary Material (Figures S4, S5, S6) and were similar to those reported for the optimal N treatments. Across soil quality levels, Yg-S showed ranges of 9.6–25.8%, 6.0–17.7%, 9.9–22.1% and 10.2–26.9% of Yp (or Yw) for irrigated maize in NE and NCP, and rainfed maize in NE and SW, respectively.

Significant differences in soil properties such as SOM, TN, Olsen-P, available K and pH, were found for different soil quality levels in all maize cropping systems (Table 3). Lower SOM and Avail-K content were found in trials with irrigated maize in NE on medium and low soil quality levels (SOM, 25.5–25.6 g/kg; Avail-K, 141.7–148.1 mg/kg) compared with trials with very high and high soil quality levels (SOM, 25.7–27.2 g/kg; Avail-K, 151.1–157.3 mg/kg). Olsen-P was similar for trials with very high, high and medium soil quality levels (20.3–21.1 mg/kg), but significantly lower in trials with low soil quality levels (19.1 mg/kg). For irrigated maize in NCP, SOM contents in trials with very high and high soil quality levels (SOM, 15.9 g/kg) were significantly greater than those in trials with medium and low soil quality levels (SOM, 14.4–15.2 g/kg), and Olsen-P in trials with low soil quality levels (20.8 mg/kg) was significantly lower than in trials with higher soil quality levels (22.5–24.1 mg/kg). For rainfed maize in NE, SOM contents in trials with very high soil quality level (SOM, 30.9 g/kg) were significantly greater than those in trials with low soil quality level (SOM, 29.1 g/kg); and Olsen-P and Avail-K were similar in trials with high, medium and low soil quality levels (Olsen-P, 24.2–26.1 mg/kg; Avail-K, 138.3–144.3 mg/kg), but lower than in trials with very high soil quality level (Olsen-P, 30.4 mg/kg; Avail-K, 161.7 mg/kg). For rainfed maize in SW, only Olsen-P significantly increased from 17.0 mg/kg with low soil quality level to 20.44 mg/kg with very high soil quality level; and Avail-K was similar in trials with very high, high, and medium soil quality levels, but lower in trials with low soil quality level (111.4 mg/kg).

4. Discussion

4.1. *Magnitude of maize yield gaps in China*

Maize yield gaps were estimated and decomposed for the main maize cropping systems (irrigated and rainfed) in China. Thousands of on-farm trials conducted with four different applied fertilizer treatments were linked to biophysical data and to simulated Yp and Yw available from

Table 3
Soil factors across different soil quality levels in irrigated and rainfed maize cropping systems of China. Different letters within each column indicate significant differences among various soil quality levels ($P < 0.05$). SOM, soil organic matter; Olsen-P, soil available phosphorus; Avail-K, soil available potassium.

Irrigation systems	Region	Soil quality levels	Number (n)	SOM (g/kg)	TN (g/kg)	Olsen-P (mg/kg)	Avail-K (mg/kg)	pH
Irrigated	Northeast China	Very high	197	27.18 (±1.07) a	1.37(±0.058) a	21.10 (±1.08) a	157.25 (±4.15) a	7.27 (±0.074) a
		High	441	25.72 (±0.64) ab	1.37(±0.040) a	20.86 (±0.62) a	151.08 (±2.62) ab	7.21 (±0.050) ab
		Middle	456	25.56 (±0.63) b	1.38(±0.041) a	20.34 (±0.62) a	148.1 (±2.67) b	7.15 (±0.048) b
		Low	515	25.51 (±0.55) b	1.44(±0.035) a	19.11 (±0.57) b	141.68 (±2.35) c	7.17 (±0.045) b
	North China Plain	Very high	179	15.94 (±0.30) a	1.02 (±0.023) a	24.05 (±1.03) a	113.53 (±3.46) a	7.62 (±0.052) c
		High	419	15.92 (±0.19) a	0.99 (±0.016) ab	23.72 (±0.67) a	114.6 (±2.07) a	7.71 (±0.032) bc
		Middle	434	15.17 (±0.18) b	0.93 (±0.016) b	22.49 (±0.62) a	114.68 (±2.14) a	7.80 (±0.025) a
		Low	474	14.35 (±0.18) c	0.91 (±0.014) c	20.77 (±0.55) b	111.86 (±1.70) a	7.76 (±0.027) ab
Rainfed	Northeast China	Very high	129	30.93 (±1.29) a	1.61 (±0.088) a	30.36 (±1.49) a	161.69 (±6.80) a	6.47 (±0.081) a
		High	279	30.29 (±0.79) ab	1.59 (±0.059) ab	26.13 (±0.89) b	143.57 (±3.55) b	6.45 (±0.051) a
		Middle	279	30.32 (±0.79) ab	1.72 (±0.073) a	24.22 (±0.79) b	144.28 (±3.80) b	6.35 (±0.053) a
		Low	335	29.07 (±0.69) b	1.57 (±0.058) b	24.32 (±0.76) b	138.34 (±3.58) b	6.34 (±0.050) a
	Southwest China	Very high	135	27.89 (±1.02) a	1.61 (±0.063) a	20.44 (±1.18) a	125.28 (±4.84) a	6.28 (±0.091) a
		High	300	27.61 (±0.66) a	1.55 (±0.037) a	18.35 (±0.77) b	117.60 (±3.36) a	6.20 (±0.058) a
		Middle	302	27.90 (±0.63) a	1.63 (±0.040) a	17.83 (±0.68) bc	125.32 (±3.43) a	6.24 (±0.057) a
		Low	354	26.80 (±0.68) a	1.53 (±0.038) a	16.96 (±0.69) c	111.35 (±3.26) b	6.11 (±0.056) a

the Global Yield Gap Atlas (www.yieldgap.org). Results indicate that maize yield gaps ranged from 2.8 to 8.1 Mg/ha across N treatments and maize cropping systems (Fig. 4). In absolute terms, yield gaps in irrigated maize cropping systems were greater than those in rainfed maize cropping systems (Fig. 4). In relative terms (experimental yields as a percentage of Yp or Yw), yield gaps were similar across maize cropping systems (Fig. 4). The average yield gap across cropping systems and three N rate treatments was 27–40% of Yp or Yw which is similar to the 35–42% of Yp or Yw reported by earlier studies on maize yield gaps in China (Liu et al., 2017; Meng et al., 2013; Tao et al., 2015).

As over- and under-applications of N fertilizer are common in actual farmers' practices in maize production in China (Zhang et al., 2008; Fan et al., 2012; Cui et al., 2018), the yield gap derived from the on-farm trials with four N application rates may well reflect the actual yield gap variation of maize production at field scale in China. Previous research on the quantification of yield gaps in Chinese cropping systems focused on national or regional scales (Liu et al., 2017; Meng et al., 2013; Liu et al., 2016; Tao et al., 2015), and such results help informing national and regional agricultural policies. However, national or regional analysis always mask the heterogeneity of yield gaps at field scale (van Ittersum et al., 2013), especially for smallholder farming systems (Cui et al., 2018; Tittonell and Giller, 2013). Quantifying and understanding Yg variation at field scale is a key approach towards enabling policy makers and farmers to take concrete action on land management.

4.2. Yield gap components and soil quality yield gap

The Y_{HE} in the four maize cropping systems approximated or even exceeded 80% of Yp or Yw, resulting in a small Yg-T of 2% of Yw in NE and 7.0–12% of Yp in NE and NCP. (Figs. 4 and 5). This Yg-T is much lower than that estimated in other cereal production systems in Southeast Asia and East Africa (Silva et al., 2017a, 2017b, 2019, Assefa et al., 2020). This is explained by the high Y_{HE} for maize in China, which is a result of intensive crop management practices (Zhang et al., 2012; Fan et al., 2012). Moreover, it is also possible that Yp and Yw are underestimated for maize cropping systems in China (see Supplementary Material). Generally, the results suggest less scope to further increase yields of rainfed maize compared to irrigated maize, considering the fact that Yg-T is only 2% of Yw for rainfed maize in NE and considering the highly heterogeneous production environment for rainfed maize in SW (see Supplementary Material).

The magnitudes of Yg-M and Yg-R were strongly associated with N rate in all maize cropping systems (Fig. 4; Table S2). Yg-R accounted for a larger proportion of Yg for treatments with no or low N rates (17.4–27.0% of Yp or Yw), but very small to nil proportion with optimal and high N supply (Fig. 4). Yg-M accounted for 6.0–13.7% of Yp (or Yw) across maize cropping systems and N treatments, and its value was nearly constant in low, optimal and high N treatments (Fig. 4; Table S2). N fertilizer application in current on-farm trials is split to match maize requirements at different growth stages and represented locally available practices based on agronomic knowledge. Thus, Yg-M could be greater under farmers' management practices than in on-farm trials analyzed, due to inefficient N management strategies deployed (Zhang et al., 2012). However, the results of Yg-M and Yg-R with optimal N rate indicate that current recommended optimal N rates could match the maize crop requirements, but the timing, placement and form of the N fertilization remain important to explain yield gaps in maize cropping systems across China, suggesting it is possible to further improve crop management (Chen et al., 2014; Cui et al., 2018).

Yg-S explained the largest share of the total yield gap and ranged between 11.0 % and 24.0% of Yp or Yw, which is equivalent to 33.0%–52.1% of the total yield gap (Figs. 4 and 5). The Yg-S in NCP was lower than in other maize cropping systems most likely because in this region maize is cultivated in a hot rainy season (June to October), which is likely beneficial for soil nutrient mineralization and provision. In contrast, maize in NE and SW is cultivated in a spring season (April to May), when low temperatures in early spring and/or drought have a negative effect on Yexp. Thus, soil constraints for maize production in NCP are less pronounced than in other cropping systems. Yg-S in low N, optimal N and high N treatments was similar in all maize cropping systems, but lower than that in control treatment (Fig. 4), which suggests that yield gaps due to poor soil quality can be partly overcome through adequate N fertilizer rates (Cassman, 1999). Moreover, experimental yield responses to N fertilizer decreased with increasing soil quality levels (Table 2). Yet, soil quality explains a large share of the total yield gap, even when sufficient N is applied. The total yield gap decreased from low to high soil quality levels (Fig. 5). Yg-S contributed to more than half of total yield gap in on-farm trials under optimal N rate in medium and low soil quality levels, but only a quarter to a third in high soil quality levels (Fig. 5). These results confirm the statistically significant positive effect of soil quality on experimental yields (Table 2) and are consistent with the hypothesis that lower levels of soil quality substantially accounted for maize yield gaps in China. Depending on maize cropping systems, SOM, TN, soil Olsen-P, available K and/or pH were significantly different between different soil quality levels (Table 3). For instance, the association between SOM and soil quality levels were greater in the irrigated maize cropping systems of NE and NCP than in the rainfed maize cropping systems of SW (Table 3). The latter may be attributed to heterogeneous biophysical conditions across regions. The climate in NE and NCP is colder than that in SW, so that higher SOM translated into greater availability of nutrients. Besides, SOM content was lowest in NCP, and soil management practices fostering C sequestration have been proposed as an effective strategy to enhance soil quality in NCP region (Lal, 2009; Fan et al., 2013; Wei et al., 2016). Soil Olsen-P and available K also showed positive associations with soil quality, suggesting the importance of soil nutrient supply on soil quality. As an exceptional case, soil available K had a smaller significant association with soil quality in irrigated maize cropping systems in NCP than in the other maize cropping systems (Table 3), which could be attributed to the widespread return of straw to the field in this region (He et al., 2015). Clearly, management of soil nutrients, SOM and/or pH can be key strategic options towards obtaining higher soil quality as a means to narrow Yg-S in diverse maize production regions. For maize cropping systems in NE and NCP, soil management practices should prioritize elevating SOM, whereas optimized fertilizer management practices can contribute to improve soil nutrient pools in rainfed maize cropping systems in SW.

It must be acknowledged that the use of nutrient omission plots to assess soil quality introduced uncertainties in the assessment of Yg-S. The Yg-S was calculated as the difference between Y_{TEx} and Y_{SEx} in a given climate zone × year × soil type combination, which is likely to minimize the contribution of non-soil factors to Yg-S. Yet, other factors, most notably crop variety, which can exhibit different responses to soil quality, might also be captured in the Yg-S due to lack of data to explicitly consider this factor in the analysis in addition to the key manageable soil properties used to explain Yg-S (Table 3). Other soil constraints not considered in the analysis, and likely to contribute to the Yg-S, include thinned topsoil and soil compaction, which have demonstrated detrimental effects on maize yields in China (Lindert, 2000; Fan et al., 2013).

5. Conclusion

Maize yield gaps were highly variable within and across the major maize cropping systems in China. The magnitude of the intermediate yield gaps varied with N application rates, soil quality levels and cropping systems. Overall, the efficiency yield gap explained most of the maize yield gap in China. The soil quality component of the efficiency yield gap accounted for a considerable proportion (33.0–52.0%) of the total maize yield gap. The management and resource yield gaps accounted for 11.7–46.6% and 0–46.7% of the total yield gap, respectively. The technology yield gap was generally small (2–12% of Yp or Yw).

This study highlights the importance of soil factors and N management practices in maize yield gaps and informs policy makers and practitioners about the magnitude and causes of maize yield gaps in China. The method employed to estimate the role of soil quality in narrowing yield gaps may also be meaningful for other developing countries, sub-Saharan Africa in particular, where yield gaps remain high and where crop production is being challenged by shortage of fertilizers and poor soil fertility.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fcr.2021.108304.

References

An, N., Fan, M., Zhang, F., Christie, P., Yang, J., Huang, J., Guo, S., Shi, X., Tang, Q., Peng, J., Zhong, X., Sun, Y., Lv, S., Jiang, R., Dobermann, A., 2015. Exploiting Co-benefits of increased rice production and reduced greenhouse gas emission through optimized crop and soil management. PLoS One 10, e140023.
An, N., Wei, W., Qiao, L., Zhang, F., Christie, P., Jiang, R., Dobermann, A., Goulding, K. W.T., Fan, J., Fan, M., 2018. Agronomic and environmental causes of yield and nitrogen use efficiency gaps in Chinese rice farming systems. Eur. J. Agron. 93, 40–49.
Assefa, B.T., Chamberlin, J., Reidsma, P., Silva, J.V., Ittersum, M.K., 2020. Unravelling the variability and causes of smallholder maize yield gaps in ethiopia. Food Secur. 12, 83–103.
Beza, E., Silva, J.V., Kooistra, L., Reidsma, P., 2017. Review of yield gap explaining factors and opportunities for alternative data collection approaches. Eur. J. Agron. 82, 206–222.
Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J.W., Brussaard, L., 2018. Soil quality – a critical review. Soil Biol. Biochem. 120, 105–125.
Cassman, K.G., 1999. Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. Proc. Natl. Acad. Sci. 96, 5952–5959.
Cassman, K.G., Dobermann, A., Walters, D.T., Yang, H., 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. Annu Rev Env Resour 28, 315–358.
Chen, X., Cui, Z., Fan, M., Vitousek, P., Zhao, M., Ma, W., Wang, Z., Zhang, W., Yan, X., Yang, J., Deng, X., Gao, Q., Zhang, Q., Guo, S., Ren, J., Li, S., Ye, Y., Wang, Z., Huang, J., Tang, Q., Sun, Y., Peng, X., Zhang, J., He, M., Zhu, Y., Xue, J., Wang, G., Wu, L., An, N., Wu, L., Ma, L., Zhang, W., Zhang, F., 2014. Producing more grain with lower environmental costs. Nature 514, 486–489.
Coelli, T., Henningsen, A., 2013. Frontier: stochastic frontier analysis. R Package Version 1, 1-0.
Cui, Z., Chen, X., Miao, Y., Zhang, F., Sun, Q., Schroder, J., Zhang, H., Li, J., Shi, L., Xu, J., Ye, Y., Liu, C., Yang, Z., Zhang, Q., Huang, S., Bao, D., 2008. On-farm evaluation of the improved soil N–based nitrogen management for summer maize in North China plain. Agron. J. 100, 517.
Cui, Z., Zhang, H., Chen, X., Zhang, C., Ma, W., Huang, C., Zhang, W., Mi, G., Miao, Y., Li, X., Gao, Q., Yang, J., Wang, Z., Ye, Y., Guo, S., Lu, J., Huang, J., Lv, S., Sun, Y., Liu, Y., Peng, X., Ren, J., Li, S., Deng, X., Shi, X., Zhang, Q., Yang, Z., Tang, L., Wei, C., Jia, L., Zhang, J., He, M., Tong, Y., Tang, Q., Zhong, X., Liu, Z., Cao, N., Kou, C., Ying, H., Yin, Y., Jiao, X., Zhang, Q., Fan, M., Jiang, R., Zhang, F., Dou, Z., 2018. Pursuing sustainable productivity with millions of smallholder farmers. Nature 555, 363–366.
Di Mauro, G., Cipriotti, P.A., Gallo, S., Rotundo, J.L., 2018. Environmental and management variables explain soybean yield gap variability in Central Argentina. Eur. J. Agron. 99, 186–194.
Fan, M., Shen, J., Yuan, L., Jiang, R., Chen, X., Davies, W.J., Zhang, F., 2012. Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China. J. Exp. Bot. 63, 13–24.
Fan, M., Lal, R., Cao, J., Qiao, L., Su, Y., Jiang, R., Zhang, F., 2013. Plant-based assessment of inherent soil productivity and contributions to China's cereal crop yield increase since 1980. PLoS One 8, e74617.
FAO, 2019. FAOSTAT—Agriculture Database. Available at: http://faostat.fao.org/.
Fermont, A.M., van Asten, P.J.A., Tittonell, P., van Wijk, M.T., Giller, K.E., 2009. Closing the cassava yield gap: an analysis from smallholder farms in East Africa. Field Crop Res 112, 24–36.
Fischer, R.A., 2015. Definitions and determination of crop yield, yield gaps, and of rates of change. Field Crop Res 182, 9–18.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327, 812–818.

He, P., Yang, L., Xu, X., Zhao, S., Chen, F., Li, S., Tu, S., Jin, J., Johnston, A.M., 2015. Temporal and spatial variation of soil available potassium in China (1990–2012). Field Crop Res 173, 49–56.

Hochman, Z., Horan, H., 2018. Causes of wheat yield gaps and opportunities to advance the water-limited yield frontier in Australia. Field Crop Res. 228, 20–30.

Kumbhakar, S.C., Lovell, C.A.K., 2000. Stochastic Frontier Analysis. Cambridge University Press.

Lal, R., 2009. Soils and food sufficiency. A review. Agron. Sustain. Dev. 29, 113–133.

Lindert, P.H., 2000. Shifting Ground: The Changing Agricultural Soils of China and Indonesia. MIT Press, Cambridge, MA.

Liu, Z., Yang, X., Hubbard, K.G., Lin, X., 2012. Maize potential yields and yield gaps in the changing climate of northeast China. Glob. Change Biol. Bioenergy 18, 3441–3454.

Liu, Z., Yang, X., Lin, X., Hubbard, K.G., Lv, S., Wang, J., 2016. Maize yield gaps caused by non-controllable, agronomic, and socioeconomic factors in a changing climate of Northeast China. Sci. Total Environ. 541, 756–764.

Liu, B., Chen, X., Meng, Q., Yang, H., van Wart, J., 2017. Estimating maize yield potential and yield gap with agro-climatic zones in China—distinguish irrigated and rainfed conditions. Agr. Forest Meteorol. 239, 108–117.

Lobell, D.B., Cassman, K.G., Christopher, B.F., 2009. Crop yield gaps: their importance, magnitudes, and causes. Ann. Rev. Environ. Res. 34 (1), 179–204.

Meng, Q., Hou, P., Wu, L., Chen, X., Cui, Z., Zhang, F., 2013. Understanding production potentials and yield gaps in intensive maize production in China. Field Crop Res. 143, 91–97.

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2012. Closing yield gaps through nutrient and water management. Nature 490, 254–257.

National Bureau of Statistics of China, 2017. China-Agriculture Database. Beijing, China.

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., Core Team, R., 2015. nlme: Linear andNonlinear Mixed Effects Models.

Ramankutty, N., Foley, J.A., Norman, J., McSweeney, K., 2002. The global distribution of cultivable lands: current patterns and sensitivity to possible climate change. Global Ecol. Biogeogr. 11, 377–392.

Silva, J.V., Reidsma, P., Laborte, A.G., van Ittersum, M.K., 2017a. Explaining rice yields and yield gaps in Central Luzon, Philippines: an application of stochastic frontier analysis and crop modelling. Eur. J. Agron. 82, 223–241.

Silva, J.V., Reidsma, P., van Ittersum, M.K., 2017b. Yield gaps in Dutch arable farming systems: analysis at crop and crop rotation level. Agr. Syst. 158, 78–92.

Silva, J.V., Baudron, F., Reidsma, P., Giller, K.E., 2019. Is labour a major determinant of yield gaps in sub-Saharan Africa? A study of cereal-based production systems in Southern Ethiopia. Agr. Syst. 174, 39–51.

Tao, F., Zhang, S., Zhang, Z., Rötter, R.P., 2015. Temporal and spatial changes of maize yield potentials and yield gaps in the past three decades in China. Agric. Ecosyst. Environ. 208, 12–20.

Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. 108, 20260–20264.

Tittonell, P., Giller, K.E., 2013. When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. Field Crop Res. 143, 76–90.

van Ittersum, M.K., Rabbinge, R., 1997. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crop Res. 52, 197–208.

van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance—a review. Field Crop Res. 143, 4–17.

van Wart, J., van Bussel, L.G.J., Wolf, J., Licker, R., Grassini, P., Nelson, A., Boogaard, H., Gerber, J., Mueller, N.D., Claessens, L., van Ittersum, M.K., Cassman, K.G., 2013. Use of agro-climatic zones to upscale simulated crop yield potential. Field Crop Res. 143, 44–55.

Wei, W., Yan, Y., Cao, J., Christie, P., Zhang, F., Fan, M., 2016. Effects of combined application of organic amendments and fertilizers on crop yield and soil organic matter: An integrated analysis of long-term experiments. Agr. Ecosyst. Environ. 225, 86–92.

Yang, H.S., Dobermann, A., Lindquist, J.L., Walters, D.T., Arkebauer, T.J., Cassman, K.G., 2004. Hybrid-maize—a maize simulation model that combines two crop modeling approaches. Field Crops Res. 87 (2–3), 131–154.

Zhang, F., Wang, J., Zhang, W., Cui, Z., Ma, W., Chen, X., Jiang, R., 2008. Nutrient use efficiencies of major cereal crops in China and measures for improvement. Acta Pedologica Sinica 45 (5), 915–924.

Zhang, F., Cui, Z., Chen, X., Ju, X., Shen, J., Chen, Q., Liu, X., Zhang, W., Mi, G., Fan, M., Jiang, R., 2012. Integrated nutrient management for food security and environmental quality in China. Adv. Agron. 116, 1–40.

Zhang, W., Cao, G., Li, X., Zhang, H., Wang, C., Liu, Q., Chen, X., Cui, Z., Shen, J., Jiang, R., Mi, G., Miao, Y., Zhang, F., Dou, Z., 2016. Closing yield gaps in China by empowering smallholder farmers. Nature 537, 671–674.