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Multi-scale assessment of winter wheat yield gaps with an integrated evaluation framework in the Huang-Huai-Hai farming region in China

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Abstract

Quantifying reasonable crop yield gaps and determining potential regions for yield improvement can facilitate regional plant structure adjustment and promote crop production. The current study attempted to evaluate the yield gap in a region at multi-scales through model simulation and farmer investigation. Taking the winter wheat yield gap in the Huang-Huai-Hai farming region (HFR) for the case study, 241 farmers' fields in four typical high-yield demonstration areas were surveyed to determine the yield limitation index and attainable yield. In addition, the theoretical and realizable yield gap of winter wheat in 386 counties of the HFR was assessed. Results showed that the average field yield of the demonstration plots was 8282 kg/ha, accounting for 0.72 of the potential yield, which represented the highest production in the region. The HFR consists of seven sub-regions designated 2.1–2.7: the largest attainable yield gap existed in the 2.6 sub-region, in the southwest of the HFR, while the smallest was in the 2.2 sub-region, in the northwest of the HFR. With a high irrigated area rate, the yield gap in the 2.2 sub-region could hardly be reduced by increasing irrigation, while a lack of irrigation remained an important limiting factor for narrowing the yield gap in 2.3 sub-region, in the middle of the HFR. Therefore, a multi-scale yield gap evaluation framework integrated with typical field survey and crop model analysis could provide valuable information for narrowing the yield gap.

Introduction

In the context of world population growth, increased demand for bio-energy, climate change and the deterioration of the ecological environment, the growing problem of food security is becoming increasingly serious. Therefore, increasing crop production is necessary to ensure food security (Liu *et al.*, 2013; Gobbett *et al.*, 2017). Narrowing the gap between the actual yield of farmers and the potential yield of crops is an important way to increase grain production. The study of yield gaps can indicate the potential for yield improvement and reveal the limiting factors (natural, technological and economic) for increasing production at the regional scale (Lobell *et al.*, 2009). As wheat is a major staple food in diets worldwide, increasing wheat production is helpful for ensuring food security (Ebrahimi *et al.*, 2016).

As the most important grain-producing area, the planting area of wheat in the Huang-Huai-Hai farming region (HFR) was 1545×10^4 ha in 2016, accounting for more than 0.63 of the total wheat area in China (H. Jia, unpublished data). The household farm is the dominant agricultural production system. Moreover, the wheat yield in the HFR has exceeded the average national yield because of efficient cultivation practices (Anderson, 2010). However, achieving higher wheat yields in the HFR is very challenging (Carberry *et al.*, 2013) due to climate change (Zhang *et al.*, 2013), a lack of water resources (Shen *et al.*, 2013), the deterioration of the ecological environment (Huang *et al.*, 2017) and yield stagnation (Chen *et al.*, 2017). There has been a significant increase in crop production in the HFR, with a substantial increase in fertilizer inputs (Lin *et al.*, 1994), an improvement of irrigation infrastructure and pedigree development (Li *et al.*, 2016), since 1990. Nevertheless, the wheat yield potential has not yet been achieved due to adaptation to the climate, poor soil and crop cultivation management, which indicates that there is some potential to increase wheat production (Van Ittersum and Rabbinge, 1997).

The methods for studying crop yield gaps include field experiments, participatory evaluation and crop models (Wang *et al.*, 2019). The true effects of limiting factors on crop yield can be found with field experiments (Lollato *et al.*, 2019). However, there are limits to extending the results due to differences in soil and climate. The main restrictive factors for crop production by farmers can be evaluated with the participatory evaluation approach (Studnicki *et al.*, 2019), but there is a certain degree of subjectivity and randomness in such surveys (Cheesman *et al.*, 2017). Crop models can serve as an important tool for evaluating yield potential, with the advantages of simple implementation, multifactor analysis and predictable capacity, but there are inconsistencies among crop models (Jing *et al*., 2017). The definitions and evaluation frameworks of yield gaps exhibit large differences. The yield gap model was first proposed by De Datta (1981), who defined the gap as the difference between the attainable yield at an experimental station and actual yield of farmers. Other scientists subsequently perfected the concept of the crop yield gap and proposed different evaluation models according to their research backgrounds and methods. De Bie (2000) summarized the previously proposed crop yield gap model and released a new framework for evaluating crop yield gaps, including the potential and maximum attainable yield at an experimental station, and potential and actual farmland yields. Lobell and Ivan Ortiz-Monasterio (2006) proposed that the crop yield gap model should consist of the potential yield, attainable yield and actual yield. Although the evaluation models of different scholars are different, the focus is on quantification of yield gaps and how to reduce the gaps between different yields. Methods for measuring the potential yield and quantifying the attainable yield gap are particularly important for developing technical strategies for reducing yield gaps at the regional scale. The potential yield represents the yield determined with best management practices and no limitations caused by diseases, insect pests, water or nutrients (Evans and Fischer, 1999). The yield gap between the potential and maximum attainable yields cannot be narrowed easily, while closing the gap between the attainable yield and the actual yield is more realistic (Li *et al*., 2019). The yield gap between the attainable yield and the actual yield can be narrowed by adjusting field management practices, adopting new varieties with higher yields and improving production conditions.

Previous studies of crop yield gaps in China have been based mainly on field experiments (Ha *et al*., 2015; Yang *et al*., 2015), household surveys and crop models at a field scale (Liang *et al*., 2011; Chen *et al*., 2018). There are few reports about research on crop yield gaps with integrated methods at multiple scales. Most research focusing on the quantification of crop yield gaps and the analysis of limiting factors has been carried out according to administrative divisions (Sun *et al*., 2018; Zhang *et al*., 2018), without due consideration for the differences in climate, geomorphology, soil, hydrology and natural and ecological conditions among different counties. Studies on crop yield gaps in different agricultural ecology regions are rare. In addition, previous studies were mainly carried out through experiments or crop model simulations and the extension of such findings to farmers' fields is still limited due to differential environmental conditions and the uncertainty of the model simulation. The yield gaps of different crops under various environmental conditions have been reported (Sentelhas *et al*., 2015; Tack *et al*., 2015; Tamene *et al*., 2016); however, there is a lack of comparability among regions and among methods. The current study aims to: (1) explore a method for obtaining attainable yield using crop model simulation and field surveys in a high-yielding area; (2) use a multi-scale evaluation framework integrating with crop model simulation, participatory appraisal and statistical data analysis to analyse the winter wheat yield gap and (3) provide theoretical support for narrowing the yield gap of winter wheat in the HFR.

Materials and methods

Region description

The HFR is the most important winter wheat production area in China, occupying 0.28 of the country's arable land and accounting for 0.30 of the total grain output. The HFR covers all of Beijing, Tianjin, Hebei Province, Henan Province and Shandong Province, as well as parts of Jiangsu, Anhui, Shanxi and Shaanxi Provinces. The seven farming sub-regions in the HFR include the following: 2.1 sub-region, the export-oriented double-cropping agricultural and fishing region on the coast of the Shandong Peninsula around Bohai; 2.2 sub-region, the irrigated double-cropping plain in the piedmonts of Taihang Mountain and Yan Mountain; 2.3 sub-region, the irrigated double-cropping region and the drought-affected single-cropping region in the lower Haihe Plain; 2.4 sub-region, the irrigated and drought-affected double-cropping region in the west plain and middle hills of Shandong Province; 2.5 sub-region, the irrigated and drought-affected double-cropping region in Nanyang Basin of the Huang-Huai Plain; 2.6 sub-region, the drought-affected single-cropping region and the irrigated double-cropping region in the hills of western Henan Province and 2.7 sub-region, the irrigated and drought-affected double-cropping region in the valley of the Fenhe and Weihe Rivers (Liu and Chen, 2005). Plains dominate in the HFR, and the terrain is low and flat. The climate in the HFR is mild, and the region belongs to the semi-humid warm temperate zone. The average annual temperature is 10–15 °C. The cumulative temperature above 0 °C is 4200–5000 °C, while cumulative temperature above 10 °C is 3600–4900 °C. The frost-free period in the HFR is 170–200 d. Annual precipitation ranges from 500–950 mm, spatially distributed between high precipitation in the south and low precipitation in the north (Liu and Chen, 2005; Xu *et al*., 2015). The amount of heat is suitable for the development of winter wheat.

DSSAT-CERES-Wheat model

The Decision Support System for Agrotechnology Transfer (DSSAT) was developed by the International Benchmark Sites Network for Agrotechnology Transfer project to estimate production, resource use and risks associated with different crop production practices (Jones *et al*., 1998). CERES-Wheat was developed by Ritchie and Otter (1985) and merged into the Cropping System Model (CSM) now referred to as CSM-CERES-Wheat (Jones *et al*., 2003). The model version used in the current work was DSSAT Version 4.5. As a soil-plant-atmosphere dynamics model, the carbon, nitrogen and water balance principles are integrated into the model to simulate crop growth stages, total above-ground biomass, yield and water and nitrogen balances (Palosuo *et al*., 2011; Li *et al*., 2018). In addition, it has become one of the most widely used wheat models in the world (Sarkar and Kar, 2006; Dar *et al*., 2017; Yang *et al*., 2017; Kheir *et al*., 2019).

Data collection

The meteorological data were obtained from the National Meteorological Information Centre (http://data.cma.cn/site/index.html), which covered 58 weather sites including Beijing, Tianjin, Hebei, Henan, Shandong, Anhui, Jiangsu, Shanxi, Shaanxi and other provinces. Daily meteorological data during the period 2004–2015 included the daily average temperature, daily maximum temperature, daily minimum temperature, daily rainfall, sunshine hours, relative humidity, average wind speed, 2 m wind speed and other indicators. The soil data for different sites were derived from the Resources and Environment Data Cloud Platform of the Chinese Academy of Sciences (http://www.resdc.cn/), which included the mechanical composition of

Table 1. Description of environments of testing sites, data and sources, and sub-regions characteristics in the HFR

Site	Wuqiao	Gaocheng	Luancheng	Taian	Zhengzhou	Mengjin	Yangling
Years for calibration	2008–2009	2006–20011	1987–1995	2014–2015	1991–2002	1992–2001	2008–2009
Years for evaluation	2010–2011	2011–2014	1995–2000	2015–2016	2002–2008	2001–2006	2009–2010
Cultivar	Jimai 22	Shixin 828	Shimai 15	Shannong 8355	Aikang 58	Yumai 48	Xiaoyan 22
Seeding	12 October	7 October	5 October	11 October	8 October	10 October	15–17 October
N rate (kg/ha)	0; 60; 120; 180; 240	180; 240; 300	304	0; 150; 225; 240; 300	0; 165	120	120
Water supply	Irrigated	Irrigated	Irrigated	Irrigated	Irrigated	Irrigated	Irrigated
Soil type	Salinized fluvo-aquic soil	Loam cinnamon soil	Medium-light loamy cinnamon soil	Brunisolic Soil	Fluvo-aquic soil	Loess cinnamon soil	loess soil
Silt (g/g)	0.76–0.86	0.23–0.31	0.55–0.86	0.18–0.25	0.14–0.56	0.34–0.56	0.37–0.45
Clay (g/g)	0.09–0.23	0.25–0.36	0.07–0.35	0.09–0.12	0.07–0.33	0.10–0.25	0.04–0.12
BD (g/m^3)	1.46	1.40	1.49	1.31–1.65	1.20–1.45	1.21–1.69	1.20–1.45
Organic matter (g/kg)	5.1–8.4	16.9–22.4	1.0–5.0	5.6–12.6	4.0–10.6	7.3	5.1–15.2
pH	7.5	7.4	7.5	6.7	8.2	8.3	8.4
Field capacity (mm/mm)	0.35–0.43	0.25–0.28	0.33–0.39	0.24–0.30	0.21–0.29	0.22–0.26	0.19–0.23
Wilting point (cm^3/cm^3)	8.6–22.5	10.0–14.0	9.6–16.4	11.2–19.5	4.5–18.0	8.3–9.4	8.4–13.6
Number of measuring yield	13	13	15	11	18	15	13
Resource literature	——	Zhang (2018)	Hu *et al.* (2009)	Song (2017)	Gong *et al.* (2013)	Jiang *et al.* (2009)	Wang *et al.* (2013)

different soil layers, organic carbon content, pH, total nitrogen content, wilting coefficient, soil bulk density, saturated water content and other indicators. The relevant representative varieties, the crop yield data, crop management data, phenology and yields were collected from a 4-year experiment with five nitrogen (N) levels (0, 60, 120, 180 and 240 kg/ha) conducted during the 2008–2011 growing seasons in Wuqiao (Liu *et al.*, 2015) and published journal articles (Hu *et al.*, 2009; Jiang *et al.*, 2009; Gong *et al.*, 2013; Wang *et al.*, 2013; Song, 2017; Zhang, 2018) for calibrating and evaluating the model in the seven sub-regions of the HFR. Of these data, 0.70 were used to calibrate the model and the remaining 0.30 used for model evaluation. The representative cultivars (Jimai 22, Shixin 828, Shimai 15, Shannong 8355, Aikang 58, Yumai 48 and Xiaoyan 22) and corresponding management practices were selected for each sub-region to conduct crop model simulation (Table 1). The cultivar coefficients for the model included days at optimum vernalizing temperature required for vernalization (P1V), photoperiod response (reduction in rate/10 h drop in pp; P1D), grain filling (excluding lag) phase duration (P5), kernel number per unit canopy weight at anthesis (G1), standard kernel size under optimum conditions (G2), standard, non-stressed mature tiller weight including grain (G3) and interval between successive leaf tip appearances (PHINT). An iterative process was used to adjust the genetic coefficients to minimize differences between measured and simulated values (Boote *et al.*, 1998). Their definitions and calibrated values are listed in Table 2.

The actual yield, planting area, cultivated area, grain sown area and effective irrigation area of winter wheat in 386 counties in the HFR were derived from agricultural statistics yearbooks for counties in China (The Ministry of Agriculture of the People's Republic of China, 2004–2015). The field survey was conducted in the provinces of Hebei, Shandong and Henan from 2014 to 2015, which are the typical grain-producing provinces in the HFR. The specific investigation sites were Wuqiao County in Hebei Province (116°26′E, 37°37′N, 20 m a.s.l.), Tengzhou City in Shandong Province (117°05′E, 35°06′N, 57 m a.s.l.), Xihua County in Henan Province (114°16′E, 33°44′N, 55 m a.s.l.) and Mengjin County in Henan Province (112°34′E, 34°48′N, 207 m a.s.l.). These four counties are intensive winter wheat planting areas with a long history, and the soil, climate, management and cultivar are also typical of the region. A total of 241 completed questionnaires were collected from the winter wheat demonstration plots (Cui *et al.*, 2018), experimental stations and 5-km high production areas in the region (Fig. 1).

Model performance evaluation

The 'trial and error' method was adopted to estimate the genetic parameters of crop varieties. The normalized root mean square

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Table 2. Genetic coefficients of winter wheat cultivars in DSSAT-CERES-Wheat model in the seven sub-regions of the HFR

Sub-region[a]	Variety	Calibrated value						
		P1V	P1D (%)	P5 (°C d)	G1 (#/g)	G2 (mg)	G3 (g dwt)	PHINT (°C d)
2.1	Jimai 22	35	45	530	24	36	1.5	112
2.2	Shixin 828	53	60	402	28	52	1.9	96
2.3	Shimai 15	60	45	410	32	48	1.4	86
2.4	Shannong 8355	45	45	480	30	50	1.5	86
2.5	Aikang 58	30	60	440	24	33	1.0	90
2.6	Yumai 48	30	45	550	24	45	1.8	100
2.7	Xiaoyan 22	35	55	580	23	46	1.9	90

P1 V, days, optimum vernalizing temperature, required for vernalization; P1D, photoperiod response (reduction in rate/10 h drop in pp); P5, grain filling (excluding lag) phase duration; G1, Kernel number per unit canopy weight at anthesis; G2, standard kernel size under optimum conditions; G3, standard, non-stressed mature tiller weight (including grain); PHINT, interval between successive leaf tip appearances.

[a]2.1, the export-oriented double-cropping agricultural and fishing region on the coast of the Shandong Peninsula around Bohai; 2.2, the irrigated double-cropping plain in the piedmonts of Taihang Mountain and Yan Mountain; 2.3, the irrigated double-cropping region and the drought-affected single-cropping region in the lower Haihe Plain; 2.4, the irrigated and drought-affected double-cropping region in the west plain and middle hills of Shandong Province; 2.5, the irrigated and drought-affected double-cropping region in Nanyang Basin of the Huang-Huai Plain; 2.6, the drought-affected single-cropping region and the irrigated double-cropping region in the hills of western Henan Province and 2.7, the irrigated and drought-affected double-cropping region in the valley of the Fenhe and Weihe Rivers (Liu and Chen, 2005).

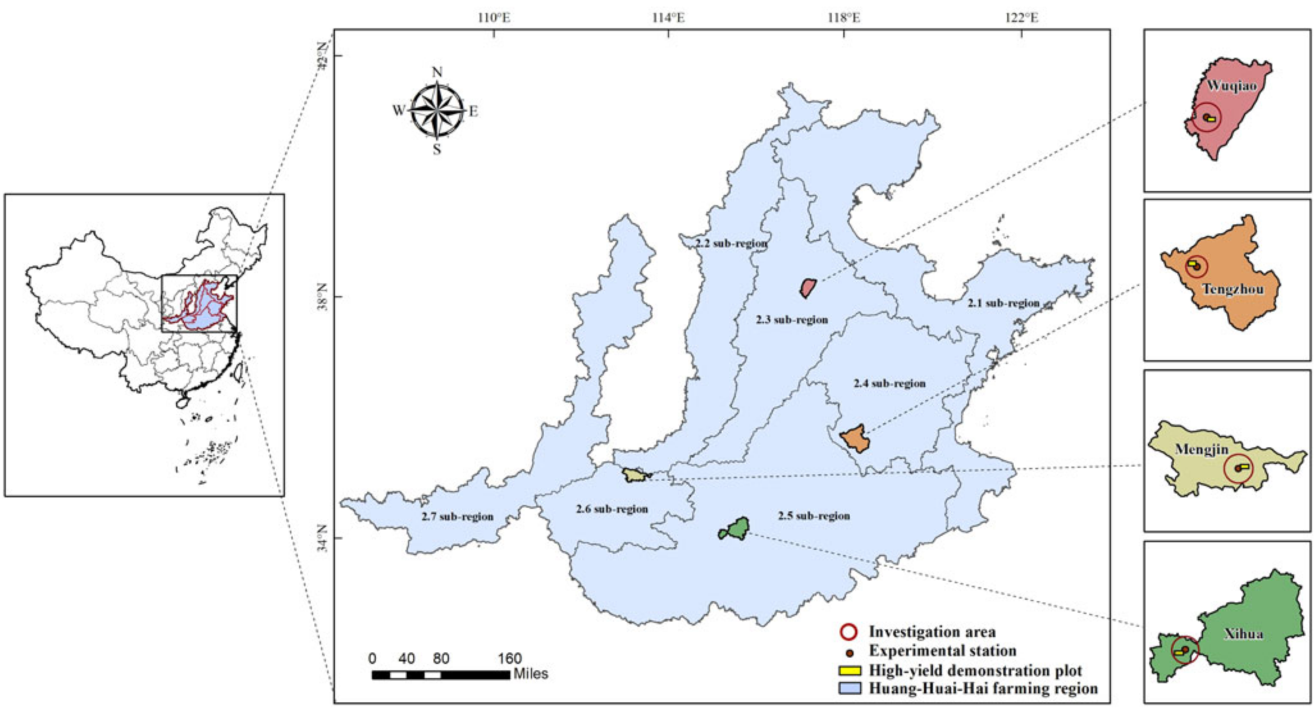

Fig. 1. (Colour online). Map of the seven sub-regions of the HFR and survey areas. See footnote of Table 2 for definitions of codes 2.1–2.7.

error (NRMSE) was used to measure the degree of relative difference between the simulated yield and the measured yield. The consistency between the simulated and measured values was verified by the index of agreement (d). The formulae are as follows:

$$NRMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i - R_i)^2}{n}} \times \frac{100}{\bar{R}} \quad (1)$$

$$D = 1 - \left[\frac{\sum_{i=1}^{n}(S_i - R_i)^2}{\sum_{i=1}^{n}(|S_i'| + |R_i'|)^2}\right] \quad (2)$$

where S_i was the simulated yield, R_i was the measured yield, $\bar{R}$ was the average of the measured yield, $S_i' = S_i - \bar{R}$, $R_i' = R_i - \bar{R}$ and n was the number of samples. When NRMSE < 10% and the D value was close to 1, simulated yield was in good agreement with measured yield, indicating that the variety parameters could accurately reflect the main genetic characteristics of the crop and could be used to simulate crop growth in studies (Liu *et al.*, 2017).

Potential yield

The potential yield was defined as the maximum yield obtained under conditions of sufficient water and fertilizer without pests

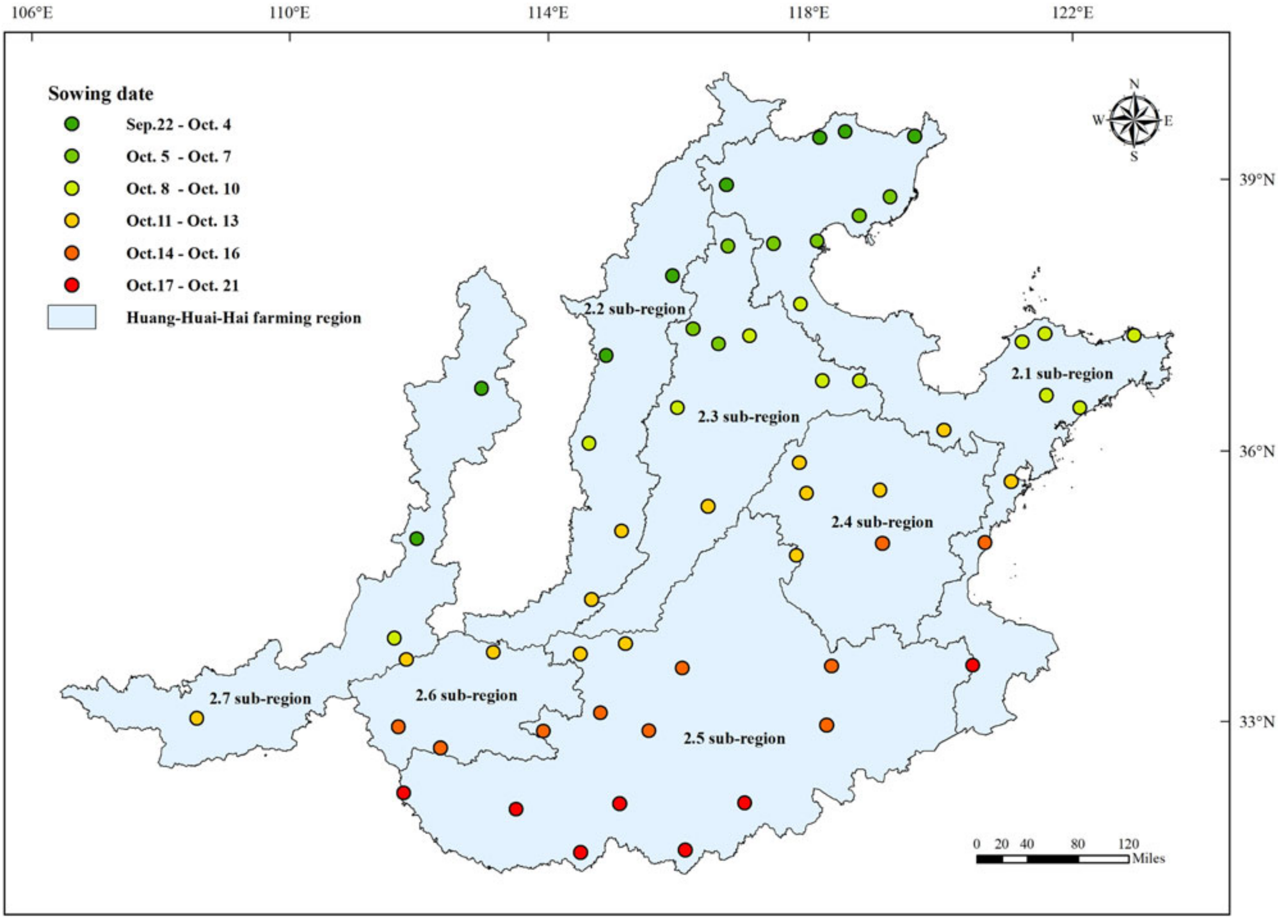

Fig. 2. (Colour online). Distribution of 58 meteorological stations and corresponding winter wheat sowing date in seven sub-regions of the HFR. See footnote of Table 2 for definitions of codes 2.1–2.7.

and diseases for a certain genetic variety (Van Ittersum and Rabbinge, 1997), acquired using model simulations and spatial interpolation. Firstly, the model was used to simulate the potential yield of 58 counties based on the varieties and management practices (Fig. 2). There were complete data for simulating potential yield, including soil, weather, variety genetic coefficients and management practices in the 58 counties. The same variety was adopted for the stations in each farming sub-region, so a total of seven wheat varieties were used for the simulation. Secondly, the potential yield of 58 stations was inserted into the entire HFR using the kriging interpolation method in ArcGIS 10.2. Thirdly, the spatial interpolation analysis module 'zonal statistic as table' in ArcGIS was used to collect the potential yields for each county. Finally, the yield gaps between potential and statistical yields were obtained for 386 counties during the period from 2004 to 2015. In order to obtain the potential yields of different sub-regions, the 386 counties were divided into seven sub-regions according to the sub-regional classification criteria and the potential yields of all counties in each sub-region were averaged to obtain the potential yield of the sub-region.

Attainable yield

The attainable yield was defined as the yield obtained with optimal agricultural practices recommended by local agro-technical extension centres. Attainable yield in the field was easy to determine, but attainable yield at the regional scale still lacked a unified standard. A combination of model simulation and field surveys was used to determine the attainable yield of winter wheat at the regional scale using the following formulae:

$$\mathrm{AY}_i = \mathrm{PY}_i \times I_c \tag{3}$$

$$I_c = \frac{\sum_{i=1}^{n} HY_i}{n} \Big/ \frac{\sum_{j=1}^{N} PY_j}{N} \tag{4}$$

where AY_i was the attainable yield in any region of the research area, PY_i was the region's potential yield calculated from the crop model, I_c was the yield limitation index, which reflected the maximum proportion of crop potential yields that could be achieved in field production, HY_i was the fields yield of the demonstration plot in the research area obtained from surveys, n was the number of high-yield demonstration plots, PY_j was the potential yield in the high-yield demonstration plots that were set by local government and N was the number of the investigated areas.

In order to evaluate the accuracy of the attainable yield acquisition method proposed, it was compared with other commonly used methods for calculating attainable yield. Lobell *et al.* (2009) proposed that 0.80 of the potential yield can be considered as the attainable yield (AY_1), while Xu *et al.* (2017) defined attainable yield (AY_2) as the maximum yield of winter wheat at

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experimental stations. The attainable yield determined by the formula above was AY_3. In addition, Waongo *et al.* (2015) proposed that the attainable yield obtained from the crop model was AY_4, which was simulated by a model with the fertilizer-N stress limitation enabled.

Statistical analysis

The yield gaps at different levels were defined with the potential yield (Y_p), attainable yield (Y_a) and actual farmers' yield (Y_{af}).

YG I was the difference between Y_p and Y_{af} (Eqn (2)).

$$\text{YG I} = Y_p - Y_{af} \quad (5)$$

YG II was the difference between Y_a and Y_{af} (Eqn (3)).

$$\text{YG II} = Y_a - Y_{af} \quad (6)$$

YG III was the difference between Y_p and Y_a (Eqn (4)).

$$\text{YG III} = Y_p - Y_a \quad (7)$$

Results

Model calibration and evaluation

The first goal was to calibrate the model to simulate the yield of winter wheat accurately from different varieties in the seven sub-regions of the HFR. The genetic coefficients of winter wheat were calibrated using 0.70 of the data from field experiments and literature collection (Table 2). The remaining data were used to evaluate the model for the study area. For the seven sub-regions, the NRMSE and *D* values were 3.40–9.92% and 0.97–0.99%, respectively (Fig. 3). The NRMSE values of the seven sub-regions were <10% and *D* values were close to 1, which indicated good performance of wheat yield estimation by the model. Thus, the variety of parameters used in the current could be used for crop yield gap analysis.

Yield gap of winter wheat in the continuous high-yielding demonstration regions

Distribution of the winter wheat yield among fields

To analyse the yield gap between actual field yield and potential yield at the farmers' scale, sites including Wuqiao County (Hebei Province), Tengzhou City (Shandong Province) and Xihua County and Mengjin County (Henan Province) were selected for the current study. The distribution of actual farmers' yield of winter wheat in four typical winter wheat areas was analysed with the cumulative probability distribution function. The results showed that the actual farmers' yield of winter wheat in Wuqiao County (Hebei Province) was mainly around 7000–8000 kg/ha, which accounted for 0.59 of the total samples. The cumulative probability distribution function showed that the difference in yield between the 0.75 and 0.25 probability was 992 kg/ha (Fig. 4(a)). The yield of winter wheat in Tengzhou (Shandong Province) ranged from 5623–8615 kg/ha and 0.71 of the farmers' yields were >7000 kg/ha, which indicated that the yields of most farmers investigated in Tengzhou (Shandong Province) had reached a relatively high level (Fig. 4(b)). The proportion of fields with winter wheat yields higher than 7000 kg/ha accounted for 0.64 of the total fields investigated in Xihua County (Henan Province) (Fig. 4(c)). The actual yield of winter wheat in Mengjin (Henan Province) ranged mainly from 6000–7000 kg/ha, which accounted for 0.63 of the surveyed samples (Fig. 4(d)). The winter wheat yields of 241 surveyed fields in the four areas ranged from 4631–9335 kg/ha. The proportion of fields with yields exceeding 6500 kg/ha accounted for 0.83 of the total surveyed samples. The average yield was 7152 kg/ha, and the coefficient of variation was 11.22%, indicating that there was little difference in winter wheat yield among fields and that the yields had reached high levels for most fields across the entire survey area of the HFR.

Yield gap of winter wheat in fields

The average potential yield of winter wheat in the survey area varied from 10 445–12 026 kg/ha, with the highest potential yield in Xihua County (Henan Province) and the lowest potential yield in Mengjin County (Henan Province). The differences in potential yields of the four areas were related mainly to the local climate, soil and varieties. The average actual farmers' yield ranged from 6749–7456 kg/ha, accounting for 0.59–0.65 of the potential yield. After the yield gap at the farmers' scale was analysed, it was found that YG I in the four research areas ranged from 3696–4932 kg/ha, with the YG I in Xihua County (Henan Province) being the largest (Fig. 5). Theoretically, the yield of winter wheat could be improved by 35.4–41.0%.

In the current study, the realizable yield gap refers to the gap between attainable and actual yield, which meant that the yield gap could be narrowed in reality. To determine the realizable yield gap of winter wheat in the HFR, the methods proposed by Lobell *et al.* (2009), Xu *et al.* (2017) and Waongo *et al.* (2015) were compared. It was shown that the average potential yield of the four survey areas was 11 439 kg/ha; the average AY_3 value was 8282 kg/ha, which accounted for 0.72 of potential yield; the average AY_2 value was 9053 kg/ha, accounting for 0.79 of potential yield and the average AY_4 value was 9207 kg/ha, which accounted for 0.81 of potential yield (Fig. 5).

The high-yield demonstration fields in four typical high-yield areas of the HFR were selected to obtain attainable yields (AY_3). However, the yield still did not reach the attainable yields obtained by the other three methods. The realizable yield gaps were greater in all four areas when using AY_1 and AY_4 as the attainable yields, with values 74.6 and 79.4% greater, respectively, than those obtained using AY_3. This difference occurred because AY_1 was obtained directly through a fixed proportion, and there were problems with insufficient consideration of field management measures, farmer willingness and actual production. The yield of winter wheat simulated by the model was given by AY_4; although the effects of cultivation management measures and meteorological factors were considered, the influence of disease, insect pests, lodging and other stresses was not taken into account. Therefore, both of these methods resulted in greater realizable yield gaps. The realizable yield gap obtained using AY_2 as the attainable yield was 66.1% greater than that obtained with AY_3. The maximum yield of wheat at experimental stations (AY_2) considered environmental factors such as soil and climate, it also reflected the actual highest yield of current regional production to a certain degree. However, it is not advisable to simply use the yield of the highest yield plots as the attainable yield. In comparison, the use of AY_3 as the attainable yield comprehensively considered combined factors such as climatic conditions, soil conditions, current winter wheat varieties and farmer cultivation techniques, which could better reflect the attainable output of the research area; AY_3 could thus be used as the attainable yield to analyse the realizable yield gap in the HFR.

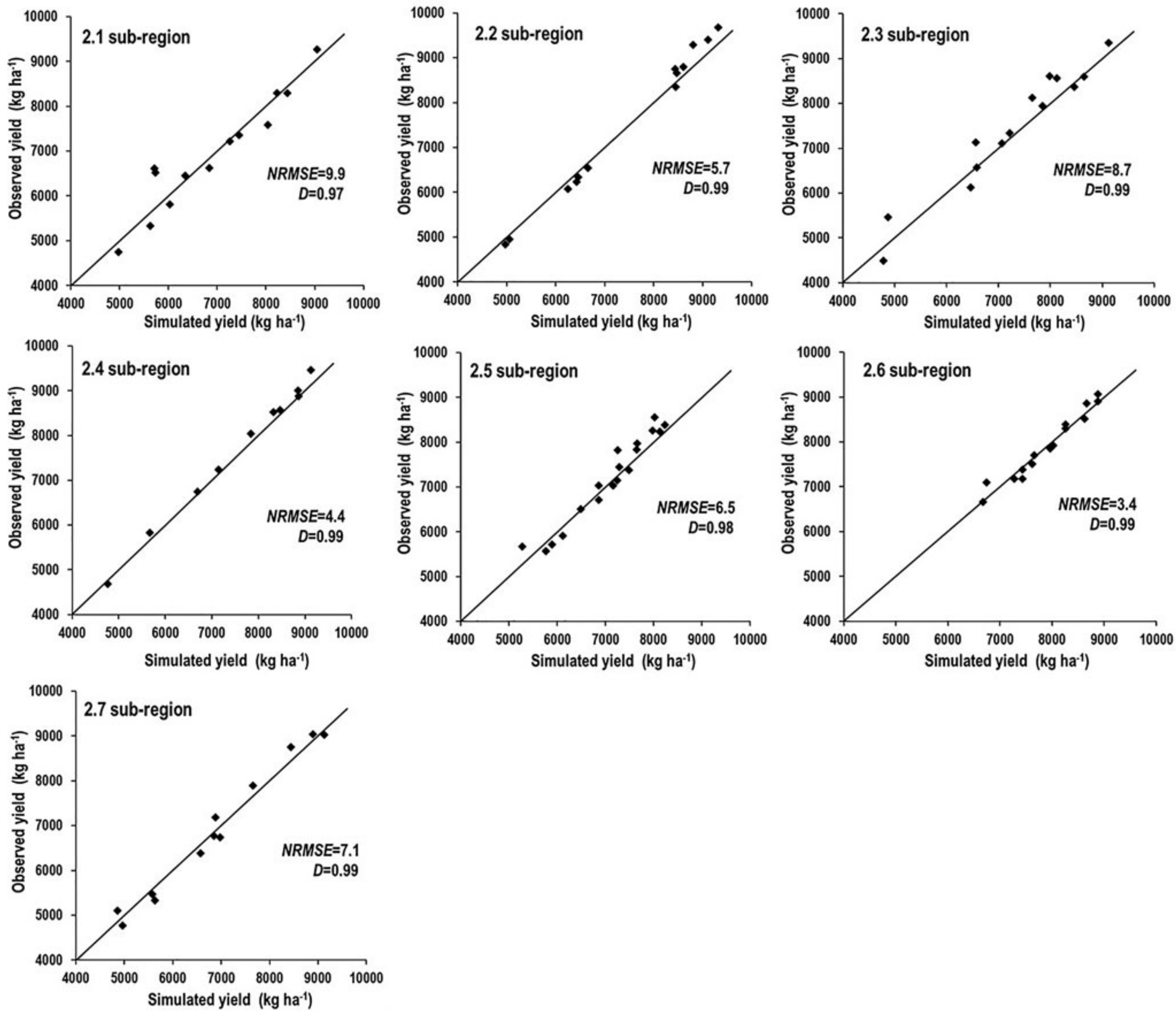

Fig. 3. Model performance for grain yield between observed and simulated data for winter wheat in seven sub-regions of the HFR. See footnote of Table 2 for definitions of codes 2.1–2.7.

When the YG II values of the four research areas were compared, the greatest gap was found in Xihua County (Henan Province), followed by Mengjin (Henan Province), Tengzhou (Shandong Province) and Wuqiao (Hebei Province), with values of 2087, 882, 869 and 827 kg/ha, respectively. The YG III value ranged from 2814–3509 kg/ha with an average value of 3158 kg/ha, which accounted for 0.28 of the potential yield. At the farmers' scale, YG II was 1166 kg/ha, which accounted for 0.14 of the attainable yield, indicating that there is little room for improvement in realizable yield gaps in high-yielding areas of the HFR.

Yield gaps and spatial distribution of winter wheat yields in the Huang-Huai-Hai farming region

Yield gap of winter wheat at the county scale

The potential yield of winter wheat among different counties in the HFR was simulated by the model and the attainable yield was obtained from the formula. The results showed that the potential yield in the HFR ranged from 8649–12 626 kg/ha and the area-weighted average yield was 10 340 kg/ha (Fig. 6(a)), while attainable yield ranged from 6262–9141 kg/ha and the area-weighted average yield was 7486 kg/ha. From a spatial distribution perspective, the potential and attainable yields were high in the east and low in the west (Fig. 6(b)). The potential yield was highest in the Shandong Peninsula and lowest in the south-western region of Henan Province. The actual yield of winter wheat for 386 counties in the HFR ranged from 2838–7585 kg/ha and the area-weighted average yield was 5944 kg/ha. The spatial distribution characteristics showed that lower actual yields were obtained in the north-western part of the region (Fig. 6(c)).

At the county scale, the YG I value in the HFR ranged from 1800–8585 kg/ha and the area-weighted yield gap of winter wheat in the HFR was 4396 kg/ha, which accounted for 0.43 of the potential yield. The distribution of the yield gap in the region presented a trend towards higher values on both sides and lower values in the central part of the region (Fig. 6(d)), which was mainly because the middle regions of the HFR were the main

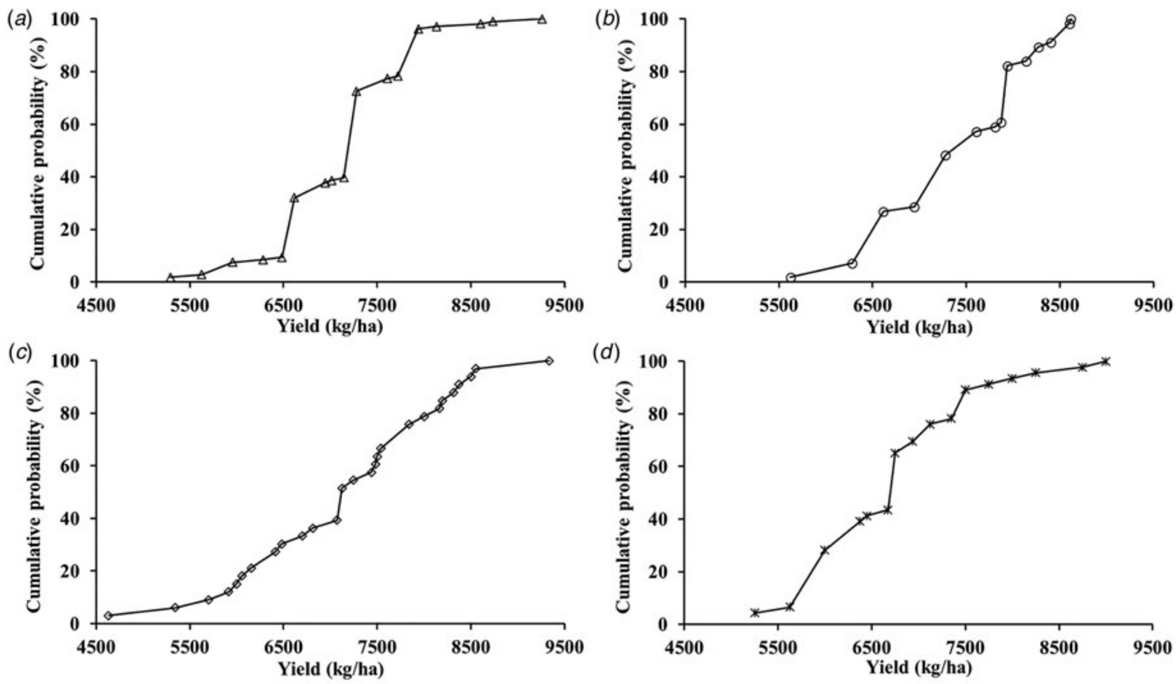

Fig. 4. Cumulative probability distributions of the winter wheat yield of farmers' fields in four research areas: (a) the Hebei Wuqiao site, (b) the Shandong Tengzhou site, (c) the Henan Xihua site and (d) the Henan Mengjin site.

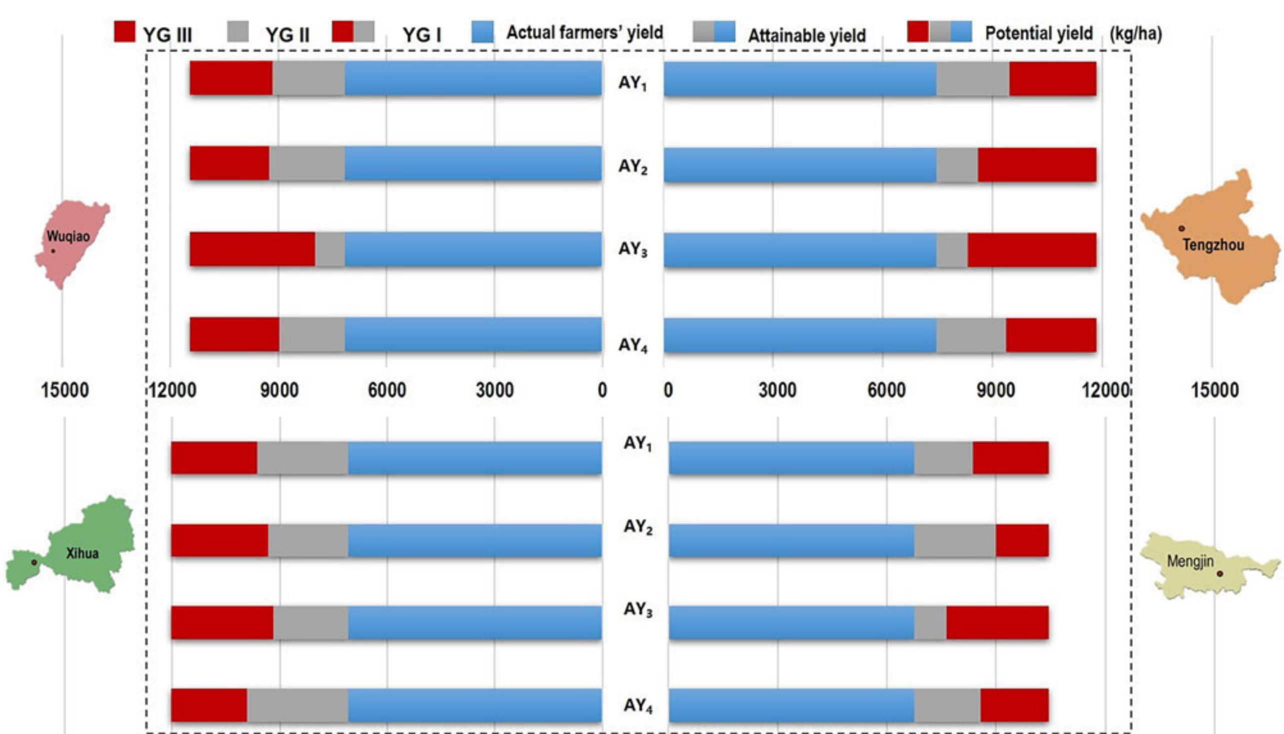

Fig. 5. (Colour online). Comparisons of yield gaps of winter wheat among farmers' fields in four research areas by four methods of calculating attainable yield: attainable yield is 80% of the potential yield (AY_1); attainable yield is the maximum yield at experimental stations (AY_2); attainable yield determines by the formula proposed in this paper (AY_3); attainable yield is obtained from the DSSAT-CERES-Wheat model with the fertilizer-N stress limitation enabled (AY_4); YG I is the yield gap between the potential yield and the actual farmers' yield; YG II is the yield gap between the attainable yield and the farmer's yield; YG III is the yield gap between the potential yield and the attainable yield.

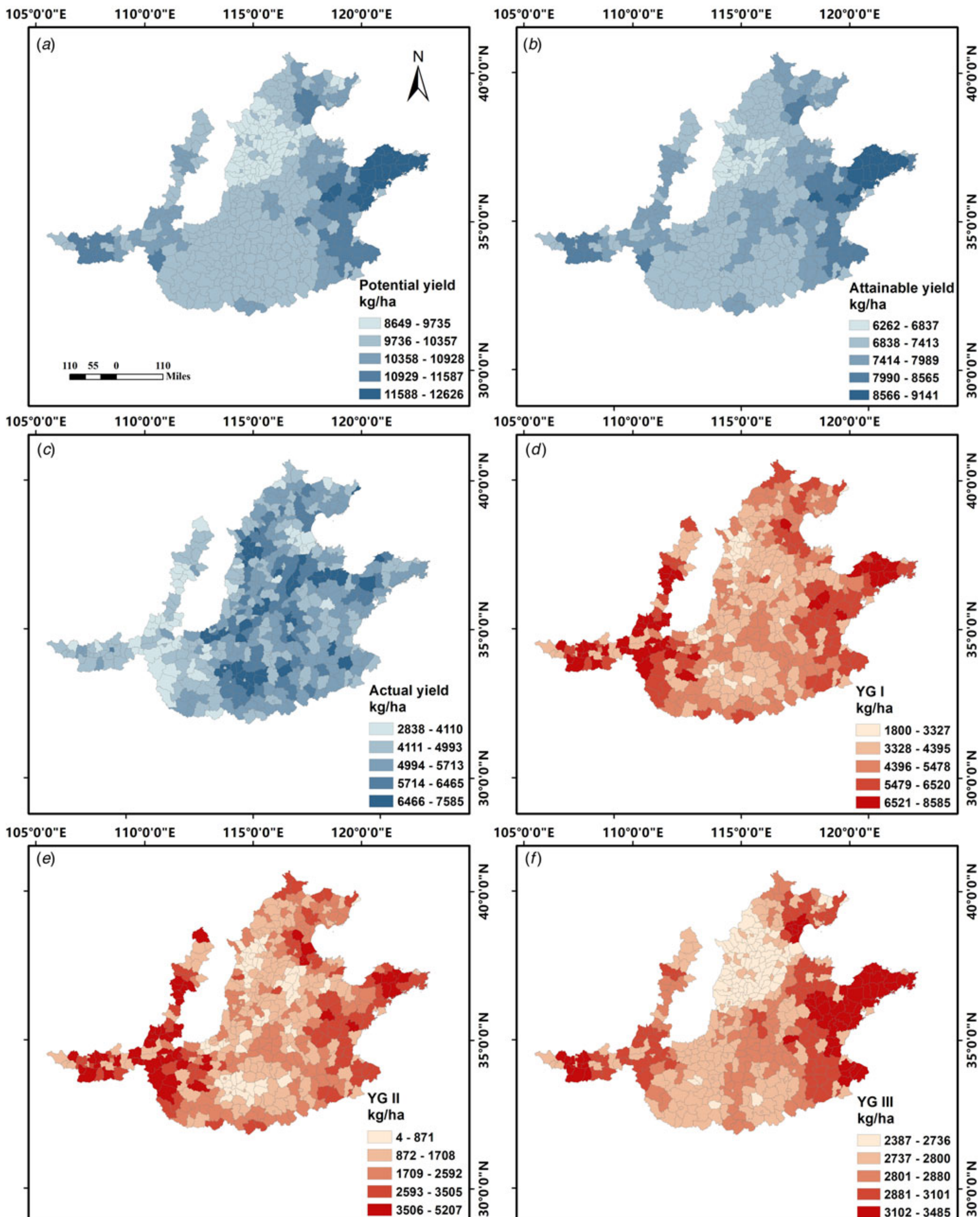

Fig. 6. (Colour online). Spatial distribution of yields and yield gaps of winter wheat at the county level.

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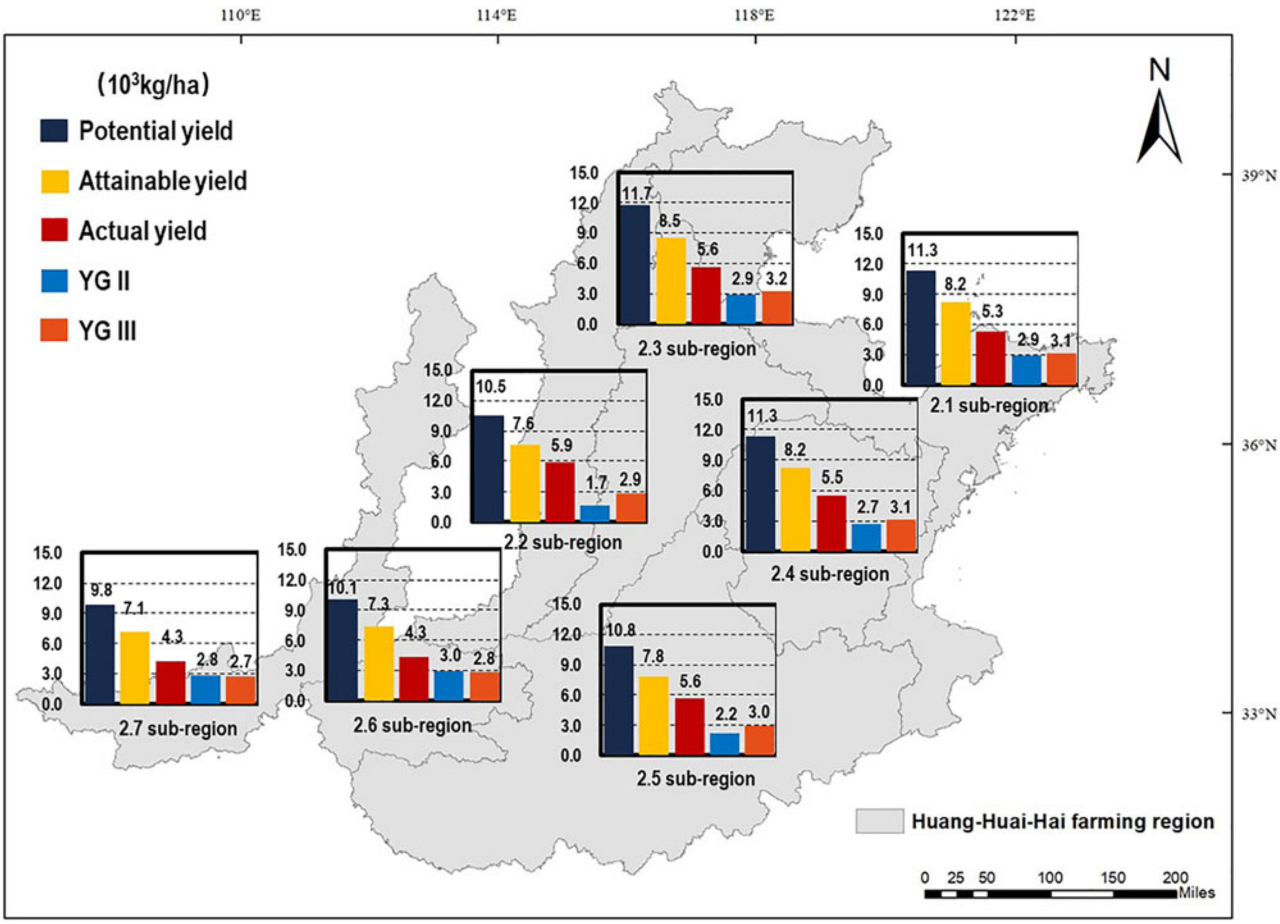

Fig. 7. (Colour online). Yield gaps of winter wheat in seven sub-regions of the HFR: YG III is the yield gap between the potential yield and the attainable yield. See footnote of Table 2 for definitions of codes 2.1–2.7.

and highest-yielding wheat farming areas with advanced cultivation techniques. For the south-western part of Henan and the south-central part of Shaanxi, due to differences in planting traditions, cultivation techniques, climate and soil conditions, the actual yield of winter wheat was lower and the yield gap between potential and actual yield was large. According to the evaluation method used to determine attainable yield in the current study, the YG II values of winter wheat ranged from 4–5207 kg/ha, which accounted for 0.001–0.62 of attainable yield, and the area-weighted average yield gap was 1542 kg/ha. The YG II values were higher on both sides of the region and lower in the central part of the region when analysing the spatial distribution in the HFR (Fig. 6(e)). The YG III value in the HFR ranged from 2387–3485 kg/ha and the area-weighted yield gap of winter wheat in the HFR was 2854 kg/ha (Fig. 6(f)).

Yield gaps of winter wheat in different sub-regions of the Huang-Huai-Hai farming region

Using the crop yield gap evaluation framework proposed above, the results showed that the yield gaps of winter wheat in each sub-region of the HFR were different. The highest potential yield of winter wheat was 11 718 kg/ha in the 2.3 sub-region, while the lowest was 9803 kg/ha in the 2.7 sub-region. The highest and lowest attainable yields of winter wheat were 8484 kg/ha and 7097 kg/ha in the 2.3 sub-region and 2.7 sub-region, respectively. The proportion of attainable yield realized as actual yield ranged from 0.59–0.78 in the sub-regions, and the YG II ranged from 1674–2990 kg/ha. The greatest YG II value was 2990 kg/ha in the 2.6 sub-region, accounting for 0.41 of attainable yield, while the smallest YG II of 1674 kg/ha was seen in the 2.2 sub-region, accounting for 0.22 of the attainable yield. The YG III ranged from 2706 kg/ha in the 2.7 sub-region, accounting for 0.38 of the attainable yield, to 3234 kg/ha in the 2.3 sub-region, accounting for 0.38 of the attainable yield (Fig. 7). For the whole farming region, as it was difficult to narrow the YG III, the key to closing the regional yield gap was in the YG II.

Limiting effects of irrigation conditions on narrowing the yield gap of winter wheat

Irrigation and fertilizer were the main factors limiting winter wheat yield, but excessive fertilizer use in the HFR was serious. In light of the new target of 'zero growth in total nitrogen fertilization in China before 2020', the strategy of increasing production by increasing fertilizer application is no longer sustainable. Therefore, as the most important wheat-producing area with intensive irrigation in China, water management and irrigation conditions are the most important factors limiting increased winter wheat production in the HFR. The effective irrigation area rate, i.e. the ratio of effective irrigation area to the cultivated

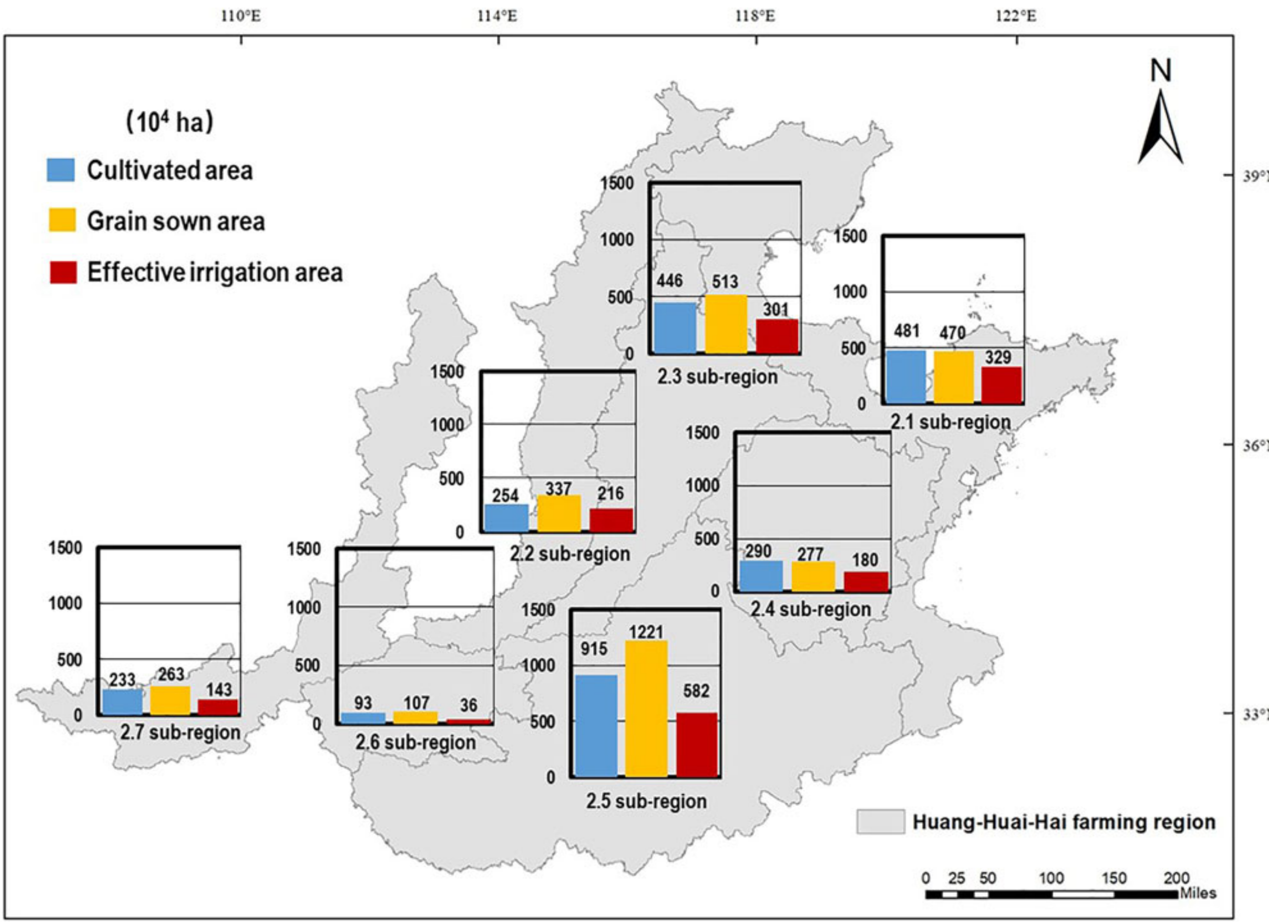

Fig. 8. (Colour online). Cultivated area, grain sown area and effective irrigation area in seven sub-regions of the HFR. See footnote of Table 2 for definitions of codes 2.1–2.7.

area, was used to indicate the level of effective irrigation supply in the region (Fig. 8).

At present, irrigation conditions in the HFR are best in the 2.1 sub-region, where the hydrothermal conditions are also suitable for winter wheat planting; thus, the potential yield of winter wheat in this sub-region is also high. The 2.2 sub-region, with the most plains, abundant water resources, high effective irrigation, more favourable geographical conditions and light and heat resources, plays an important role in ensuring food production in the HFR. The lack of water resources is an important constraint on winter wheat production in the 2.3 sub-region. The potential yield of winter wheat in this sub-region was found to be the highest; however, due to the lack of surface water, deep groundwater level and saline-alkaline soil, drought is the largest threat to winter wheat in this sub-region. The hydrothermal conditions in the 2.4 sub-region were revealed as suitable for multi-crop planting, the water resources are good and irrigation efficiency is also high, which is beneficial for the production of winter wheat. With the largest cultivated areas, good climatic conditions and soil conditions and continuous improvement of agricultural production conditions in recent years, the 2.5 sub-region has great potential for agricultural development. The actual yield was much lower in the 2.6 and 2.7 sub-regions, due to the lower effective irrigation area rates and many hilly areas. Improving irrigation conditions is a feasible way to increase the yield of winter wheat in these sub-regions.

Discussion

Attainable yield

Since the quantitative assessment of the yield gap is a widespread concern (Van Ittersum *et al*., 2013), a series of methods for calculating attainable yield is constantly emerging (Lobell *et al*., 2009; Liu *et al*., 2018; Luan *et al*., 2019). Previous studies have obtained attainable yield directly through models, fixed ratios or field experiments. The current study proposed a method of calculating attainable yield using the actual yield in demonstration plots as a proportion of the potential yield simulated by the model as the baseline, which considered the influence of climate, soil, variety, cultivation technology and farmer willingness on the crop yield in the region. The attainable yield calculation method could also be used in areas with characteristics similar to those of the research area. However, the selection of surveyed areas had a significant impact on the accuracy of this method: it was limited by the number of research sites and the evaluation standard for the yield gap must be optimized by expanding the research area.

Comparison of potential yield

The current study found that potential yield in the HFR ranged from 8649–12 626 kg/ha and the area-weighted average yield was 10 340 kg/ha. As a major wheat-producing area in China, the potential yield of winter wheat in the HFR has attracted

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much attention (Liu *et al.*, 2016; Chen *et al.*, 2017). Liu *et al.* (2016) showed that the potential yield of the North China Plain varied from 7800–11 800 kg/ha. Chen *et al.* (2017) indicated that the mean yield potential ranged from ~5000–8000 kg/ha during the period of 1981–2008 in North China. These values were similar but slightly lower than in the current study. It was found that the potential yield of the proposed by Liu *et al.* (2016) was generated primarily by agronomists in high-yielding or variety-testing experiments. Also, the calculation of potential yield depended on the model used in the current study, ignoring the impact of pests and diseases (Eitzinger *et al.*, 2013), which might lead to higher results. In the past 10 years, technological advances such as improvement of varieties and advanced cultivation management have also led to increases in potential yield (Hertel *et al.*, 2014).

Realizable yield gap of winter wheat in the Huang-Huai-Hai farming region

The yield gap between potential and attainable yields can hardly be narrowed, while the realizable yield gap, defined herein as the yield gap between attainable yield and actual yield, is more likely to be narrowed. It appears that narrowing the yield gap will be more difficult for those counties with high wheat yield. At present, the realizable yield gap of winter wheat in the HFR is clear and it is necessary to adopt measures according to the actual production conditions in the local area. For example, the realizable yield gap of winter wheat in the 2.2 sub-region was revealed to be small, which indicates that the actual yield of winter wheat in this sub-region is higher and close to the attainable yield. That is, the actual yield of winter wheat in this sub-region is hard to increase under current production conditions. Narrowing the yield gap in these areas will have little effect on overall wheat production in the HFR. However, the realizable yield gap of the 2.6 sub-region was found to be relatively large, which indicates that the area still has the potential to increase production and it will be necessary to focus on these areas to increase total grain production in the region. The proportion of medium- and low-yielding fields in the different sub-regions of the HFR ranged from 0.69–0.82; as it will be more difficult to increase the yield of winter wheat in high-yield fields continuously (Liu *et al.*, 2017), an effective way to improve winter wheat yields in the HFR will be to narrow the yield gap through effective irrigation.

Conclusion

A multi-scale yield gap evaluation framework integrating with crop model simulation, participatory appraisal and statistical data analysis was developed. The accuracy of calibration and evaluation of seven varieties in the relevant sub-region was high, indicating that the DSSAT-CERES-Wheat model performed well for simulating wheat yield in the HFR.

The yield limitation index was proposed for determining attainable yield; in the four research areas this was found to be 69.8, 70.3, 76.3 and 73.1%, respectively, which were lower than previous research results.

The winter wheat yield gap in the HFR was analysed at multi-scales. It showed that the attainable yield of winter wheat at the four sites was 8282 kg/ha and the YG II of winter wheat could be narrowed by 13.6%. At the county scale, the area-weighted average YG I in the HFR was 4396 kg/ha, while the area-weighted average YG II was 1542 kg/ha. The YG II in each sub-region ranged from 1674–2990 kg/ha, which accounted for 0.22–0.41 of attainable yield. The YG I and YG II indicated differential potential for narrowing the wheat yield gap, but more attention should be paid to narrowing the YG II, which is a more realistic way to increase actual wheat yield at current status. The quantification of reasonable yield gap can provide valuable and credible information for decision support, and it is also necessary to employ different and precise management practices to narrow the yield gap under the current production conditions.

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Conflict of interest. The authors declare there are no conflicts of interest.

Ethical standards. Not applicable.

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