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Identifying opportunities to close yield gaps in China by use of certificated cultivars to estimate potential productivity

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ABSTRACT

Even though China has increased grain output in the past decade and greatly contributed to reducing global hunger, the country is still confronted with intense food security pressure due to its huge population base and severe loss of farmland. It has become increasingly important to fully exploit yield gaps (the difference between potential and actual yields) of all staple grains and to identify priority areas in order to achieve the UN sustainable development goal of zero hunger by 2030. The objective of this study was to calculate the production and yield gaps for rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), and corn (*Zea mays* L.) across 31 provinces of mainland China, and then to propose sustainable ways to exploit the production and yield gaps in relation to the availability of natural resources and the ecological conditions of the various regions. The yield potential was estimated by assuming that certificated cultivars were adopted in each agricultural ecological zone (AEZ) and that state-of-the-art technologies and best management practices were used. The results suggested that the gross potential productivity of the three staple grains of mainland China in 2016 was 8.86×10^8 tons, with a production gap of 2.99×10^8 tons. Corn exhibited the greatest yield gap. The highest potential productivity was observed in the Northeast Plain and the Huang-Huai-Hai/North China Plain, accounting for 26.35% and 35.91% of the country's total potential productivity, respectively. The greatest yield gaps were also found in these two plains. To narrow yield gaps, farmland infrastructure, especially irrigation facilities, should be improved, and field management should be strengthened for the provinces with the greatest gaps. However, in view of natural resource constraints (e.g., water shortages in Northern China), water-saving measures and techniques have been encouraged throughout mainland China and the planting of high water-consuming crops such as rice has been discouraged and should be reduced and replaced by other crops in the North China Plain and Northwest China. Using presently available cultivars and field management technologies, China still has great potential to increase grain production and improve food security by closing exploitable yield gaps through the use of suitable production methods based on existing natural resource capacity and ecological status.

1. Introduction

Among the 17 United Nations Sustainable Development Goals, zero hunger is ranked as second place (United Nations (UN), 2015). Two of this goal's objectives deal with ending all forms of hunger and malnutrition by 2030. Recent studies suggest that in order to meet the increasing food demands resulting from population growth and diet structure changes (i.e., more meat consumption), global food production must double by 2050 (Godfray et al., 2010; Foley et al., 2011; Tilman et al., 2011; Hatfield and Walthall, 2015; Zhang et al., 2019a, 2019b; Lidwell-Durnin and Lapthorn, 2020; Liu et al., 2021). However, land use and environmental problems, such as land expansion for new construction, declining soil fertility, and water shortages, have greatly undermined the capacity and likelihood of doubling global food production by that date (Vitousek et al., 1997; Foley et al., 2011; Ray et al., 2012; Kong, 2014; Liu et al., 2020, 2021; Zhao et al., 2021; Zhou et al.,

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2021). Additionally, yields of the main grain crops have plateaued and the growth rates have slowed and even stagnated in recent decades (Ray et al., 2012; Grassini et al., 2013; Chen et al., 2014; Tao et al., 2015). This dilemma is more serious for China than for other countries due to its rank as the most populous country in the world (Chen et al., 2017). China has witnessed the loss of large amounts of high-quality farmland to urbanization, industrialization, structural adjustment of agriculture and afforestation (Kong, 2014; Song and Pijanowski, 2014; Li et al., 2014a, 2014b; Liu and Li, 2017; Liu et al., 2018), with 7.53 million hectares farmland lost in the past decade evidenced by the latest data from the third National Land Survey of China in August, 2021. Meanwhile, severe problems such as extensive soil acidification and groundwater overdraft have also appeared due to long-term intensified use of farmland (Guo et al., 2010; Kong et al., 2016; Cui et al., 2018; Zhang et al., 2020). Furthermore, the continuous outbreak of COVID-19 pandemic triggered barriers to international grain export, vulnerabilities of the agri-food supply chain, and transport restrictions, which led to new challenges in global food security, especially in China (Garnett et al., 2020; Falkendal et al., 2021; Fan et al., 2021; Laborde et al., 2021; Liu and Zhou, 2021a). Thus, it is of great significance to investigate where and how to increase grain yields in order to simultaneously meet the growing food demand while mitigating the negative impacts of agricultural production systems.

Identifying yield gaps in grain output has been proposed as an efficient approach to address this dilemma (Mueller et al., 2012; Garnett et al., 2013; Van Ittersum et al., 2013; Cui et al., 2018). Yield gap is usually defined as the difference between theoretical yield potential and actual yield (Van Ittersum et al., 2013; Zhang et al., 2016a). Theoretical yield potential refers to the crop yield without water and nutrient restrictions and without biological stress (Evans, 1993; Van Ittersum and Rabbinge, 1997; Evans and Fischer, 1999; Van Ittersum et al., 2013). Theoretical yield potential for irrigated crops could be a significant benchmark for irrigated systems with adequate water supply, while yield potential for rainfed crops is equivalent to potential yield under water limitation. Actual yield is defined in this study as the mean of actual achieved yields in a certain agricultural ecological zone.

Estimates of yield potential, actual yield, and yield gap have attracted great attention from agronomists, soil scientists, ecologists, and economists (Mueller et al., 2012; Van Ittersum et al., 2013; Fischer, 2015; Zhang et al., 2016b; Schils et al., 2018), and studies have been carried out at various scales, from field to regional (including county/province/state/country) and global (Tilman et al., 2011; Mueller et al., 2012; Van Wart et al., 2013a, 2013b; Zhang et al., 2016c), or for agricultural ecological zones (Van Wart et al., 2013a). In addition, narrowing yield gaps through improving nutrient management, increasing water use efficiency, and implementing better farmland management practices has also been widely reported (Mueller et al., 2012; Zhang et al., 2016b, 2018). Zhang et al. (2016b) suggested an innovative approach for closing yield gaps in smallholder-dominated agriculture in China. They proposed establishing the Science and Technology Backyard technological extension platform on which professionals or college researchers could teach and transfer comprehensive knowledge and techniques such as the use of novel crop varieties, and optimal planting, plowing, fertilization, and irrigation methods to farmers. Additionally, closing yield gaps while simultaneously reducing adverse environmental effects has been extensively reported across the world (Chen et al., 2014; Cui et al., 2018; Foley et al., 2011; Guo et al., 2020; Liu et al., 2021; Liu and Zhou, 2021b; Mueller et al., 2012; Schils et al., 2018; Wang et al., 2018a; Zhang et al., 2013). Thus, quantifying yield potential and yield gaps, and identifying technologies to close yield gaps without causing environmental harm have become topics of great interest. However, the concepts of potential productivity and production gaps need to be further addressed through research and discussion.

In addition to the concepts of yield potential, actual yield, and yield gaps, the more comprehensive concepts of crop potential productivity (P_p, crop yield potential multiplied by planted area), crop actual production (P_a, crop actual yield multiplied by planted area), and crop production gap (P_g, the difference between P_p and P_a) are also crucial for understanding and assessing food security. In particular, identifying where the crop production gaps are located is the first step necessary in order to take specific measures that will close yield gaps and increase production. The second step is to determine how many crop yield gaps and production gaps can be exploited based on availability of natural resources, such as accumulative temperature, rainfall, soil quality, and available water during the growing season. As reported by the FAO in 2018, China was the leading producer of three provided crops, with its actual output of wheat and rice ranking at the first place and corn the second in the world (Food and Agriculture Organization of the United Nations FAO, 2018). Thus, realization of the goal of increased food security with sustainable intensification of the agricultural production system will be attained through an analysis and understanding of both yield gaps and production gaps in relation to the availability of natural resources.

Methods for estimating yield gaps include field experiments, yield contests, household surveys, and crop growth model simulations (Lobell et al., 2009; Zhang et al., 2016c), and each method has its own advantages and disadvantages. Field experiments need to be conducted over many years to acquire robust yield potential and yield gaps (Cassman et al., 2003). Yield contests may have difficulty in obtaining consistent results. Household survey methods may lead to subjective and even biased results, especially when interviewed farmers are unable to clearly understand scientific jargon. Crop growth models are believed to be the most reliable estimation method because they can account for the complex interactions of genetics, environment, and management (Van Ittersum et al., 2013; Zhang et al., 2018). However, obtaining high quality datasets of weather, soil, crop, and field management at regional scales in order to run crop models is usually time-consuming and costly, and many times such data are not even available, and can therefore limit model effectiveness and applicability (Ramirez-Villegas and Challinor, 2012). Therefore, a method for upscaling specific local observations has been recommended to estimate yield gaps and production gaps at regional levels (Van Wart et al., 2013a).

As reported, homogeneous geographic units determined by climate and soils are often used to expand the spatial scale for assessing regional yield potential and yield gaps (Wood and Pardey, 1998; Padbury et al., 2002; Zhang et al., 2008). An agricultural ecological zone (AEZ) is a homogeneous geographic unit having similar climate, landform, and soil conditions (Food and Agricultural Organization FAO, 1978; Deng et al., 2006; Zhang et al., 2008; Van Wart et al., 2013a). Such zones have been widely used to estimate the stability and trends of yields, to analyze the main factors restricting crop growth, to assess regional-scale yield potential and yield gaps, and to identity the adapted areas for new production technologies (Caldiz et al., 2002; Deng et al., 2006; Williams et al., 2008; Araya et al., 2010; Van Wart et al., 2013b). The AEZ method has also been successfully used to estimate grain potential productivity determined by yield potential and production area through upscaling yield potential of certificated cultivars (Zhang et al., 2008). In addition, cultivar certification screening through comparative variety trials helps to identify the most suitable variety for a target region and can be used to estimate yield potential (Fischer, 2015). Compared with the theoretical yield potential estimated by crop growth models, yield potential determined by certificated cultivars represents not only the state-of-the-art highest yield, but also the most likely achieved yield potential through best management practices over a target region (Zhang et al., 2008; Fischer, 2015; Senapati and Semenov, 2020). Hence, the combined use of AEZs and certificated cultivars can be a practical approach for evaluating yield potential and potential productivity (when crop area is available), and for identifying and quantifying corresponding yield gaps and production gaps in a target region.

In summary, it is important to scientifically calculate achievable potential grain productivity at the present technology level, and to analyze the opportunity for increasing grain production. Doing so will provide the basis for production practices and decisions that will close yield gaps and production gaps. The scientifically reliable approach of combining AEZ and yields of certificated cultivars will enhance the agronomic application and impact of yield gap assessment. Initially, we hope that approaches and case studies regarding this particular problem will lead to better decisions to improve food production and security, and that the food supply can be produced in specific places and with appropriate agronomy to protect natural resources and environmental quality. Hence, the objectives of this study were to: (1) establish a method combining AEZs and yields of certificated cultivars to assess the achievable yield potential and crop potential productivity at the present agricultural technology level for the three main staple grain crops (rice, wheat, and corn) across 31 provinces/autonomous regions/municipalities (hereafter referred to as provinces) of mainland China; (2) identify the spatial distribution characteristics of potential productivity, production gap, yield potential, and yield gap for the three staple grain crops in mainland China in 2016; and (3) suggest possible approaches to close production gaps and yield gaps for those provinces by simultaneously considering their natural resources and environmental sustainability.

2. Materials and methodologies

2.1. Definitions of yield potential, actual yield, and yield gaps

Yield potential (Y_p'), is defined as the maximum possible output achieved when crop growth is only determined by natural factors such as atmospheric CO_2, solar radiation, and temperature but without water and soil nutrient restrictions or biological stress (Fig. 1, Van Ittersum et al., 2013). Water-limited yield (Y_w) is similar to Y_p' except that crop growth is also limited by water supply. Actual yield (Y_a) is defined as the actually achieved output from a field by farmers, which may be less than Y_p' because of lack of agricultural infrastructure and facilities, shortage of labor and material inputs, or improper management (Fig. 1a).

Because Y_p' is only a theoretical reference value, many studies have used 80% of Y_p' as the exploitable potential yield to further estimate the achievable yield gap (Cassman et al., 2003; Lobell, 2009; Chen et al., 2017; Schils et al., 2018). As we have indicated above, the potential yield achieved by a certificated cultivar through comparative variety trials represents the most likely achievable potential yield under the current state of the art production system, and would be a more appropriate proxy of exploitable yield potential (Fischer, 2015). Thus, this study used the yield of certificated grain cultivars as exploitable yield potential (Y_p) to estimate exploitable yield gaps (Y_g) (Fig. 1b),

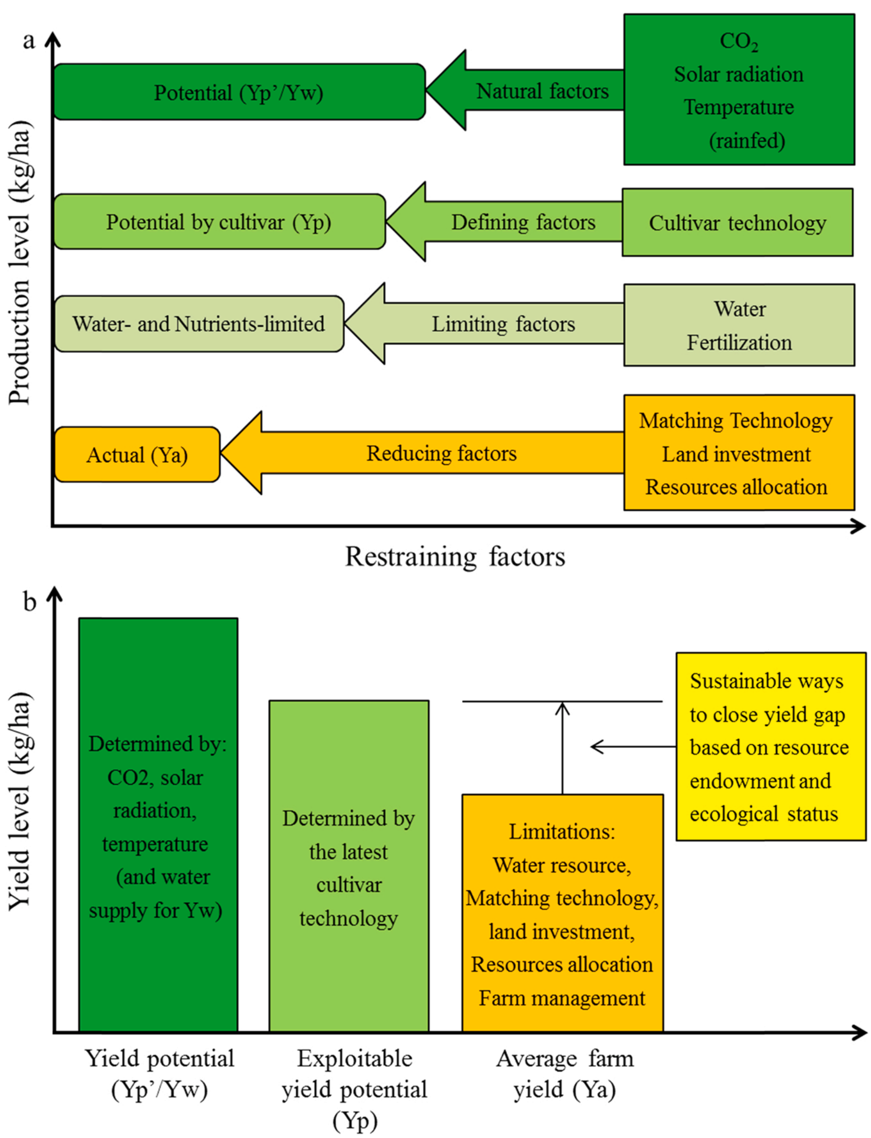

Fig. 1. Different productivity levels constrained by natural, defining, limiting, and reducing factors (panel a). Theoretical yield potential (Yp') of irrigated crops without water and nutrient constraints is determined by local climatic conditions. Water-limited yield (Yw) represents the maximum yield of rainfed crops (Van Ittersum and Rabbinge, 1997). Exploitable yield potential (Yp) represents the most likely achievable potential yield when applying certificated cultivars with best farmland management practices; exploitable yield gap represents the difference between exploitable potential yield and actual yield (panel b). Fig. 1 is modified from Lobell et al. (2009) and Van Ittersum et al. (2013).

which was the difference between Y_p and Y_a. Furthermore, when determining and recommending measures to narrow yield gaps, the spatial heterogeneity of local naturally available resources and environmental conditions should also be taken into account (Fig. 1b).

2.2. Methodologies

2.2.1. Identification of basic assessment unit

According to the national file of "Regulation on classification and gradation on agricultural land quality (GB/T 28407–2012)" issued by the Standardization Administration of China, mainland China is divided into 41 AEZs, each of which is a relatively uniform area with similar climate, geomorphology, natural resources, and socio-economic conditions, and with the same or similar cropping systems (Standardization Administration of China SAC, 2012). Given that the suitable AEZs for all certificated cultivars are usually specified, this AEZ classification scheme was adopted in this study. In order to estimate potential yields and yield gaps at the provincial level, the overlapping areas of AEZs and provinces were used as the basic assessment units in this study (Fig. 2).

2.2.2. Estimation of potential crop yield and productivity at provincial level

The potential crop yield in each AEZ was calculated as:

$$Y_{pi} = \frac{\sum_{k=1}^{m} Y_{pik}}{m} \tag{1}$$

where $Y_{pi}$is the average crop yield potential determined by certificated cultivars in AEZ i, kg ha^{-1}; m is the number of certificated cultivars in AEZ i; $Y_{pik}$is the reported yield of certificated cultivar k, kg ha^{-1}. The average crop yield potential of wheat ($Y_{pi}{}^{w}$), corn ($Y_{pi}{}^{c}$), and rice ($Y_{pi}{}^{r}$) in AEZ i was calculated based on Eq. (1).

The crop yield potential in each province was calculated as:

$$Y_{pj}{}^{*} = \frac{\sum_{i=1}^{l} Y_{pi} \cdot A_i}{\sum_{i=1}^{l} A_i} \tag{2}$$

where $Y_{pj}{}^{*}$is the average crop yield potential determined by the yields of certificated cultivars in province j, kg ha^{-1}; l is the number of AEZs in province j; A_i is the planted crop acreage in AEZ i in province j, ha. The average crop yield potential of wheat ($Y_{pj}{}^{w}$), corn ($Y_{pj}{}^{c}$), and rice ($Y_{pj}{}^{r}$) in province j was calculated based on Eq. (2), and their summation was the grain yield potential (Y_{pj}).

The crop potential productivity in each province was calculated as:

$$P_{pj} = Y_{pj}{}^{w} \times S_j{}^{w} + Y_{pj}{}^{c} \times S_j{}^{c} + Y_{pj}{}^{r} \times S_j{}^{r} \tag{3}$$

where P_{pj} is the total potential grain productivity determined by certificated cultivars in province j in 2016, kg; $S_j{}^{w}$, $S_j{}^{c}$, and $S_j{}^{r}$ are the planted acreages of wheat, corn, and rice of province j in 2016, respectively.

2.2.3. Calculation of actual grain yield and productivity at provincial level

The total actual grain production in each province was calculated as:

$$P_{aj} = P_{aj}{}^{w} + P_{aj}{}^{c} + P_{aj}{}^{r} \tag{4}$$

where P_{aj} is the total actual grain production in province j in 2016, kg; $P_{aj}{}^{w}$, $P_{aj}{}^{c}$, and $P_{aj}{}^{r}$ are the total actual production of wheat, corn, and rice for province j in 2016, respectively.

The average actual grain yield in each province was calculated as:

$$Y_{aj} = \frac{P_{aj}}{S_j{}^{w} + S_j{}^{c} + S_j{}^{r}} \tag{5}$$

where $Y_{aj}$is the average actual grain yield in province j in 2016, kg ha^{-1}. Accordingly, $Y_{aj}{}^{w}$, $Y_{aj}{}^{c}$, and $Y_{aj}{}^{r}$ are the average actual crop yields of wheat, corn, and rice for province j in 2016, respectively.

2.2.4. Calculation of yield gaps and total production gaps

The gap between potential and actual grain yield in province j was calculated as:

$$Y_{gj} = Y_{pj} - Y_{aj} \tag{6}$$

The gap between potential grain productivity and total actual grain production in province j was calculated as:

$$P_{gj} = P_{pj} - P_{aj} \tag{7}$$

2.2.5. Exploitation ratio of potential grain productivity

Exploitation ratio (E) of grain yield potential reflects the exploitation degree of potential grain productivity, which was defined as the actual yield divided by the potential yield. The exploitation ratio in province j (E_j) was calculated as:

$$E_j = \frac{Y_{aj}}{Y_{pj}} \tag{8}$$

2.2.6. Methods to measure the potential to close production gaps

In this study, precipitation and soil organic matter were considered to be natural resources affecting the agricultural system, while agricultural water consumption, agricultural plastic film consumption, chemical fertilizer consumption, and agricultural pesticide consumption were classified as input elements. In order to measure the potential to close production gaps, linear regression models were used to identify the relationships between production gaps and natural resources or input elements. Negative relationships regarding precipitation and soil organic matter (the two natural resource parameters) would indicate that production gaps decreased as precipitation or soil organic matter increased. Positive relationships regarding the four input elements would indicate that production gaps increased as use of an input element increased.

2.3. Data sources

Certificated crop cultivars used by companies, scientific research institutions, or universities in experiments and for research were confirmed and approved through the corresponding national or provincial institution. A total of 117 rice cultivars, 315 corn cultivars, and 161 wheat cultivars certificated in 2013–2016 by national and provincial governments were collected from the seed business network (Seed Business Network (SBN), 2017), the first seed network (First Seed Network (FSN), 2017), and the China Rice Data Center (CRC) (2017). The reported information included cultivar name, biological characteristics, productivity, suitable areas, management requirements, breeding institutions, yield potential, etc. The descriptive statistics on plant height, ears per hectare, number of rows, kernels per ear, kernels per row, 1000-kernel weight, and growing season days for rice, wheat, and corn are provided in Table 1. Thus, cultivars with a given high yield potential for each AEZ were obtained and averaged to estimate potential yield in that AEZ. The planted acreages of rice, wheat and corn, and the above four input elements in 2016–2018 were obtained from the China Statistical Yearbook and Statistical Yearbook for each province in 2017–2019 (National Bureau of Statistics of China NBS, 2017). Then the average acreage during 2016–2018 was used to estimate the potential productivity. The descriptive statistics on planted area for rice, wheat, and corn are shown in Table 2. Because the AEZ did not exactly match county boundaries and usually included several complete counties, the planted crop area of each AEZ was the sum of the crop area in corresponding counties. The soil organic matter in 2010 in each province was taken from Hu et al. (2018). The annual precipitation was from China Water Resource Bulletin (China Water Resource Bulletin (CWRB), 2016).

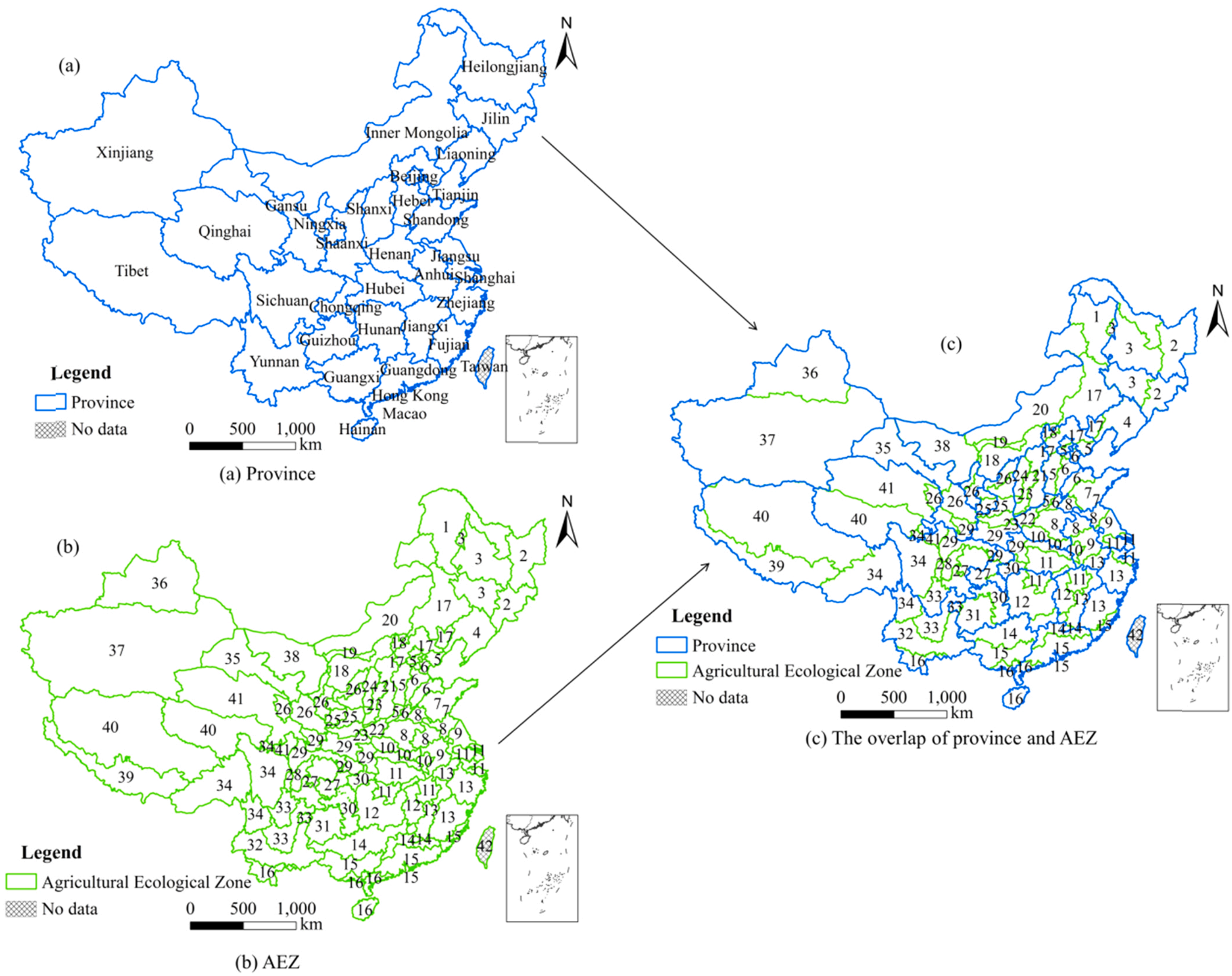

Fig. 2. The overlapping areas of provinces and agricultural ecological zones (AEZ) of China. Panel a shows the provincial administrative divisions; Panel b shows the 41 AEZs from the national file of "Regulation on classification and gradation on agricultural land quality (GB/T 28407–2012)" issued by the Standardization Administration of China (SAC, 2012); Panel c shows the overlapping areas of provinces and AEZs.

Table 1
Descriptive statistics for crop growth of rice, wheat, and corn in mainland China.

Crop	Characteristics										Experimental years	Certificated years
	Plant height (cm)		Ears per ha for rice and wheat (10^3), number of rows for corn (rows)		Kernel per ear for rice and wheat, kernels per row for corn		1000-kernel weight (g)		Growth season (days)			
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation		
Rice	110	13	2769	1023	167	44	27	2	142	15	2011–2015	2012–2016
Wheat	85	8	5337	1368	37	9	43	4	196	52	2011–2015	2015–2016
Corn	268	33	16	6	36	3	342	40	111	18	2011–2015	2013–2017

Table 2
Descriptive statistics for planted area of rice, wheat, and corn in mainland China.

Crop	**Year** (10^3 ha)			**Mean** (10^3 ha)	**Standard deviation** (10^3 ha)
	2016	**2017**	**2018**		
Rice	30178	30747	30190	30372	325
Wheat	24187	24508	24266	24320	167
Corn	36768	42399	42130	40432	3176

3. Results

3.1. Total potential grain productivity, actual production, and production gap for mainland China in 2016

The calculation results showed that the total P_p of mainland China in

2016 was 8.86×10^8 tons[1] that was comprised of 2.64×10^8 tons of rice, 1.82×10^8 tons of wheat, and 4.41×10^8 tons of corn (Fig. 3a). In contrast, the total P_a was 5.87×10^8 tons that was comprised of 2.11×10^8 tons of rice, 1.32×10^8 tons of wheat, and 2.45×10^8 tons of corn. Consequently, the total P_g was 2.99×10^8 tons, equivalent to approximately 50.94% of the P_a. Thus, China's grain production still has great potential for growth if state-of-the-art grain varieties and best management practices can be applied. Furthermore, the P_g of corn was the largest of the three crops (1.96×10^8 tons), accounting for 65.55% of the total P_g, indicating that corn output had the greatest potential for growth among the three main staple grains in China. The P_g of wheat and rice were relatively smaller, with production gaps of 0.50×10^8 and 0.53×10^8 tons, accounting for 16.72% and 17.73% of the total P_g, respectively (Fig. 3a).

When averaged across all 31 provinces, the average yield potentials of rice, wheat, and corn were 8686, 7477, and 10902 kg ha^{-1}, respectively. The corresponding actual yields were 6935, 5408, and 6066 kg ha^{-1}, respectively (Fig. 3b). Corn had the largest yield gap of 4836 kg ha^{-1}, indicating that corn had the greatest potential for increasing yield. In contrast, the opportunity for yield increases of rice and wheat was relatively smaller, with yield gaps of 1751 and 2069 kg ha^{-1}, respectively.

3.2. Inter-provincial differences in potential productivity, actual production, and production gap in 2016

3.2.1. Inter-provincial differences in potential productivity

When the production values of the three crops were summed for each province, the top three provinces with the highest P_p were Heilongjiang, Henan and Shandong, with potential productivity of 9.18×10^7, 8.85×10^7, and 7.34×10^7 tons, respectively (Fig. 4a). The top eight provinces together contributed 58.44% of mainland China's total P_p. In contrast, the three provinces with the least P_p were Qinghai, Beijing, and Tibet, with potential productivity of 9.19×10^5, 6.04×10^5, and 2.99×10^5 tons, respectively. Furthermore, the ten provinces with the least P_p together only contributed 4.23% of the total P_p.

The highest P_p values were mainly found in the Northeast Plain (including Heilongjiang, Liaoning, Jilin, and part of Inner Mongolia) and the Huang-Huai-Hai/North China Plain (hereafter referred to as the North China Plain, including Henan, Shandong, Hebei, Anhui, and Jiangsu), with potential productivity of 2.34×10^8 and 3.18×10^8 tons, accounting for 26.35% and 35.91% of mainland China's total P_p, respectively. In contrast, Northwest China (including Shaanxi, Gansu, Ningxia, Qinghai, and Xinjiang) and Southeast China (including Guangdong, Zhejiang, Fujian, Hainan, and Shanghai) had relatively smaller P_p, with potential productivity of 6.53×10^7 and 2.97×10^7 tons, accounting for 7.37% and 3.34% of the total P_p, respectively.

Results for specific crops showed high P_p of rice was mainly found in eight provinces (Hunan, Heilongjiang, Jiangxi, Jiangsu, Anhui, Hubei, Sichuan, and Guangxi), amounting to 1.91×10^8 tons (72.54% of mainland China's total rice P_p). Similarly, high P_p of corn was also mainly found in eight provinces of northern China (Heilongjiang, Jilin, Inner Mongolia, Shandong, Hebei, Henan, Liaoning, and Shanxi), amounting to 3.17×10^8 tons (71.98% of the total corn P_p). However, the P_p of wheat was more concentrated, as the five provinces of the North China Plain contributed a total P_p of 1.36×10^8 tons, equivalent to 74.56% of mainland China's total wheat P_p.

3.2.2. Inter-provincial differences in actual production

The three provinces with the highest P_a were the same (Heilongjiang, Henan, and Shandong) as found for P_p, with actual production of 6.23×10^7, 6.19×10^7, and 4.97×10^7 tons (10.60%, 10.54%, and 8.47% of mainland China's total P_a), respectively (Fig. 4b). In contrast, the total P_a of the ten lowest producing provinces was only 2.65×10^7 tons (4.51% of total P_a).

Similar to what was observed for P_p, high P_a was also mainly found in the Northeast Plain and the North China Plain, with actual production of 1.47×10^8 and 2.17×10^8 tons (24.95% and 36.97% of mainland China's total P_a), respectively. Meanwhile, the P_a values for the northwest and the southeast regions were still the smallest, with actual production of 3.76×10^7 and 2.35×10^7 tons (only 6.40% and 4.01% of the total P_a), respectively.

Results for specific crops showed that the spatial distribution of P_a was generally similar to that of P_p. The same eight provinces and Guangdong together produced 77.48% of mainland China's total rice P_a. And the same eight provinces in northern China and Sichuan together produced 77.55% of the total corn P_a. Likewise, five provinces of the North China Plain together produced 78.09% of the total wheat P_a.

3.2.3. Inter-provincial differences in production gap

The ten provinces with the highest P_g were Heilongjiang, Henan, Shandong, Hebei, Jilin, Inner Mongolia, Anhui, Yunnan, Liaoning, and Shanxi, and together these ten provinces comprised 68.06% of mainland China's total P_g (Fig. 4c). Interestingly, except for Yunnan, the other nine provinces were located in northern China. Furthermore, the P_g was mainly found in the North China Plain and the Northeast Plain, with production gaps of 1.01×10^8 and 8.70×10^7 tons (comprising 33.83% and 29.11% of the total P_g), respectively.

High corn P_g was mainly found in the Northeast Plain and the North China Plain, with production gaps of 7.56×10^7 and 5.59×10^7 tons (38.65% and 28.58% of mainland China's total corn P_g), respectively. A more concentrated spatial distribution was found for the wheat production gap, as the North China Plain alone comprised 65.32% of the total wheat P_g. In contrast, the distribution of high rice P_g was relatively dispersed, scattered across the Middle and Lower Reaches of the Yangtze River Plain (hereafter referred to as the Yangtze Plain; Hunan and Jiangxi), North China Plain (Anhui and Jiangsu); and Northeast Plain (Heilongjiang).

3.3. Yield gaps and exploitation ratio of potential productivity for rice, wheat, and corn in mainland China

3.3.1. Yield potential and actual yield at provincial level

The highest yield potential for the three grain crops was observed for corn, followed by rice and wheat (Fig. 5). In contrast, the highest actual yield was observed for rice, followed by corn and wheat. Actual corn yields ranged from 4257 to 7689 kg ha^{-1}, and the corn yield potential varied from 7980 to 14,223 kg ha^{-1}. The actual rice yields ranged from 5154 to 8922 kg ha^{-1}, and the rice yield potential ranged from 6737 to 11,130 kg ha^{-1} (Fig. 5a). The actual wheat yields ranged from 513 to 6368 kg ha^{-1}, while the wheat yield potential ranged from 4045 to 8408 kg ha^{-1} (Fig. 5b).

Across 31 provinces in mainland China, there were 13 provinces with the actual wheat yield higher than the national average value, accounting for 41.94% of the number of provinces (Fig. 5b). However, there were 14 provinces whose wheat yield potential exceeded the national average value, accounting for 45.16%. The actual corn yield in 18 provinces was higher than the national average value, accounting for 58.06% (Fig. 5c). However, the corn yield potential in 16 provinces exceeded the national average value, accounting for 51.61%. Thus, the yield potential of wheat and corn in each province was generally higher, while the corresponding actual yield was generally lower (Fig. 5). However, across 31 provinces in mainland China, the actual rice yield in 17 provinces reached the national average level, which was similar to the number of provinces (20) that reached the rice yield potential, accounting for 54.84% and 64.52%, respectively.

Interestingly, Henan, Hebei, and Shandong were the top four provinces with the highest yield potential and the highest actual yields of wheat. Ningxia was the major rice producing province that with the

[1] Metric ton.

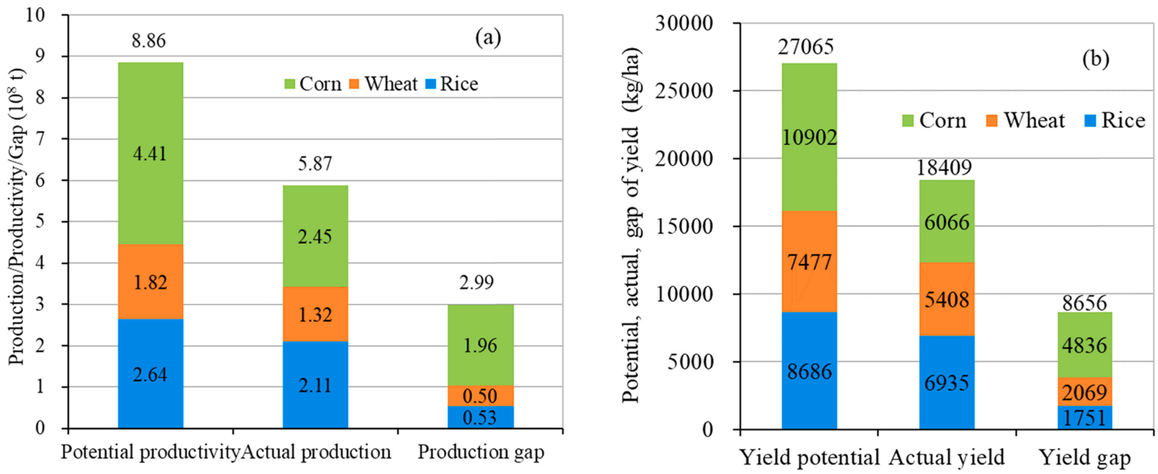

Fig. 3. Total potential grain productivity (Pp), total actual production (Pa), and production gap (Pg) (panel a); and yield potential (Yp), actual yield (Ya), and yield gap (Yg) (panel b) for mainland China in 2016.

highest yield potential, and Xinjiang was the major rice producing province that with the highest actual yield. Tianjin was the major corn producing province and had the highest yield potential, and Xinjiang was the major corn producing province that had the highest actual yield.

3.3.2. Yield gaps at provincial level

Considering all three crops across the 31 provinces, corn Y_g was the largest, ranging from 2449 to 8486 kg ha^{-1}, while Y_g values for rice and wheat were relatively smaller, with ranges of 114–4404 and 388–4750 kg ha^{-1}, respectively (Fig. 5).

The provinces with the largest corn Y_g were Tianjin, Zhejiang, Jiangxi, Gansu, and Hunan, ranging from 6920 to 8486 kg ha^{-1} (Fig. 5), which was mainly due to their relatively higher Y_p and smaller Y_a. Despite the large corn P_g observed at Hebei and Inner Mongolia, only moderate corn Y_g values were observed for those two provinces (5667 and 5449 kg ha^{-1}, respectively), because of the relatively greater Y_a values of 5633 and 6878 kg ha^{-1}, respectively. The smallest corn Y_g values were observed for Jiangsu, Guangdong, Guangxi, Sichuan, and Chongqing, ranging from 2449 to 3490 kg ha^{-1}, a result of relatively lower corn Y_p and higher corn Y_a.

Beijing, Yunnan, Tibet, and Hebei had the highest rice Y_g, with values of 3666, 4404, 4159, and 3796 kg ha^{-1} (Fig. 5), respectively, far exceeding the average for all of mainland China (1925 kg ha^{-1}). All four provinces had relatively higher Y_p (ranging from 9516 to 10505 kg ha^{-1}). Of the seven provinces with the highest rice P_g values, only Yunnan had a high Y_g, while the remaining six provinces (Heilongjiang, Hunan, Jiangxi, Anhui, Jiangsu, and Guangxi) had relatively low Y_g (ranging from 1835 to 2729 kg ha^{-1}). Even though Jiangsu had a high rice Y_p (10,561 kg ha^{-1}), the Y_g for this province was small due to a high rice Y_a (8569 kg ha^{-1}). In contrast, the smaller rice Y_g in Jiangxi, Hunan, Anhui, and Guangxi was caused by relatively smaller rice Y_p.

Jiangxi, Fujian, and Jilin had the highest wheat Y_g, with yield gaps of 4750, 4447, and 4304 kg ha^{-1}, respectively (Fig. 5), followed by Inner Mongolia and Hunan. In the seven provinces with the highest wheat P_g, Shandong had a Y_g slightly higher than the mean for all of mainland China (2142 kg ha^{-1}), while Y_g values for Jiangsu, Anhui, Hebei, and Henan were lower than the average. Interestingly, as we mentioned previously, the Y_p values for wheat in the five provinces in the North China Plain were among the highest, but their Y_g values were generally moderate or even lower than the mean of all 31 provinces. This result may be due to their relatively high Y_a. In fact, the Y_a values for wheat in the five provinces of the North China Plain were generally much higher than the actual wheat yields in other regions.

3.3.3. Exploitation ratio of potential productivity at provincial level

The mean exploitation ratio (E) of potential productivity of rice was higher than that of wheat and corn (averaged across 31 provinces, dotted lines in Fig. 6, with values of 0.76 (rice), 0.62 (wheat), and 0.52 (corn)). This result indicated that corn had the greatest potential for future yield increases, with wheat having moderate potential and rice having the least potential for future yield increases. This result is consistent with the results reported in Sections 3.1 and 3.3.2. Furthermore, the standard deviations of E for rice, wheat, and corn were 0.17, 0.22, and 0.13, respectively, indicating that E values for the 31 provinces varied most for wheat and least for corn.

Hubei, Liaoning, Sichuan, and Tianjin had the largest rice E (values greater than 0.90, well above the mean of 0.76) (Fig. 6). Jiangxi, Guangxi, Ningxia, Guizhou, Heilongjiang, Hunan, Zhejiang, and Inner Mongolia all had rice E values close to the mean, with values ranging from 0.74 to 0.79. The smallest rice E values were found in Yunnan, Tibet, and Beijing. In contrast, Tibet and Beijing were the only two provinces with wheat E above 0.90, followed by Liaoning, Heilongjiang, Shanghai, and Chongqing, both of whom had E greater than 0.80. Although Inner Mongolia had a relatively high wheat P_g, its E was relatively small. Compared with rice and wheat, the highest values of corn exploitation ratio were much smaller, with the E values for the top three provinces (Chongqing, Xinjiang, and Beijing) being 0.70, 0.67, and 0.65, respectively. In the provinces with high P_g, Shandong, Heilongjiang, and Jilin had relatively higher corn E, with values of 0.63, 0.62, and 0.58, respectively. In contrast, in spite of high production gaps, Hebei, Yunnan, Shanxi, Gansu, and Shaanxi had relatively small E values, ranging from 0.43 to 0.49.

3.4. The relationship of production gaps and natural resources and input elements

The regression results showed a relatively strong negative linear relationship between production gaps in 2016 and annual precipitation in 2016 (slope=−0.5331, P = 0.062, Fig. 7a), and a relatively weak and non-significant negative relationship between production gaps in 2016 and soil organic matter content in 2010 (slope=−11.673, P = 0.616, Fig. 7b). Because production gaps decreased with increasing precipitation, investments in building water-saving irrigation facilities could close the production gap. However, the non-significant relationship that we found between soil organic matter and production gaps was in contrast to other studies that have indicated that increasing soil organic matter was an effective approach to close production gaps in China (see references in Table 3).

A non-significant positive relationship was observed between

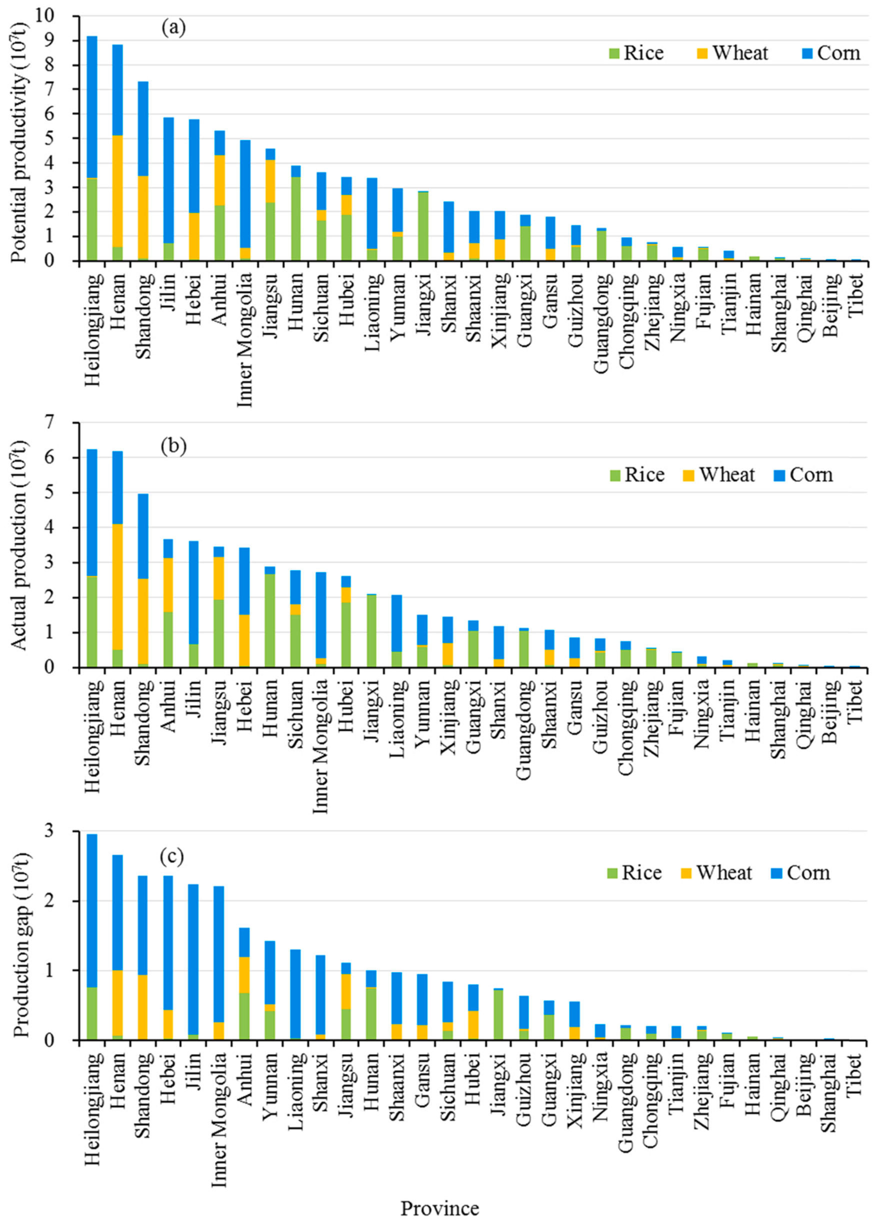

Fig. 4. Potential productivity (a), actual production (b), and production gap (c) at provincial level for mainland China in 2016.

production gaps and agricultural water consumption ($P = 0.083$, Fig. 7c). Significant positive linear relationships were found between production gaps and chemical fertilizer consumption, agricultural pesticide consumption, and agricultural plastic film consumption recorded over all of 2016 ($P < 0.01$. Fig. 7d, e, f). We had expected these relationships to be negative, with increasing consumption and use of these agricultural products decreasing the production gap. However, since the opposite relationship was observed, it is possible that the wide overuse of these input elements actually did some environmental harm resulting in increased production gaps for these three major agricultural crops.

4. Discussion

4.1. Yield potential of rice, wheat, and corn in mainland China

The current study reported a nation-wide mean rice Y_p of 8864 kg ha^{-1}, and suggested that the North China Plain had the largest mean Y_p (9893 kg ha^{-1}). The latter value may be attributed to the estimation method adopted. In the current study, Y_p was determined by certificated cultivars grown with best management practices, without considering the constraints of limited water and nutrients, and insect stress. Under these assumptions, the most severe constraints on rice growth in the North China Plain, especially the water constraint, were lifted. This result was highly consistent with previous studies. Zhang et al. (2019a, 2019b) reported a mean Y_p of 10,378 kg ha^{-1} (slightly higher than observed in the current study) for the North China Plain by using field trial data and the CERES–Rice crop model. Wang et al. (2018b) reported a long-term average rice Y_p of 12,900 kg ha^{-1} for the North China Plain using the ORYZA crop growth model. This value may denote the theoretical highest yield when all abiotic and biotic stresses are eliminated.

For wheat, the Y_p range reported in the current study (4045–8408 kg ha^{-1}) across mainland China was similar to the range of 4100–8500 kg ha^{-1} reported by Chen et al. (2017). The average Y_p of 6218 kg ha^{-1} across all 31 provinces was significantly lower than the values of 8140 kg ha^{-1} and 8000 kg ha^{-1} reported for the North China Plain by Li et al. (2014a, 2014b) and Lu and Fan (2013), respectively. Despite this finding, the wheat Y_p for the five provinces in the North

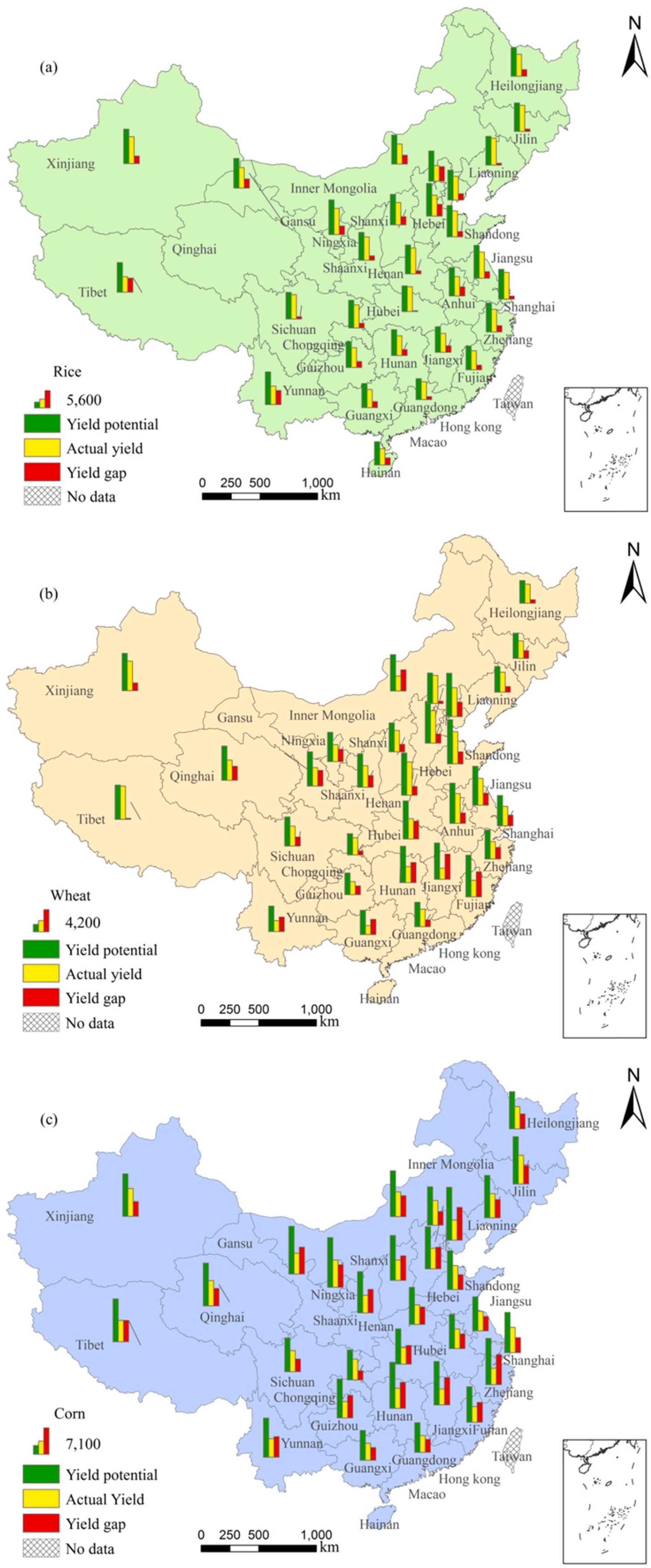

Fig. 5. Yield potential, actual yield, and yield gap at the provincial level for rice (a), wheat (b), and corn (c) grown on mainland China in 2016.

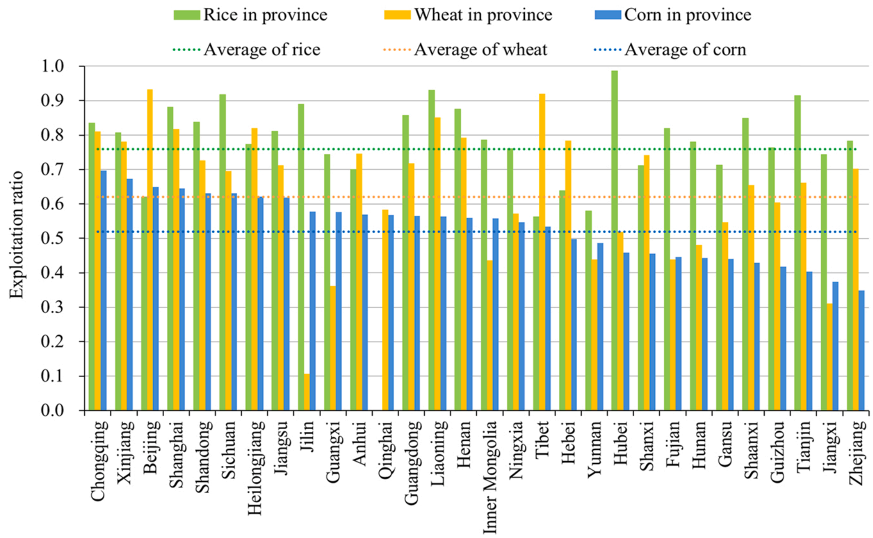

Fig. 6. Exploitation ratio (bars) of potential productivity for rice, wheat, and corn for all 31 provinces in mainland China, and mean exploitation ratios for the three crops (dotted lines).

China Plain reported in this current study also ranked as the highest, and were significantly higher than the national mean (Fig. 5).

This study reported a mean corn Y_p of 10,491 kg ha^{-1} across mainland China, which was significantly lower than the value reported by Liu et al. (2017) of 14,200 kg ha^{-1}. Higher Y_p can also be found in the other studies. For instance, a very high Y_p value of 15,100 kg ha^{-1} in the US was reported by Van Wart et al. (2013b), perhaps due to better field management and better climatic conditions for corn growth, or perhaps because the value was estimated by crop growth models.

4.2. Yield gaps for rice, wheat, and corn in mainland China

The average Y_g for rice was 1925 kg ha^{-1} across mainland China, significantly lower than the value of 4800 kg ha^{-1} reported by Wang et al. (2018b) who used the ORYZA crop model to estimate Y_p for Northeast China during 1981–2010. This remarkable difference may be in part attributed to the difference in estimation methods, but may also be attributed to the relatively favorable climate conditions in Northeast China for rice growth. Zhang et al. (2019a, 2019b) also reported a significantly higher Y_p for this region than for other regions, such as the Middle and Lower Reaches of the Yangtze River. Furthermore, the range of 114–4404 kg ha^{-1} for rice Y_g was significantly lower than that of 4100–8100 kg ha^{-1} found in the US (Espe et al., 2016). The large difference was mainly generated by the higher Y_p in the US (11,500–14,500 kg ha^{-1}), although the US Y_a values (7400–9600 kg ha^{-1}) were also higher than those in China (a mean of 7027 kg ha^{-1} in this study) (Espe et al., 2016).

The mean wheat Y_g of 2142 kg ha^{-1} in the present study was slightly lower than that of 2700 kg ha^{-1} reported by Lu and Fan (2013), and much lower than that of 3627 kg ha^{-1} reported by Li et al. (2014a, 2014b). Nevertheless, taking 80% of the theoretical Y_p reported by Li et al. (2014a, 2014b) as an exploitable yield potential result in a Y_g of 2000 kg ha^{-1}, which is only slightly lower than the value determined in the present study.

Corn had the largest Y_g among the three crops (4965 kg ha^{-1}). Nevertheless, this value was lower than the Y_g of 6000 kg ha^{-1} reported by Liu et al. (2017), but higher than the value of 3400 kg ha^{-1} reported for the US (Van Wart et al., 2013b). The low value from the US may be attributed to the assumptions of best field management practices and the lifting of the constraints imposed by limited water and nutrients, and insect stress.

4.3. Narrowing production gaps and yield gaps by considering resource and environmental sustainability in mainland China

Because of China's growing population and changing diet, total grain demand will peak in 2030 at 7.18 × 10^8 tons (Cheng et al., 2016). Thus, current actual grain production of 5.56 × 10^8 tons is far from meeting the peak demand in 2030, with a large gap of 1.62 × 10^8 tons, which accounts for 61.83% of the P_g. Fortunately, current certificated potential productivity is higher than peak grain demand, indicating that it is possible to eliminate the production difference by means of scientific and technological progress. In order to achieve the zero hunger of SDGs by 2030, comprehensive measures driven by the knowledge on the multiple dimensions of food systems transformations must be taken to narrow the huge gap between peak grain demand predicted for 2030 and the current actual grain production (Liu, 2018; Guo et al., 2020; Kalibata, 2021; Turnhout et al., 2021; Fig. 8).

Considering the effects on food security by the uncertainty of COVID-19 pandemic, extreme climate and international grain trade, science and policy may need to be developed that will prioritize the crops and regions having higher potential to narrow the yield gaps (Guo et al., 2020; Zhou et al., 2021; Fan et al., 2021; Turnhout et al., 2021). Given the research methods adopted in this study, it is suggested that official certificated cultivars should be promoted and adopted in corresponding AEZs, and certificated cultivars verified through comparative variety trials help to identify the most suitable variety for a target AEZ. Additionally, the best management practices as designated in the cultivar certification documents should be followed, it not only the state-of-the-art, but also the best practical operation knowledge and techniques for a target region. The popularization and optimization of the best management should be strengthened to make it easy to be accepted by agricultural producers. Furthermore, it is a crucial way to close yield gaps and achieve agricultural sustainability by farmland consolidation through building farmland infrastructure of field roads and irrigation facilities and improving farmland size (Zhang et al., 2019b; Duan et al., 2021).

Nevertheless, more comprehensive and sustainable approaches should be developed and followed, given the intertwined and interconnected relationships between land use and the environment (Fig. 8). Sustainable methods for narrowing production gaps and yield gaps for the major grain production regions are provided in Table 1, which includes 80–90% of the total grain production gap for wheat, corn, and rice. The most recent decades have witnessed a remarkable increase in grain output in China, accompanied by severe agricultural

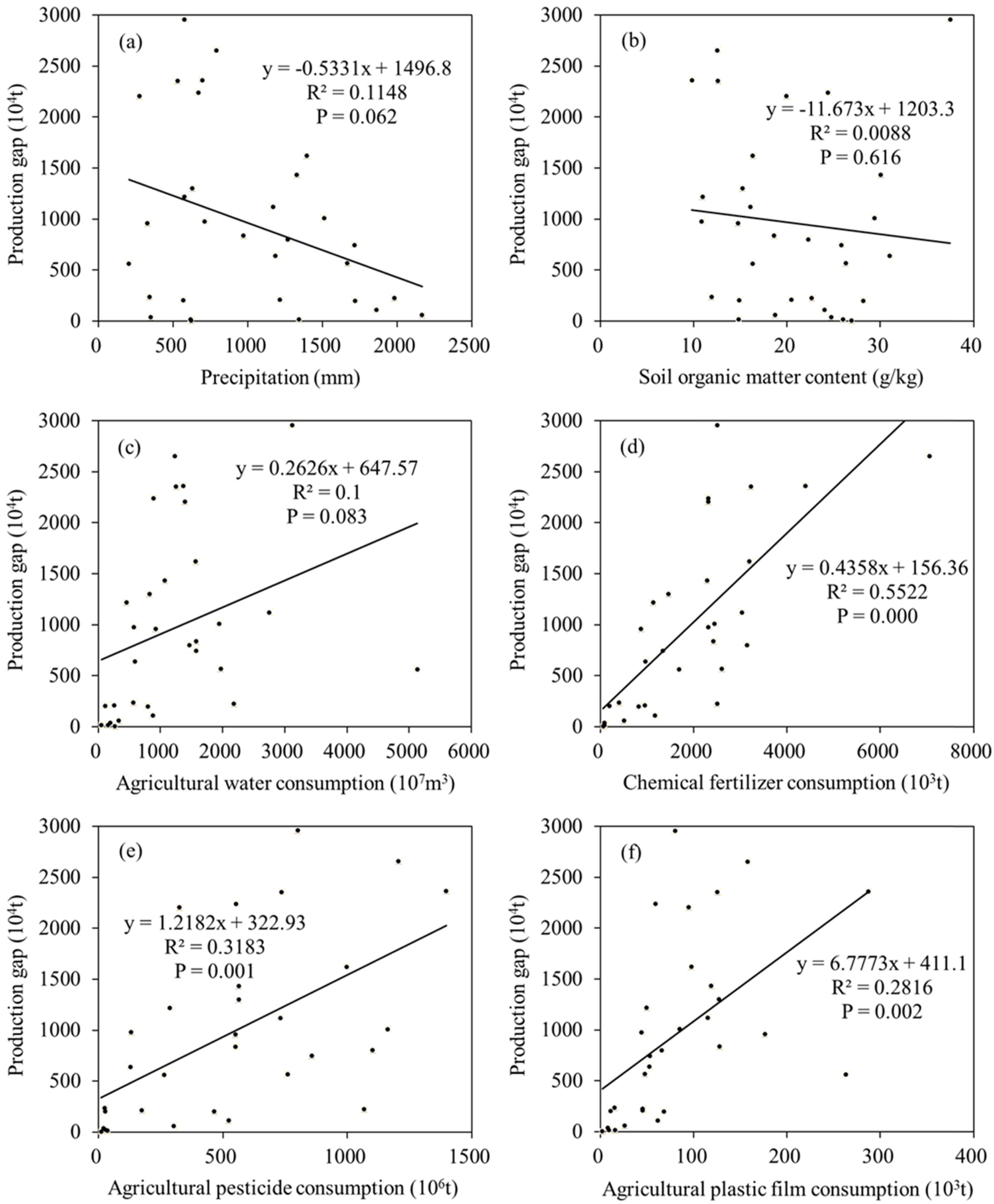

Fig. 7. Relationships between production gaps and precipitation (a), soil organic matter content (b), agricultural water consumption (c), chemical fertilizer consumption (d), agricultural pesticide consumption (e), and agricultural plastic film consumption (f). .

environmental problems such as groundwater overdraft in the North China Plain, degradation of black soil in the Northeast Plain, and soil degradation and overuse of mulch films in Northwest China (Kong et al., 2016; Gu et al., 2018; Gao et al., 2019; Wang and Liu, 2020). Thus, in order to narrow yield gaps, it is imperative to adopt sustainable methods to simultaneously address agricultural environmental problems. For example, nitrogen fertilizers have been overused across China (Cui et al., 2018), resulting in extensive soil acidification, water body pollution, and greenhouse gas emissions (Guo et al., 2010; Zhang et al., 2016b; Cui et al., 2018; Zhao et al., 2019). Hence, in all major grain-production areas, it is crucial to promote the use of organic inputs through application of animal manures or returning straw residues to the soil in order to reduce the application of nitrogen fertilizer (Cui et al., 2018). Additionally, greater attention must be given to increasing water availability in order to reduce production gaps due to the spatial mismatch between production gaps and annual precipitation. Another urgent research need is to understand how to narrow production gaps while simultaneously decreasing input elements because of the general and widespread overuse of water, fertilizer, mulch, and pesticides in mainland China.

Long-term intensive farming in the Northeast Plain has caused the problem of black soil degradation (i.e., decreasing soil organic matter content and declining soil fertility; Wang et al., 2018c). Preventing the destruction of the black soil layer, especially the topsoil (Gu et al., 2018), and promoting conservation tillage to restore soil fertility (Zhang

Table 3
Narrowing yield gaps and production gaps for key provinces in mainland China by considering resource and environmental sustainability.

Regions	Provinces	Dominant cropping system	Annual precipitation (mm)†	Soil organic matter (g/kg)	Natural constraints and main environmental problems associated with agriculture	Sustainable ways to narrow yield gaps
Northeast Plain	Heilongjiang, Jilin, Liaoning	Single cropping of corn/rice	500–850	25.70	Soil acidification due to overuse of N (Guo et al., 2010; Cui et al., 2018). Wetland loss due to farmland invasion (Niu et al., 2011, 2012). Black soil degradation due to long-term predatory farming (Gu et al., 2018; Wang et al., 2018c).	Reduce the application of N fertilizer. Conserve wetlands (Niu et al., 2011, 2012). Promote conservation tillage and organic inputs (i.e., manure and returning straw to field) (Zhang et al., 2015). Build water-saving irrigation facilities.
	Inner Mongolia	Single cropping of corn	200–650	19.94	Grassland degradation. Soil erosion by wind. Overuse of N fertilizer (Cui et al., 2018).	Return farmland to grassland. Conservation of water and soil. Reduce the application of N fertilizer. Build water-saving irrigation facilities.
North China Plain	Henan, Hebei, Shandong, Shanxi	Double cropping of wheat-corn	400–1000	11.47	Water shortage and groundwater overdraft (Kong et al., 2016). Soil acidification due to overuse of N(Guo et al., 2010;Cui et al., 2018).	Build water-saving irrigation facilities. Reduce irrigation intensity on wheat or plant one season of corn (Kong et al., 2016; Xie et al., 2018). Reduce the application of N fertilizer. Promote organic inputs, such as returning straw to field.
	Jiangsu, Anhui	Double cropping of wheat/corn/rice	800–1300	16.21	Soil acidification due to overuse of N (Guo et al., 2010; Cui et al., 2018). Water shortage due to lack of facility.	Reduce the application of N fertilizer. Build water-saving irrigation facilities. Promote organic inputs, such as returning straw to field.
Northwest	Shaanxi, Gansu, Xinjiang	Single cropping of corn/wheat	100–600	13.96	Extreme water shortage. Overuse of mulch films. (Liu et al., 2014a, 2014b). Soil erosion by wind and water (Teng et al., 2019). Overuse of N fertilizer (Guo et al., 2010; Cui et al., 2018).	Build water-saving irrigation facilities. Reduce, recycle, and reuse mulch films (Liu et al., 2014a, 2014b). Conservation of water and soil. Reduce the application of N fertilizer.
South China	Hubei, Sichuan, Yunan, Hunan, Guizhou, Jiangxi, Guangxi	Double cropping of rice/corn	1200–1600	26.21	Soil acidification due to overuse of N (Guo et al., 2010; Cui et al., 2018). Sloping crop land.	Reduce the application of N fertilizer. Return sloping farmland to forest.

†The annual precipitation was averaged from 1985 to 2012, and obtained from Geographical Information Monitoring Platform of China (Geographical Information Monitoring Platform of China GIM, 2019).
The soil organic matter in each province was taken from Hu et al. (2018), and then averaged at regional scale

et al., 2015) needs to be urgently addressed. Due to limited rainfall in many regions, it is vital to build water-saving irrigation facilities to conserve water resources while simultaneously closing the corn yield gap (Jiang et al., 2017; Liu and Li, 2017). Furthermore, as a large amount of natural wetlands have been reclaimed for use as arable lands (mainly paddy land), it is imperative that local governments issue laws or administrative decrees to impose bans on wetland reclamation and take measures to restore wetlands, given the great amount of ecosystem services provided by wetlands (Niu et al., 2011, 2012; Liu et al., 2021).

In the North China Plain, where large production gaps and severe water shortages exist, it will be necessary to develop water-saving irrigation facilities by land consolidation in order to simultaneously narrow yield gaps and conserve water resources (Kong et al., 2016; Long and Qu, 2018; Qu et al., 2019; Liu et al., 2020). Hebei and Shandong have seen a serious groundwater overdraft problem in the last decades, with a mean annual decline of 2–3 m in the water table (Kong et al., 2016). Hence, radical means such as prohibitions on groundwater exploitation must be taken to restore the water level in these two provinces. Some extreme situations exist, such as in the municipalities of Hengshui, Cangzhou, and Dezhou where overdraft has caused the groundwater table to decline by 38–77 m in recent decades (Kong et al., 2016; Xie et al., 2018). For these situations, extreme measures such as reducing irrigation intensity and frequency, changing the double cropping system of wheat-corn to single cropping, or even fallowing farmland may be necessary. In the southern part of the North China Plain, mainly in Jiangsu and Anhui where rainfall is relatively sufficient for crop production, building irrigation facilities may also be required to reduce the negative effects of seasonal drought and to close yield gaps to the greatest extent possible.

In Northwest China, where long-term water shortages are common, building water-saving irrigation facilities to exploit yield gaps is also a reasonable measure to consider. Although the extensive application of plastic mulch has greatly increased grain yield by approximately 20–35% in the past three decades, 110–259 kg ha^{-1} of film residues has caused serious “white pollution” problems, destroyed soil structure, affected crop growth, and decreased nutrient availability (Liu et al., 2014a, 2014b). Thus, prompt measures should be taken to enhance the reclamation and recycling of these residual plastics. In addition, about 60% of the territory in China experiences soil erosion, especially in the Loess Plateau area (Teng et al., 2019), and corresponding measures to conserve soil and water resources urgently need to be taken.

In the South China provinces of Hubei, Sichuan, Yunnan, Hunan, Guizhou, Guangxi, and Jiangxi, and in other provinces where a large amount of land is farmed on slopes, severe soil and water loss as well as frequent drought and flood events occur. It is important to continue the “grain for green” program in these areas to conserve the vegetation and soil and water resources in order to promote long-term agricultural sustainability.

5. Conclusions

In order to ensure food security and to achieve the zero hunger goal set by the UN while at the same time protecting the environment from further deterioration, viable methods for fully exploiting the yield gaps

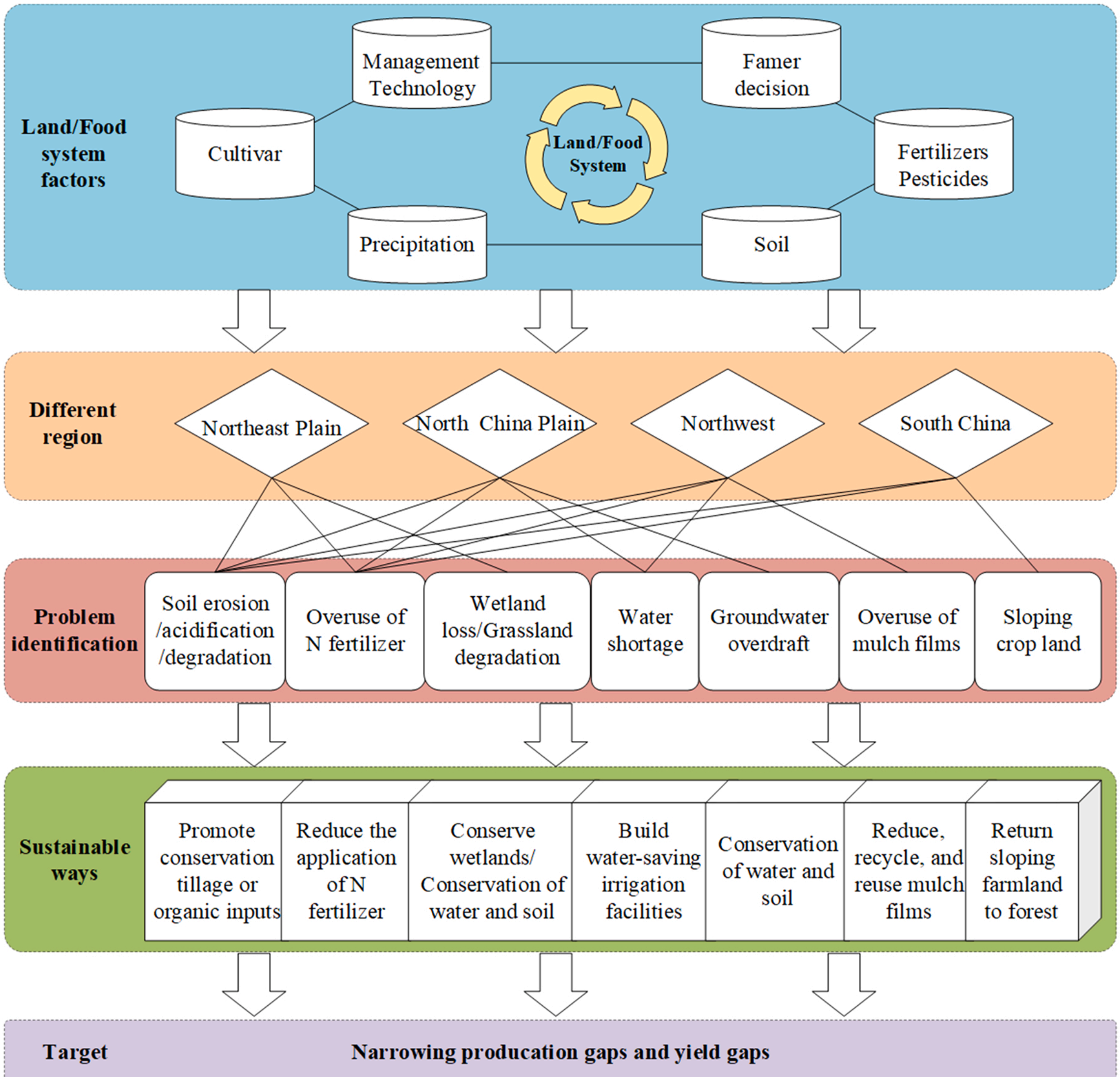

Fig. 8. The conceptual framework map on sustainable ways to narrow production gaps and yield gaps from the perspective of land/food systems.

of various crops on limited land resources must be determined, as well as identifying the potential regions and crops providing the best opportunities for exploiting those yield gaps. The current study applied a method of using the yield trial results of certificated cultivars in corresponding AEZs to calculate the potential yields of three staple grains (wheat, rice, and corn) across 31 provinces of mainland China. After subtracting actual yields in 2016, yield gaps of the three crops were obtained.

The results indicated that the gross grain potential productivity of mainland China in 2016 was 8.86×10^8 tons, leaving a total production gap of 2.99×10^8 tons that can be taken advantage of. This production gap was nearly half the size of the actual production (5.87×10^8 tons). Among the three crops, corn had the greatest growth potential, and 65.55% of corn's total production potential was available for exploiting. On a per unit area output basis, corn's production gap converted to the largest yield gap (4836 kg ha^{-1}) of the three crops. The current potential productivity exploitation ratios for rice, wheat, and corn were 0.76, 0.62, and 0.52, respectively.

In terms of spatial differences, the highest grain potential productivity was mainly found in the North China Plain and the Northeast Plain, which also had the highest production gap, accounting for 29.11% and 33.83% of the average production gap for mainland China, respectively. For specific crops, these two regions also accounted for a total of 67.23% of mainland China's total corn production gap, and the North China Plain alone accounted for 65.32% of the total wheat production gap. In contrast, the production gap for rice was relatively more dispersed across China. Tianjin, Zhejiang, and Jiangxi had the highest yield gaps for corn. Yunan, Tibet, and Hebei had the highest yield gaps for rice. And Jiangxi, Fujian, and Jilin had the highest yield gaps for wheat. A high yield potential did not guarantee a high yield gap because both a high yield potential and a low actual yield were necessary for a high yield gap.

According to the above results, it is suggested that corn grown in all regions of the North China Plain and the Northeast Plain should be prioritized in the process of exploiting production gaps. Additionally, official certificated cultivars verified through cultivar trials should be promoted and adopted in corresponding AEZs, and best management practices designated in cultivar certification documents should be followed. Furthermore, sustainable methods should be used when attempting to narrow yield gaps. Based on analyzing the main environmental problems associated with agricultural production in each region, corresponding approaches were suggested for each region, with the objective of ensuring sustainability of the agricultural production ecosystem. Furthermore, science, technology, and policy must work hand-in-glove to promote food systems transformations and simultaneously achieve zero huger poverty of SDGs.

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