Winter Wheat Yield Gaps Across the Loess Plateau of China

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Abstract

The Loess Plateau is among the major winter wheat (*Triticum aestivum* L.) production areas of China. However, wheat production is uncertain across the Loess Plateau, and its potential for yield improvement remains unknown. In the present study, we divided winter wheat growing areas on the Loess Plateau into four climatic zones: arid (zone I), semi-arid (zone II), semi-humid (zone III), and humid (zone IV). Then, we used the validated Agricultural Production Systems Simulator (APSIM) to model Y_p (potential yield) and attainable yield (water-limited yield, Y_w; nitrogen-limited yield, Y_n) of winter wheat on the Loess Plateau from 1961 to 2016. The simulated means for weighted Y_p, Y_w, and Y_n were 8.87, 6.49, and 5.42 t ha^{-1}, respectively. Y_a reached only 57% of Y_p, which represents the amount of room available for yield improvement. Across the Loess Plateau, the yield gap caused by water limited (YGw) and nitrogen restricted (YGn) were 27% and 39% of potential wheat production. The difference between YGw (3.54 t ha^{-1}) and YGn (3.87 t ha^{-1}) was not significant in the semi-arid climate (zone II), due to low precipitation rates. Compared with irrigation, nitrogen deficiency was the key factor causing the winter wheat yield gap. However, the yield gap caused by nitrogen restriction varies regionally. Irrigation in arid (zone I) was more important than in the other climates, whereas these climate regions required nitrogen more pressing. Areas with a large potential for increased winter wheat yield on the Loess Plateau were mainly distributed in the semi-arid climate (zone II).

Keywords Winter wheat · APSIM · Yield gaps · Climatic zones

Introduction

The greatest challenge currently facing global agriculture is to feed the growing population and reduce malnutrition (Godfray et al., 2011). In China, a new fertility policy that encourages population growth is being implemented, which means that the population will continue to grow and the demand for food will increase significantly (Cheng et al., 2017). However, large amounts of high-quality arable land have been lost to urban expansion and heavy metal contamination, resulting in scarcity of cultivated land for growing cereals (Kong, 2014). Converting forests and grasslands into cultivated land causes substantial environmental imbalances, such as ecosystem degradation and reduced biodiversity (Lambin & Meyfroidt, 2011). Thus, total production is unlikely to increase through expansion of sowing areas; to ensure food supply, it will be necessary to increase grain yield per unit of land (Schierhorn et al., 2014).

Wheat (*Triticum aestivum L.*) is the third largest crop worldwide and an essential source of carbohydrates and protein for millions of people (Asseng et al., 2011; Shewry & Hey, 2015). In China, more than 50% of the population relies on wheat as a staple food, with winter wheat accounting for 91% of the total wheat production (Sun et al., 2018). Therefore, increasing winter wheat yield in China is of great significance to national-level food security and the alleviation of hunger and poverty. The Loess Plateau is among the major winter wheat production areas of China. Identifying areas on the Loess Plateau where there is the potential to improve winter wheat yield is crucial for solving the food demand problem, similar to what has been done in other important winter wheat producing regions of the world (Lollato et al., 2017). Irrigation and fertilization are important measures to increase production (Kalra et al., 2007; Mueller

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et al., 2012). The primary factor limiting increased wheat production in a Loess Plateau gully region was reported to be fertilizer rather than water in years with normal rainfall rates, such that dryland wheat yield decreased by 6.3% due to insufficient water and 42.4% due to insufficient fertilizer (Li et al., 1991). The combination of N, P and organic fertilizer was found to be the best method for achieving maximum wheat yield growth potential in a central Loess Plateau gully region (Li et al., 1999); however, another study reported that water had a far greater effect on yield than nitrogen application in the western Loess Plateau (Ru et al., 2019). To date, the key factor restricting winter wheat yield across the Loess Plateau remains unknown. To expand the knowledge on this area, yield gap analyses should be conducted to guide wheat production management strategies, increase irrigation or nitrogen fertilizer efficiency, and raise yield on existing cropland.

Yield gaps are differences between potential yield (Y_p) and actual yield (Y_a), or Y_p and attainable yield (water-limited yield, Y_w; nitrogen-limited yield, Y_n) (Rabbinge, 1993). Variation between regions can be caused by differences in cultivar, local environment, and management techniques. For a crop with unrestricted growth in a perfectly managed environment, Y_p depends only on growth determination factors that are affected by incoming solar radiation, temperature, and genetic characteristics of the crop (Rabbinge, 1993). However, it is neither economically feasible nor environmentally desirable for crops to reach Y_p (Cassman, 1999; van Ittersum et al., 2013). Attainable yield refers to the yield achieved when the crop is limited by water (Y_w) or nitrogen (Y_n) during the growing season. In agricultural production, actual crop growth rate and yield are limited by water and/or nutrient availability, as well as pests, diseases, weeds, market distance, crop prices, and other factors (Pradhan et al., 2015). Understanding the gap between Y_p and Y_a, Y_p and Y_w/Y_n provides opportunities to increase yield in specific regions affected by factors limiting production. Many studies have been conducted to elucidate wheat yield gaps, from the field scale to regional, national, and global scales. For example, Hochman and Horan (2018) reported that insufficient nitrogen fertilizer supply led to a 40% drop in wheat production in Australia, and recommended management measures in terms of tillage, sowing date, summer fallow weeds, and seedling density. Khaliq et al. (2019) reported that only 36–67% of potential rice and wheat yields were attained in a Punjab rice–wheat system in Pakistan, and that nitrogen, rather than water, deficiency was a major factor causing these large yield gaps. In winter wheat farm trials in Kansas, USA, wheat yield increased via increases in nitrogen and sulfur supply, plant population density, and foliar fungicide application, which reduced the yield gap (de Oliveira et al., 2020; Jaenisch et al., 2019). Evaluation of commercial field data from yield contest winners also in Kansas, USA, confirmed the aforementioned results in which

foliar fungicides and N management were important factors determining the yield gap in the region (Lollato et al., 2019a, 2019b). In a European study, the mean annual yield gap of cereal crops including wheat, barley, and maize was found to be 239 Mt, which represented only 42% of Y_p; increased nitrogen use efficiency was suggested as a necessary measure for closing the yield gap (Schils et al., 2018). In the Netherlands, the yield gap of winter wheat accounts for 35–40% of Y_p (Silva et al., 2020). Most studies of winter wheat yield gaps in China have focused on the North China Plain (Bai et al., 2019; Chen et al., 2017), Southwest China (He et al., 2017), or national-scale agriculture (Li et al., 2016; Sun et al., 2018), whereas few have examined wheat production on the Loess Plateau.

Among the various research methods applied to quantify yield gaps, field experiments examining the effects of different management measures provide accurate and detailed results, but are costly (Bhatia et al., 2008). The results from variety performance trials can help guide growers to choose varieties suitable for specific environments × management scenarios, but the major challenge was the lack of consistency in data collection and reporting (Munaro et al., 2020). Participatory assessment by farmers can effectively identify the causes of yield gaps, but involves collecting large amounts of data, which is time consuming (Edreira et al., 2017). In contrast, crop production models use meteorological and cultivation management data to explore the effects of various production situations to determine yield under different soil fertility, tillage system, sowing density and time, and fertilizer application rate, and cultivar selection settings. The interaction between crop yield and management practices (genotype × environment × management) quantitatively describes the extent to which management strategies affect crop growth and development over long periods of time. Consequently, crop models have become important tools for quantifying yield gaps (Liu et al., 2019; Nyombi, 2019; Zu et al., 2018) and to explore complex crop response to management practices such as N fertilizer (Hochman & Waldner, 2020).

The objectives of the present study were to (i) quantify potential, attainable [water-limited (Y_w) and nitrogen-limited (Y_n)], and Y_a of winter wheat in different regions of the Loess Plateau; (ii) estimate yield gaps and identify critical limiting factors; and (iii) evaluate which areas provide the greatest opportunities for increasing yield.

Materials and Methods

Study Area and Climate Zone Classification

The study area is located in areas of the Loess Plateau that are mainly dedicated to winter wheat. We identified 160 counties that had sowed winter wheat for longer than 10

consecutive years (2005–2016) as winter wheat growing areas (Fig. 1). The percentage of winter wheat sowing area within the cultivated area of each county was higher in the south (> 40%) than in the north (< 25%) of the study area. The primary cropping system of the region is winter wheat and summer maize rotation.

We divided the study area into different climatic zones for two reasons. First, the same climate zone is likely to share wheat varieties and cultivation management practices that may be used in Y_p simulations. Second, it is reasonable to upscale Y_p and yield gaps to regional levels using an area-weighted method if the sites are within the same climate zone. The growing degree days (GDD) greater than 0 °C and aridity index (annual precipitation/annual potential evapotranspiration) were obtained from the Global Yield Gap Atlas Extrapolation Domain (GYGA-ED) method (van Wart et al., 2013). We also obtained digital elevation model (DEM) of the study area, precipitation during the winter wheat growing period. Based on gradients of these four indices, we divided the Loess Plateau winter wheat sowing area into four climatic zones (Fig. 1; Table 1).

Climate and Soil Data

Climate data from 32 meteorological stations and 36 agro-meteorological stations were obtained from the China Meteorological Administration climate data-sharing system (Fig. 1), including daily precipitation (P), maximum temperature (T_{max}), minimum temperature (T_{min}), and sunshine hours, from 1961 to 2016. Solar radiation (Radn) data were converted from observed sunshine hours (Black et al., 1954). Winter wheat sowing dates from 1992 to 2013 were obtained from agrometeorological stations and used to determine the "seeding window" for crop simulations.

Soil data used in our study were obtained from the Soil Properties Parameters database, Soil Hydraulic Parameters database (Dai et al., 2013), and Changwu Research Station of Agriculture and Ecology on the Loess Plateau of China. These data included soil bulk density (BD), 15-bar lower limit (LL15), drained upper limit (DUL), saturated volumetric soil water content (SAT), soil organic carbon (SOC), and soil pH (PH) in different soil layers. Using the longitude and latitude of the meteorological stations, we extracted soil data for each station using the ArcGIS software and used

Fig. 1 Distribution of meteorological and agro-meteorological stations in winter wheat sowing areas of the Loess Plateau. Green shading indicates the percentage of winter wheat sowing areas among total cultivated area in each county from 2005 to 2016. The study area was divided into four climatic zones: arid (zone I), semi-arid (zone II), semi-humid (zone III), and humid (zone IV)
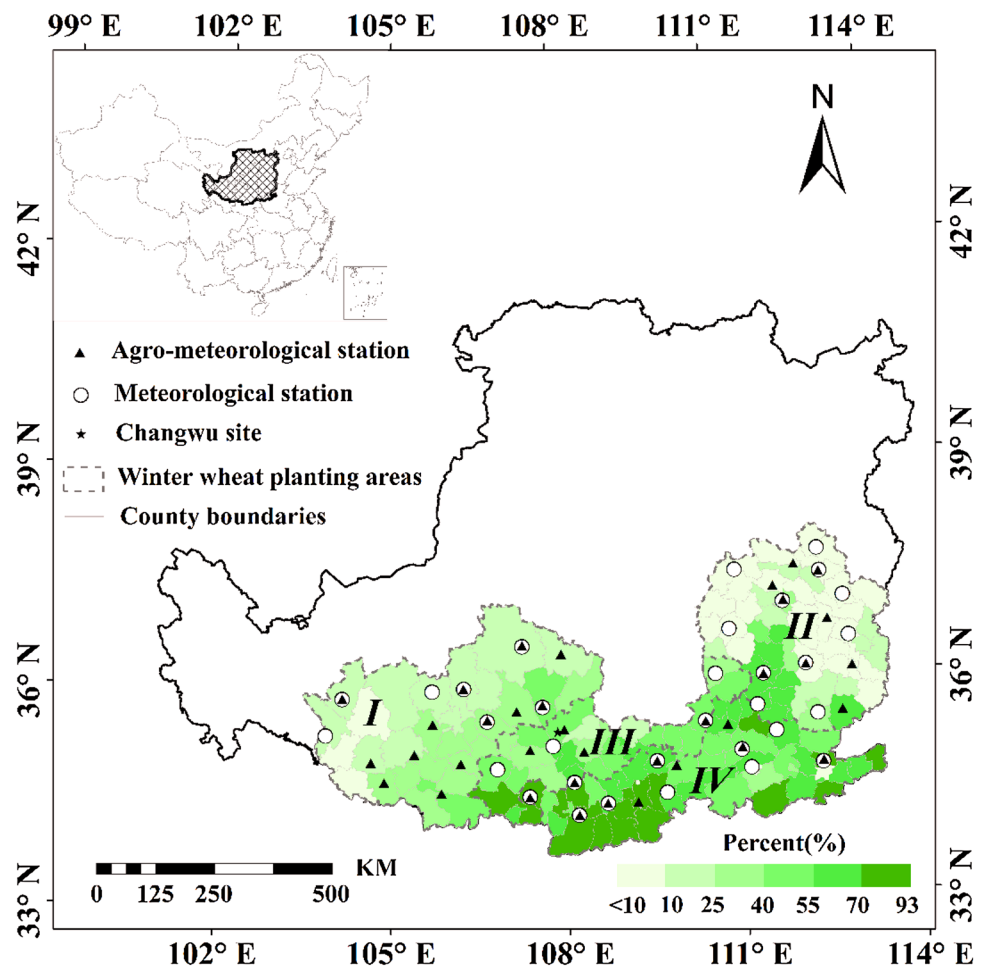
Table 1 Growing degree days (GDD), aridity index, and digital elevation model (DEM) characteristics for four climate zones in the winter wheat sowing area on the Loess Plateau

Climatic zone	GDD (≥ 0 °C)	Aridity index	DEM (m)	precipitation
Arid (zone I)	2671–3791 °C	3894–5689	1400–3963	180–220
Semi-arid (zone II)	3170–4829 °C	3894–4791	550–2000	220–255
Semi-humid (zone III)	3792–4829 °C	4792–5689	1000–1400	255–290
Humid (zone IV)	3792–5949 °C	5690–6588	221–1000	285–334

these data for winter wheat potential and attainable yield simulations. When the soil of the meteorological station is not the predominant agricultural soil type, change it to the main agricultural soil type of the neighboring weather station. Soil data from the Changwu site are listed in Table S1.

Agricultural Production Systems Simulator (APSIM)

The APSIM model predicts yield based on the status of each component of a dryland agro-ecosystem; it is sensitive to environmental changes and their effects on crop yield (McCown et al., 1996). Thus, APSIM is an effective tool for studying the effects of climate change and management practices on crop yields (Keating et al., 2003; Wang et al., 2008). Previous studies have calibrated and applied APSIM for winter wheat growth and yield prediction on the Loess Plateau (Chen et al., 2008; He et al., 2015). In this study, we used APSIM-Wheat to simulate the Y_p, Y_w, and Y_n of winter wheat on the Loess Plateau. To ensure accurate simulation of winter wheat growth and development, we identified representative cultivars of winter wheat sowing areas in the Loess Plateau based on the previous studies. Winter wheat cultivars are generally selected according to regional climatic conditions such as GDD and precipitation. Therefore, we selected widely grown winter wheat cultivars as representative varieties for each climate zone: Xifeng24 (zone I), Jinmai47 (zone II), Changwu89134 (zone III) and Xiaoyan22 (zone IV). The four varieties were modern wheat cultivar with extensive disease resistance, drought and cold tolerance. Xifeng24 was a winter variety with strong frost resistance and suitable for planting in dry plateaus with higher altitudes (Shi, 2008). Jinmai47 has good lodging resistance, it suitable for planting in supplementary irrigation areas. Changwu 89134 was a weak winter variety, suitable for planting in dry and fertile land. Xiaoyan22 was a variety with weak spring nature, suitable for planting in areas with good water and fertilizer conditions (Li et al., 2010).

Winter wheat yields were obtained from field experiments in Changwu Research Station of Agriculture and Ecology on the Loess Plateau of China (2002–2006) and the Institute of Water-saving Agriculture in Arid Areas of China (IWSA) (2011–2014), as well as collected from published literatures (Table S2, Li et al., 2017; Lian et al.,2020; Lu et al., 2019; Xu et al., 2013; Zhou et al., 2020). These yield datasets were obtained under water-limited or nitrogen-limited conditions.

Statistical indices including the determination coefficient (R^2), root mean square error (RMSE), and normalized root mean square error (NRMSE) were calculated to evaluate the performance of the APSIM-Wheat model.

Y_p, Attainable Yield, Y_a, and Yield Gaps

In this study, we defined four levels of yield: Y_p, Y_w, Y_n, and Y_a. APSIM-Wheat simulations produced Y_p, Y_w, and Y_n using climate data from 1961 to 2016. Y_p is affected only by climatic conditions, such that winter wheat grew without water or nutrient stress; the total soil water deficit of each layer exceeded 20 mm, and the irrigation amount was the soil water deficit after supplementary irrigation. Simulation of nitrogen application was 300 kg ha^{-1} every year, at a rate of 150 kg ha^{-1} at sowing and again as topdressing (150 kg ha^{-1}) at the jointing stage. Soil nitrogen and soil organic matter were reset at harvest each year. For Y_w, water was supplied only from precipitation, with no additional irrigation; nitrogen application settings were the same as those for Y_p. For Y_n, no nitrogen fertilization was applied. The simulated nitrogen mainly comes from soil nitrogen and soil organic matter, and they were reset every year after the winter wheat harvest; irrigation conditions were the same as those for Y_p. We defined the seeding window from the earliest to the latest sowing dates recorded by the agrometeorological stations. Seeding was conducted when cumulative precipitation reached 25 mm for 7 consecutive days and extractible soil water (ESW) relative to LL15 reached 100 mm. If both conditions were not met during the seeding window, then winter wheat was sown on the last day of the seeding window. Sowing density was set at 350 plants m^{-2}, sowing depth at 50 mm, and row spacing at 250 mm. Precipitation and soil water availability conditions were also based on agrometeorological station data. According to records, the effective initial soil water content at winter wheat planting was between 60 and 43%, which was evenly distributed in the soil (180 cm).We used the inverse distance weighting (IDW) method in the ArcGIS software to interpolate yields based on Y_p, Y_w, and Y_n from the meteorological stations for sites across the entire region, at a resolution of 0.02° × 0.02°. A similar interpolate method was executed to obtain the spatial distribution of climatic elements.

Y_a was the average of the winter wheat yield from 2005 to 2016. Previous studies have shown that using a long period to

calculate Y_a can lead to underestimation of recent Y_a (Grassini et al., 2015). Thus, in arid climates, the average of the latest 10–20 years can better represent Y_a for the region (van Ittersum et al., 2013). We therefore used the average winter wheat yield for each county on the Loess Plateau from 2005 to 2016 to represent Y_a in this study. Winter wheat sowing area and yield, effective irrigated area, and agricultural input data for each county were obtained from statistical yearbooks and agricultural statistical yearbooks, detailed information were shown in the Supplementary Material. (Fig. S1 and Table S4). The average Y_a in each climatic zone was area weighted according to the sowing area of winter wheat in each county in the region. Region-scale averages of Y_p, Y_w, and Ya were obtained similarly.

In our analysis, we defined three yield gaps: YG_t, YG_w, and YG_n, where YG_t is the difference between Y_p and Y_a [Eq. (1)]; YG_w is the difference between Y_p and Y_w (Eq. 2); and YG_n is the difference between Y_p and Y_n [Eq. (3)]. YG_{tp}, YG_{wp}, and YG_{np} were calculated as YG_t, YG_w, and YG_n relative to Y_p, respectively, expressed as percentages (Eqs. 4, 5, 6).

$$YG_t = Y_p - Y_a \tag{1}$$

$$YG_w = Y_p - Y_w \tag{2}$$

$$YG_n = Y_p - Y_n \tag{3}$$

$$YG_{tp} = YG_t / Y_p \times 100\% \tag{4}$$

$$YG_{np} = YG_n / Y_p \times 100\% \tag{5}$$

$$YG_{wp} = YG_w / Y_p \times 100\% \tag{6}$$

Linear regression analysis was used to detect trends of climatic elements, yield and yield gaps. The slope of the linear regression line against time was evaluated using Student's t test at 95% or 99% confidence intervals. To clarify the impact of climate change on the Y_p, Y_w and Y_n of winter wheat over the past 55 years, we used correlation analysis and multiple linear stepwise regression methods to study the trends of Y_p, Y_w and Y_n with climate factors, including solar radiation, temperature, and precipitation. And similar analysis was used to analyze the influence of agricultural condition factors on Ya in each climate zone.

Results

## Climate Changes During the Winter Wheat Growth Period

From 1961 to 2016, the average maximum and minimum temperature ranged from 11.15 to 14.65 °C and 1.63 °C to 4.18 °C, respectively, during the winter wheat growing period on the Loess Plateau (Fig. 2a, c). Both values were highest in zone IV (13.95 °C and 3.15 °C, respectively) and lowest in zone I (11.90 °C and -0.09 °C, respectively) (Table 2). There was an increasing trend in maximum and minimum temperatures from sowing to anthesis, as well as during the whole growth period in all regions. However, the minimum temperature tended to decrease during the anthesis to physiological maturity period (Fig. 2b, d and Table 2). The rate of warming for the entire region was 0.22 °C per decade (Table 2). In contrast, precipitation showed a declining trend, with a decrease of 11.76 mm per decade (Fig. 2e, f and Table 2). The greatest drought trends occurred in zone III, where precipitation significantly decreased by 14.58 mm per decade. The rate of precipitation decline was greatest during the vegetative growth period of winter wheat (sowing to anthesis). During this period, the rate of decline was higher in zone IV than that in other climatic regions, reaching 15.9 mm per decade. The average solar radiation on the Loess Plateau was 3375.5 MJ m^{-2}, with a significant declining trend from 1961 to 2016 (Fig. 2g, h and Table 2). Among all climate zones, zone I had the highest amount of radiation and the slowest rate of decline. However, the rate of decrease in solar radiation was greatest in zone IV during the sowing to anthesis period.

Y_p, Y_w, Y_n and Ya

We validated the model for the four cultivars used in this study (Xifeng 24, Changwu 89134, Xiaoyan 22, and Jinmai47). As shown in Fig. 3, simulated biomass and yield were well correlated to the observed results ($R^2 > 0.80$; NRMSE < 0.06). RMSE values reflected small relative errors in the simulations (Fig. 3). Our results clearly indicate that APSIM-Wheat is applicable for simulating the growth and yield of the four winter wheat cultivars on the Loess Plateau.

The estimated regional area-weighted average Y_p, Y_w, and Y_n of winter wheat were approximately 8.87, 6.49, and 5.42 t ha^{-1}, respectively, during 1961–2016 (Table 3). Y_p varied from 7.9 to 10.7 t ha^{-1} across all climate zones (Fig. 4a). The highest Y_p was observed in the northwestern Loess Plateau, mainly distributed in zone I (Fig. 4a).

Fig. 2 Spatial distribution and climate trends in average **a** yearly and **b** decade-scale maximum temperature (T_{max}, °C); **c** yearly and **d** decade-scale minimum temperature (T_{min}, °C); **e** yearly and **f** (P, mm); and **g** yearly and **h** decade-scale radiation (Radn, MJ m^{-2}) during the winter wheat growth period on the Loess Plateau from 1961 to 2016
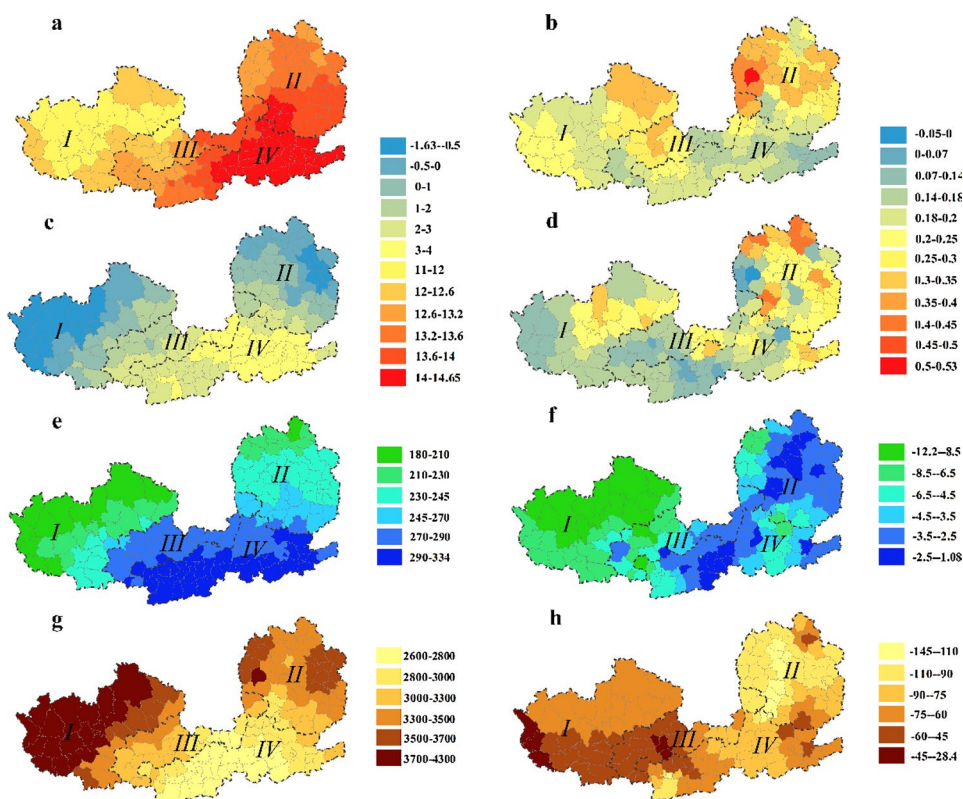
Relatively low yields were observed in the central counties, below 8.6 t ha^{-1}. Y_w ranged from 4.3 to 7.9 t ha^{-1} (Fig. 4c). In the northeastern counties, winter wheat generally had lower Y_w, resulting in lower yield in zone II (5.44 t ha^{-1}) than in the other climate zones (Table 3). Y_n varied from 4.2 to 6.5 t ha^{-1} (Fig. 4e), below both Y_p and Y_w. Contrary to the spatial variation in Y_p, there was a clear gradient from the central region to the east and west, related to the soil properties. In zones I and II, Y_n was relatively low, primarily due to poor soil fertility (Fig. S2).

The Y_a showed a clear spatial distribution, with high yields in the southeastern Loess Plateau (Fig. 4g). Yields varied from 1.03 to 6.4 t ha^{-1} (Fig. 4g), with an average value of 3.66 t ha^{-1} over the 12-year study period (Table 3). Across the four climate zones, the highest (4.27 t ha^{-1}) and lowest Y_a (2.37 t ha^{-1}) were observed in zones IV and I, respectively (Table 3).

Temporal trends in the Y_p of winter wheat across the entire study region are shown in Fig. 4b and Table 3. Y_p decreased significantly over the study period (Table 3), declining by 0.013 to 0.015 t ha^{-1} per year (Fig. 4b). Similar to the trend of total precipitation during the winter wheat growth season (Fig. 3f), Y_w decreased significantly by 0.021 t ha^{-1} per year (Table 3). The most rapid decreases in Y_p and Y_w were observed in zone IV, by 0.013 and 0.023 t ha^{-1} per year, respectively. In contrast, Y_n increased by 0.001 t ha^{-1} per year but not significantly (Table 3). Relatively large increases were distributed in the northwestern and northeastern parts of the study area (Fig. 4f).

During the 12-year study period, Y_a increased significantly across most of the study area (Fig. 4h), by an average of 0.064 t ha^{-1} per year (Table 3). The slow rate of increase and low Y_a in zone III may have been caused by insufficient water and fertilizer input in this region (Tables 3 and 4; Fig. S1). As shown in Table S4, the percentage of effective irrigated area was 25%. The largest increase (0.11 t ha^{-1} per year) in Y_a was observed in zone I (Table 3). In this area, climatic factors changed more severely and were not favorable for yield increase, such as rapid solar radiation decline and greater increases in temperature (Table 2); however, the gross increase in agricultural machinery power was largest in zone II, at 0.37 kw ha^{-1} per year (Fig. S1). While a significant correlation and stronger correlation (0.78) was observed between Ya and agricultural machinery power in zone II (Table S5). Thus, yield may have increased due to technological improvements despite the negative effects of climate change (Olesen & Bindi, 2002).

Climatic Factors

In contrast with the increasing maximum and minimum temperatures, solar radiation and precipitation decreased from 1961 to 2016 on the Loess Plateau. In each climatic zone and the whole region, Y_p was significantly positively correlated

Table 2 Average and linear trends of climatic factors for each climate zone during the winter wheat growth period on the Loess Plateau from 1961 to 2016

Meteorological variables	Whole region	Climate zone			
		I	II	III	IV
T_{max} (°C)					
S-PM	12.98	11.9	13.49	12.92	13.95
Trend (per decade)					
S-A	0.28**	0.29**	0.37**	0.31**	0.17*
A-PM	0.01	0.13	0.04	− 0.17**	0.09
S-PM	0.22**	0.22**	0.26**	0.23**	0.18**
T_{min} (°C)					
S-PM	1.16	-0.09	0.45	2.07	3.15
Trend (per decade)					
S-A	0.14*	0.15*	− 0.04	0.21*	0.2**
A-PM	− 0.11**	0.04	− 0.24**	− 0.13	− 0.09
S-PM	0.2**	0.18**	0.25**	0.15	0.18**
P (mm)					
S-PM	254	196	233	289	308
Trend (per decade)					
S-A	− 7.9**	− 6.5*	− 7.5	− 2.9	− 15.9**
A-PM	− 4.7*	− 0.003	− 7.8	− 1.6	− 8.63*
S-PM	− 11.76**	− 12.82**	− 9.10	− 14.58**	− 11.62**
Radn (MJ m^{-2})					
S-PM	3375.5	3824.5	3397.9	3134.2	2869.2
Trend (per decade)					
S-A	− 61.69**	− 32	− 76.9**	− 10.7	− 118.07**
A-PM	− 13.7**	− 6.12	− 33.12**	− 4.28	− 7.63
S-PM	− 72.09**	− 59.36**	− 92.42**	− 61.03**	− 73.51**

The * and ** indicate statistically significant at $p < 0.05$ and $p < 0.01$, respectively

S-PM sowing to physiological maturity; *S-A* sowing to anthesis; *A-PM* anthesis to physiological maturity

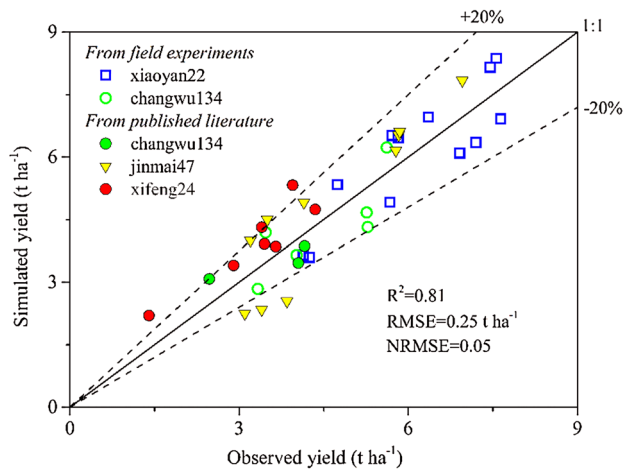**Fig. 3** Comparison of simulated and observed yield of winter wheat. Diagonal solid line: 1:1 ratio; dotted lines: ± 20% deviation from 1:1 line

with solar radiation, and negatively correlated with minimum temperature (Table 4). The change of Y_p on the Loess Plateau was mainly driven by solar radiation and maximum temperature (Table 5).

Due to the lack of additional irrigation during the winter wheat growth season, water became the main limiting factor of Y_w on the Loess Plateau (Tables 4 and 5). A weaker (− 0.42 to − 0.58) but significant correlation was observed between Y_w and maximum temperature across the study region (Table 4). During the 55-year study period, increasing Y_n was primarily affected by maximum temperature and precipitation. Y_n was positively correlated with maximum temperature and negatively correlated with precipitation in each climatic zone and the whole region, while Y_a was the opposite (Table 4). Across the Loess Plateau, solar radiation and maximum temperature explained 52% of the variation in Y_p (Table 5).

Yield Gaps

YG_t is the difference between the crop yield and theoretical production limit at the current production level, which was

Table 3 Averages and linear trends of Y_p, Y_w, Y_n, and Y_a during the winter wheat growth period for each climate zone and the entirety of the Loess Plateau

Climate zone	Y_p (t ha^{-1})		Y_w (t ha^{-1})		Y_n (t ha^{-1})		Y_a (t ha^{-1})	
	Mean	Trend (per year)	Mean	Trend (per year)	Mean	Trend (per year)	Mean	Trend per year
I	9.69	− 0.003	6.44	− 0.019*	4.92	0.004	2.37	0.047
II	8.97	− 0.008	5.44	− 0.014	5.10	0.002	3.82	0.11*
III	8.86	− 0.007	6.76	− 0.02*	5.29	0.003	3.09	0.042*
IV	8.59	− 0.013*	6.68	− 0.023*	5.67	− 0.001	4.27	0.057*
Whole region	8.87	− 0.01*	6.49	− 0.021*	5.42	0.001	3.66	0.064*

Y_p, Y_w, and Y_n simulations were from 1961 to 2016, whereas that of Y_a was from 2005 to 2016. The * indicate statistically significant at $p < 0.05$

Fig. 4 a, **c**, **e**, **g** Spatial distribution of winter wheat yield (t ha^{-1}) and **b**, **d**, **f**, **h** its trend over time (t ha^{-1} per year) on the Loess Plateau. **a**, **b** Y_p, (**c**, **d**) Y_w, **e**, **f** Y_n, from 1961 to 2016. **g**, **h** Ya during 2005–2016
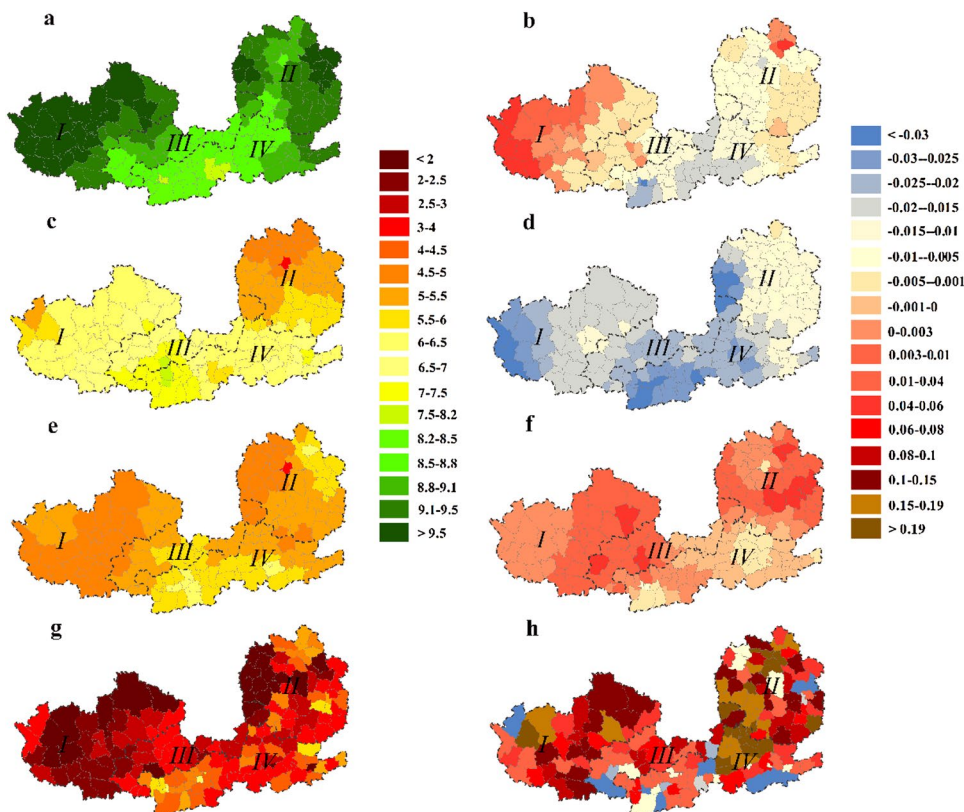
the largest possible increase space for the Y_a. From 2005 to 2016, YG_t varied from 1.38 to 9.0 t ha^{-1}, and the regional area-weighted average YG_t was 5.05 t ha^{-1} (Fig. 5a and Table 6). Low YG_t values were concentrated in the central Loess Plateau, mainly below 4.5 t ha^{-1}. High YG_t values were distributed in the northwestern and parts of the northeastern Loess Plateau. Among the four climate zones, the lowest (4.07 t ha^{-1}) and highest (7.32 t ha^{-1}) YG_t values were observed in zones I and IV, respectively.

YG_w, the difference between Y_p and Y_w of winter wheat, indicates the reduction in winter wheat yield due to water deficit. YG_w varied from 0.29 to 5.6 t ha^{-1}, and showed a regional distribution similar to that of YG_t (Fig. 5d). The average YG_w on the Loess Plateau was 2.35 t ha^{-1} during

1961–2016 (Table 4). In zones III and IV, YG_w was relatively low, suggesting that water limitation has a smaller effect on yield in these areas, whereas zones I and II had higher YG_w values (Table 4). Generally, YG_w varied from 2.0 to 3.0 t ha^{-1}.

YG_n, the yield gap between Yp and Yn, represents the yield reduction caused by lack of nitrogen fertilizer during winter wheat growth. The spatial variation in YG_n was greater than that of YG_w. From 1961 to 2016, YG_n varied from 1.77 to 5.68 t ha^{-1}, with an average of 3.43 t ha^{-1} (Table 4). Relatively low YG_n (< 3.0 t ha^{-1}) was observed in the central region of zone IV and high values (> 4.5 t ha^{-1}) were observed in the western zones II and I (Fig. 5g).

Table 4 Influence of climate factors on the temporal distributions of Y_p, Y_w, Y_n and Y_a of winter wheat in each climate zone and the entire Loess Plateau

Climate zone	Item	Correlation coefficient			
		T_{max} (°C)	T_{min} (°C)	P (mm)	Radn (MJ m^{-2})
I	Y_p	0.20	− 0.36**	− 0.26	0.44**
	Y_w	− 0.56**	0.15	0.70**	0.02
	Y_n	0.58**	0.10	− 0.21	− 0.03
	Y_a	− 0.01	0.30	0.53	0.85**
II	Y_p	0.15	− 0.08	− 0.05	0.64**
	Y_w	− 0.42**	0.25	0.61**	0.10
	Y_n	0.61**	0.13	− 0.19	0.13
	Y_a	− 0.25	0.48	0.5	− 0.55
III	Y_p	0.23	− 0.53**	− 0.17	0.57**
	Y_w	− 0.59**	0.18	0.55**	0.01
	Y_n	0.66**	− 0.09	− 0.37**	0.19
	Y_a	− 0.59**	0.12	0.45	− 0.4
IV	Y_p	0.14	− 0.51**	− 0.23	0.69**
	Y_w	− 0.58**	0.07	0.47**	0.15
	Y_n	0.64**	− 0.11	− 0.35**	0.21
	Y_a	− 0.29	0.41	0.38	− 0.21
Whole region	Y_p	0.11	− 0.48**	− 0.13	0.64**
	Y_w	− 0.57**	0.10	0.61**	0.11
	Y_n	0.63**	− 0.04	− 0.32**	0.15
	Y_a	− 0.33	0.34	0.48**	− 0.52

Y_p, Y_w and Y_n from 1961 to 2016, Y_a during 2005–2016. The * and ** indicate statistically significant at $p < 0.05$ and $p < 0.01$, respectively

Table 5 Results of stepwise regression analysis of climatic factors and Y_p, Y_w, Y_n and Y_a of winter wheat in each climate zone and the entire Loess Plateau

Climate zone	Item	Fitting formula	R^2
I	Y_p	Y = 0.17 + 0.002Radn + 0.25Tmax	0.31
	Y_w	Y = 3.51 + 0.013P	0.37
	Y_n	Y = 0.88 + 0.34Tmax	0.34
	Y_a	Y = 0.78–0.003P	0.28
II	Y_p	Y = − 3.8 + 0.004Radn + 0.7Tmax	0.39
	Y_w	Y = 2.34 + 0.013P	0.49
	Y_n	Y = − 2.8 + 0.001Radn + 0.4Tmax	0.40
	Y_a	Y = 13.8–0.003Radn	0.30
III	Y_p	Y = 1.05 + 0.001 Radn + 0.26Tmax	0.29
	Y_w	Y = 3.85 + 0.01P	0.43
	Y_n	Y = − 3 + 0.59Tmax	0.45
	Y_a	Y = 7.23–0.29Tmax	0.34
IV	Y_p	Y = 3.91 + 0.001Radn	0.32
	Y_w	Y = 11.75–0.57Tmax + 0.01P	0.60
	Y_n	Y = 1.05 + 0.34Tmax	0.23
	Y_a	Y = 6.5–0.22Tmax + 0.003P	0.43
Whole region	Y_p	Y = − 1.5 + 0.002Radn + 0.25Tmax	0.52
	Y_w	Y = 3.53 + 0.01P	0.42
	Y_n	Y = − 5.73 + 0.001Radn + 0.55Tmax	0.54
	Y_a	Y = 2.53 + 0.004P	0.40

At the regional scale, the YG_t decreased at a rate of 0.17 t ha^{-1} per year from 2005 to 2016 (Table 6). Most counties of the Loess Plateau showed varying degrees of reduction, ranging from 0.003 to 0.45 t ha^{-1} per year (Fig. 5b). The largest decline in YG_t was observed in zone II at a rate of 0.22 t ha^{-1} per year; declines were also observed in zones I and IV, at 0.16 t ha^{-1} per year (Table 6). In contrast, YG_w increased over the past 55 years, at a rate of 0.012 t ha^{-1} per year across the entire study area (Table 6). In the western Loess Plateau YG_w was relatively high due to increased Y_p, whereas Y_w decreased in these areas (Fig. 5b). The trend of YG_w was lowest in zone II, at 0.006 t ha^{-1} per year, and highest in zone I, at 0.017 t ha^{-1} per year. Across the region, YG_n showed a significantly decreasing trend similar to that observed in YG_t, at 0.011 t ha^{-1} per year (Table 6) and ranging from –0.03 to 0.014 t ha^{-1} per year (Fig. 5h). However, the trends of YG_n were inconsistent among the counties; YG_n increased over time in the western Loess Plateau, but decreased in other regions (Fig. 5h). The highest decreasing trend was observed in zone IV, at 0.012 t ha^{-1} per year, which was more than double the rate

of decline in zone I (Table 6). Weaker decreasing trends were observed in zones II and III.

From 2005 to 2016, the average YG_{tp} was 57% (Table 6), which indicates that Y_a only reached 43% of Y_p on the Loess Plateau during the past few decades and that winter wheat yield can improve greatly in this region. As shown in Fig. 5c, regional differences in YG_{tp} varied greatly (18% to 93%) across the counties, but were mainly distributed between 50 and 75%. Similar to the regional distribution of YG_t (Fig. 5a), relatively high YG_{tp} values were observed in the northwestern Loess Plateau (Fig. 5c). The greatest YG_{tp} (76%) was located in zone I, and was much higher than that of zone IV (47%) (Table 6). On average over the Loess Plateau, YG_w was 27% of Y_p (Table 6). YG_{wp} ranged from 3 to 52% across the entire study area (Fig. 5f). In the central region, YG_{wp} was relatively low (Fig. 5f), primarily due to high Y_w (Fig. 5c), whereas YG_{wp} was relatively high in the northwestern and northeastern regions, consistent the higher Y_n observed in these areas. The lowest YG_{wp} value was observed in zone IV (22%), at almost half of that in zone II (40%) (Table 6). YG_{np} of winter wheat varied from 22 to 54% (average, 39%) throughout the Loess Plateau, indicating the potential for 39% improvement in yield by increasing nitrogen application or improving nitrogen use efficiency. YG_{np} values < 35% were observed in the central Loess Plateau, whereas those > 45% were mainly found in
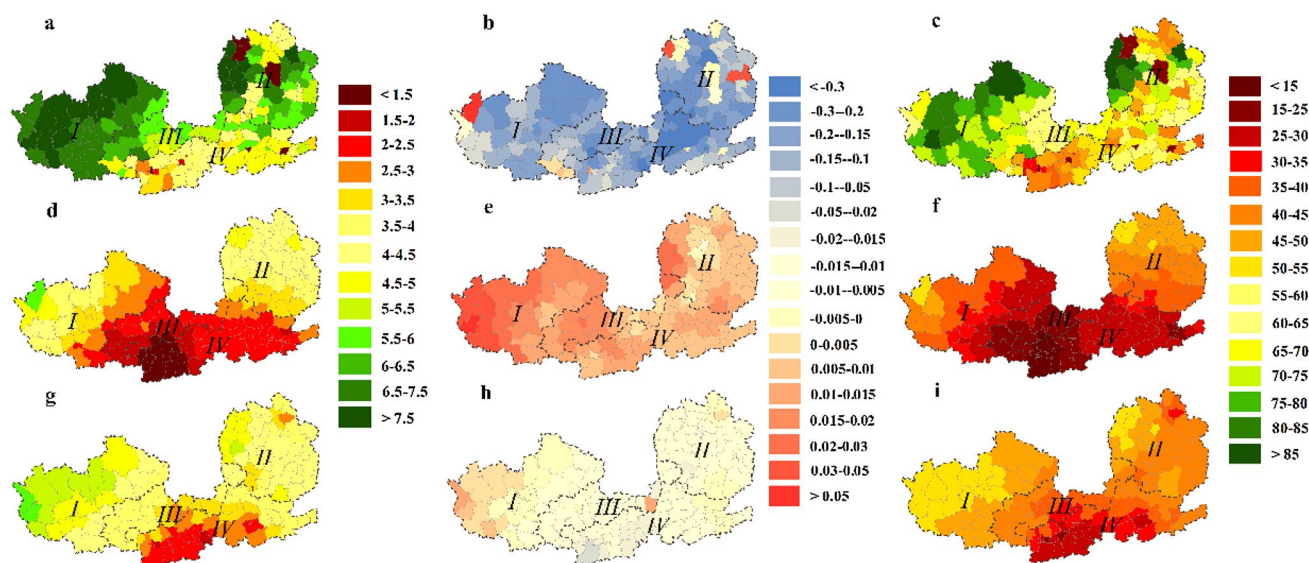
Fig. 5 Yield gaps (t ha^{-1}) between (**a–c**) Y_p and Y_a (YG$_t$); (**d–f**) Y_p and Y_w (YG$_w$); and (**g–i**) Y_p and Y_n (YG$_n$). Spatial distribution, yearly trends, and percentage of Y_p are shown for each county of the Loess Plateau

Table 6 Average and linear trends of YG$_t$, YG$_w$, and YG$_n$, as well YG$_{tp}$, YG$_{wp}$, YG$_{np}$ in each climate zone and the entire Loess Plateau

Climate zone	YG$_t$ (t ha^{-1})		YG$_w$ (t ha^{-1})		YG$_n$ (t ha^{-1})		YG$_{tp}$ (%)	YG$_{wp}$ (%)	YG$_{np}$ (%)
	Mean	Trend(per year)	Mean	Trend(per year)	Mean	Trend(per year)			
I	7.32	− 0.16*	3.26	0.017	4.77	− 0.006	76	34	49
II	5.07	− 0.22*	3.54	0.006	3.87	− 0.01 *	57	40	43
III	5.72	− 0.13*	2.08	0.014	3.55	− 0.009*	64	23	40
IV	4.07	− 0.16*	1.87	0.011	2.89	− 0.012*	47	22	34
Whole region	5.05	− 0.17*	2.35	0.012	3.43	− 0.011*	57	27	39

The time range of YG$_w$, YG$_n$, YG$_{wp}$, YG$_{np}$ were from 1961 to 2016, while the YG$_t$ and YG$_{tp}$ from 2005 to 2016. The * indicate statistically significant at $p < 0.05$

northwestern and northeastern counties (Fig. 5i). The greatest YG$_{np}$ was found in zone I (49%), and the lowest in zone IV (34%) (Table 6).

Discussion

Simulated Y_p

The average simulated Y_p (8.87 t ha^{-1}) of winter wheat in this study was similar to that reported by Li et al. (2001), which was 8.29 t ha^{-1}. Other previous studies reported similar Y_p values of 6.77 in the Indo-Gangetic Plains (Pathak et al., 2003), 8.98 in the Yellow and Huai River Valleys (Sun et al., 2018), and 7.8 t ha^{-1} in Khorasan province (Dei-himfard et al., 2015), suggesting that our results were reliable. Li et al. (2001) reported that Y_p ranged from 7.97 to 8.65 t ha^{-1} for winter wheat on the Loess Plateau; however,

our simulations produced a broader range in this study (7.87–10.7 t ha^{-1}). The difference may be related to factors such as selected cultivars and management measures. In the present study, we selected cultivars appropriate for each climate zone, such as Changwu 89,134, which was bred after 2000 (Zhang et al., 2009), whereas the cultivars used by Li et al. (2001) were the main varieties planted from the late 1980s to the early 1990s. Improved cultivars may have increased the crop yield in our study (He et al., 2015; Liu et al., 2013).

Y_p was mainly determined by temperature and solar radiation during the winter wheat growing season (Tables 4 and 5), which is consistent with the results were reported by Rabbinge (1993). Similar results were reported by Li et al. (2014). Our results also indicate a strong positive effect of solar radiation on Y_p during both the vegetative and reproductive growth periods (flowering to physiological maturity) (0.5 and 0.48, respectively) (Table S3). This may be due to

the fact that the rate of decrease of solar radiation was higher during the sowing to flowering period than during flowering to physiological maturity (Table 2). Previous research have shown that solar radiation in reproductive period is a fine regulatory factor of wheat yield, and the positive correlation between the increase of solar radiation and yield in this period may be due to the increase of grain weight (Lollato & Edwards, 2015; Wardlaw, 1994). Increased temperature shortens the winter wheat growth period, which in turn increases evaporation and decreases soil available water, leading to reduced yield due to drought (Lobell & Asner, 2003; Yu, 1998). Our study found a decreasing trend of minimum temperature from flowering to physiological maturity (Table 2), which explained the negative effect of minimum temperature on Y_p during this period than from sowing to flowering (Table S3).

In the simulation of Yp, nitrogen mainly came from soil organic matter, and we did not consider the effect of long-term winter wheat planting on soil nutrients. After the winter wheat is harvested, the soil organic matter was reset when planting the next year. In actual production, long-term fertilization has an impact on soil physical and chemical properties and soil enzyme activities, which in turn affects winter wheat yield. In follow-up research, this needs to be paid attention to.

Possible Causes of Winter Wheat YG$_t$ Values on the Loess Plateau

The results of this study showed a large gap between Y_p and Y_a. The potential to enhance winter wheat yield on the Loess Plateau by reducing the YG_t was largest in zone I (Table 6), which had the highest Y_p and lowest Y_a values (Table 3). One reason for this result is that Y_p is mainly affected by temperature and solar radiation (Table 4) and the highest solar radiation during the winter wheat growing season was observed in this region (Fig. 3, Table 2). Another reason is that fertilizer input and irrigation are important factors affecting crop yields (Mueller et al., 2012), whereas fertilizer amount per unit area had the greatest impact on Y_a in zone I ($r = 0.86$) (Table S5), and was lower than that of all other climate zones (Table S4). The lowest YG_t was found in zone IV (4.07 t ha^{-1}) (Table 6), leaving smaller potential for further yield improvement than in the other climate zones. This result may be due to the high level of agricultural investment in this area (Table S4), which increased the actual yield of winter wheat. However, we found that the Y_a of the zone was stagnant. Traditional tillage was the most common tillage practice in zone IV region and lead to high erosion rates. Therefore, erosion of agricultural soils in this area may have led to stagnant yields, for example, by reducing soil fertility and effective water holding capacity. Other factors contributing to the yield tendency to stagnate may be variety, shift of

winter wheat production areas to regions with poorer soils and climate, and insufficient or poorly oriented investment in agricultural research and development (Grassini et al., 2013; Licker et al., 2010; Patrignani et al., 2014). Our survey found that many irrigated and well-fertilized arable lands in zone IV have been converted to cash crops, such as medicinal herbs and horticultural crops, driven by economic interests. And winter wheat, which has relatively low economic interest, was planted by farmers on poor quality cropland.

YG_t declined across the study region, which was closely related to increases in agricultural inputs, including irrigation, fertilizer and agricultural machinery (Fig. S1 b, c, d). The continuous decline in winter wheat sowing area indicates that it was difficult to maintain or expand the existing sowing area to increase the total winter wheat yield to reduce the yield gap (Fig. S1a), as described by Foley et al. (2011). Therefore, agronomic technology innovations could be an important strategy for closing the YG_t. For example, the use of early-maturity cultivars and supplementary irrigation could eliminate the adverse effects of drought in late growth (Boling et al., 2010), improving nitrogen management could increase nitrogen recovery efficiency (Jiao et al., 2018), and increased use of agricultural machinery could improve crop emergence; the combined effects of these approaches would allow crops to attain more light, temperature, and nutrient resources. In addition, grain yield has been shown to increase continuously with the implementation of nutrient management policies (Dalgaard et al., 2014; Jiao et al., 2018).

Water and Nitrogen Restrictions on Winter Wheat Yield

Although the Loess Plateau is an arid and semi-arid environment, the negative effect of nitrogen deficiency on winter wheat yield was higher than that of water deficit. Across the study area, Y_w ranged from 4.3 to 7.9 t ha^{-1}, which was higher than Y_n (Table 3), perhaps because reduced precipitation during the growing increased the probability of drought (Fig. 3 and Table 2), which can decrease nitrogen use efficiency (Kersebaum & Nendel, 2014). We adopted the high nitrogen fertilizer application protocol of a previous study to minimize the possibility of nitrogen supply limiting yield in simulating Y_p and Y_w (Li et al., 2016). However, very high nitrogen application can cause excessive vegetative growth, resulting in water stress during the filling stage and leading to lower yield (van Herwaarden et al., 1998).

YG_n was generally greater than YG_w on the Loess Plateau (Table 6). Nitrogen deficiency was the primary driver for large yield gaps, as previously reported by Hochman and Horan (2018). However, the effect of nitrogen deficiency on yield varied among the climate regions. For example, YG_{np} (43%) and YG_{wp} (40%) were similar in zone II, whereas

differences between YG_{np} and YG_{wp} in zones I, III, and IV were greater than 10% (Table 6), likely due to the lack of precipitation in zone II (Table 2), which can cause nitrogen fertilizer to be underutilized. These results demonstrate that compared with the urgent demand for nitrogen fertilizer in zones I, III, and IV, supplementary irrigation was more important than increasing nitrogen fertilizer in zone II. However, closing the yield gap caused by Y_n by increasing nitrogen input would bring additional agricultural inputs and cause subsequent environmental problems (Zhu & Chen, 2002) including soil acidification (Guo et al., 2010), agriculture non-point source pollution (Conley et al., 2009), and greenhouse gas emissions (Liu et al., 2017). Therefore, it is necessary to focus on improving the efficiency of nitrogen fertilizer utilization, such as by optimizing the time and amount of nitrogen application, synergistic application of N, P, K, and genotype selection, while ensuring the reduction of the yield gap and avoiding a waste of resources (Lollato et al., 2019a, b, 2021).

Studies have shown that nitrogen application has a greater effect on grain yield and yield components of winter wheat on the Loess Plateau under irrigated conditions than under non-irrigated conditions (Fu et al., 2014; Zhai & Li, 2006). Therefore, given the current water shortage conditions on the Loess Plateau, we suggest that nitrogen should be supplemented where irrigation is implemented to increase winter wheat yield. We also emphasize that when water stress is severe, increasing nitrogen application rates would reduce the yield of winter wheat (Nielsen & Halvorson, 1991); however, excessive irrigation under the background of low nitrogen application rates could lead to increased nitrogen leaching loss, causing groundwater contamination (Xu et al., 2020).

Conclusion

In this study, we divided winter wheat sowing areas on the Loess Plateau into four agro-climatic zones, and used the APSIM model and spatial interpolation techniques to quantitatively analyze Y_p, attainable yield, and yield gaps in each climate zone. The results showed that the temporal distribution of Y_p was primarily influenced by solar radiation and minimum temperature. The attainable yield (Y_w and Y_n) was affected by precipitation and maximum temperature, whereas the effects of climate factors on attainable yield were variable. For example, precipitation had a positive effect on the temporal change of Y_w and a negative effect on Y_n.

Across the Loess Plateau, large gaps were observed between Y_a and Y_p; thus, winter wheat yield has large room for improvement. The highest yield gap between Y_a and Y_p was observed in the semi-arid (zone II) and the lowest in the humid (zone IV). A lack of nitrogen was the main factor affecting winter wheat yield across the Loess Plateau. However, the effect of nitrogen deficiency on yield varied among climate regions, and the importance of nitrogen for production was regulated by precipitation. Compared with the arid (zone I), semi-humid (zone III), and humid (zone IV) climates, which urgently require more nitrogen fertilizer application, the semi-arid climatic zone (zone II) requires increased irrigation to improve winter wheat yields. Generally, areas with large potential for increased winter wheat yield were mainly distributed in northwestern regions of the Loess Plateau.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

References

Asseng, S., Foster, I., & Turner, N. C. (2011). The impact of temperature variability on wheat yields. *Global Change Biology, 17*(2), 997–1012.

Bai, H. Q., Wang, J., Fang, Q. X., & Yin, H. (2019). Modeling the sensitivity of wheat yield and yield gap to temperature change with two contrasting methods in the North China Plain. *Climatic Change, 156*(4), 589–607.

Bhatia, V. S., Singh, P., Wani, S. P., Chauhan, G. S., Rao, A., Mishra, A. K., & Sriniuas, K. (2008). Analysis of potential yields and yield gaps of rainfed soybean in India using CROPGRO-Soybean model. *Agricultural and Forest Meteorology, 148*(8–9), 1252–1265.

Black, J. N., Bonython, C. W., & Prescott, J. A. (1954). Solar radiation and the duration of sunshine. *Quarterly Journal of the Royal Meteorological Society, 80*(344), 231–235.

Boling, A. A., Tuong, T. P., van Keulen, H., Bouman, B. A. M., Suganda, H., & Spiertz, J. H. J. (2010). Yield gap of rainfed rice in farmers' fields in Central Java, Indonesia. *Agricultural Systems, 103*(5), 307–315.

Cassman, K. G. (1999). Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. *Proceedings of the National Academy of Sciences of the United States of America, 96*(11), 5952–5959.

Chen, W., Shen, Y. Y., Robertson, M. J., Probert, M. E., & Bellotti, W. D. (2008). Simulation analysis of lucerne-wheat crop rotation on the Loess Plateau of Northern China. *Field Crops Research, 108*(2), 179–187.

Chen, Y., Zhang, Z., Tao, F. L., Wang, P., & Wei, X. (2017). Spatio-temporal patterns of winter wheat yield potential and yield

gap during the past three decades in North China. *Field Crops Research, 206*, 11–20.

Cheng, J., Yang, K., & Xiang, J. (2017). The impact of the universal two-child policy on China's medium and long term food security. *Issues in Agricultural Economy, 38*(12), 8–16. In Chinese with English abstract.

Conley, D. J., Paerl, H. W., Howarth, R. W., Boesch, D. F., Seitzinger, S. P., Havens, K. E., Lancelot, C., & Likens, G. E. (2009). Ecology controlling eutrophication: Nitrogen and phosphorus. *Science, 323*(5917), 1014–1015.

Dai, Y. J., Shangguan, W., Duan, Q. Y., Liu, B. Y., Fu, S. H., & Niu, G. (2013). Development of a China dataset of soil hydraulic parameters using pedotransfer functions for land surface modeling. *Journal of Hydrometeorology, 14*(3), 869–887.

Dalgaard, T., Hansen, B., Hasler, B., Hertel, O., Hutchings, N. J., Jacobsen, B. H., Jensen, L. S., Kronvang, B., Olesen, J. E., Schjorring, J. K., Kristensen, I. S., Graversgaard, M., Termansen, M., & Vejre, H. (2014). Policies for agricultural nitrogen management-trends, challenges and prospects for improved efficiency in Denmark. *Environmental Research Letters, 9*(11), 115002.

de Oliveira, A. S., Slafer, G. A., Fritz, A. K., & Lollato, R. P. (2020). Physiological basis of genotypic response to management in dryland wheat. *Frontiers in Plant Science, 10*, 1644.

Deihimfard, R., Mahallati, M. N., & Koocheki, A. (2015). Yield gap analysis in major wheat growing areas of Khorasan province, Iran, through crop modelling. *Field Crops Research, 184*, 28–38.

Edreira, J. I. R., Mourtzinis, S., Conley, S. P., Roth, A. C., Ciampitti, I. A., Licht, M. A., Kandel, H., Kyveryga, P. M., Lindsey, L. E., Mueller, D. S., Naeve, S. L., Nafziger, E., Specht, J. E., Stanley, J., Staton, M. J., & Grassini, P. (2017). Assessing causes of yield gaps in agricultural areas with diversity in climate and soils. *Agricultural and Forest Meteorology, 247*, 170–180.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., & Gerber, J.S., et al. (2011). Solutions for a cultivatedplanet. *Nature, 478*, 337–342.

Fu, Q. P., Wang, Q. J., Shen, X. L., & Fan, J. (2014). Optimizing water and nitrogen inputs for winter wheat cropping system on the Loess Plateau. *Journal of Arid Land, 6*(2), 230–242.

Godfray, H. C. J., Pretty, J., Thomas, S. M., Warham, E. J., & Beddington, J. R. (2011). Linking policy on climate and food. *Science, 331*(6020), 1013–1014.

Grassini, P., Eskridge, K. M., & Cassman, K. G. (2013). Distinguishing between yield advances and yield plateaus in historical crop production trends. *Nature Communications, 4*(1), 1–11.

Grassini, P., van Bussel, L. G. J., Van Wart, J., Wolf, J., Claessens, L., Yang, H., Boogaard, H., de Groot, H., van Ittersum, M. K., & Cassman, K. G. (2015). How good is good enough? Data requirements for reliable crop yield simulations and yield-gap analysis. *Field Crops Research, 177*, 49–63.

Guo, J. H., Liu, X. J., Zhang, Y., Shen, J. L., Han, W. X., Zhang, W. F., Christie, P., Goulding, K. W. T., Vitousek, P. M., & Zhang, F. S. (2010). Significant acidification in major chinese croplands. *Science, 327*(5968), 1008–1010.

He, D., Wang, J., Pan, Z. H., Dai, T., Wang, E. L., & Zhang, J. P. (2017). Changes in wheat potential productivity and drought severity in Southwest China. *Theoretical and Applied Climatology, 130*(1–2), 477–486.

He, L., Asseng, S., Zhao, G., Wu, D. R., Yang, X. Y., Zhuang, W., Jin, N., & Yu, Q. (2015). Impacts of recent climate warming, cultivar changes, and crop management on winter wheat phenology across the Loess Plateau of China. *Agricultural and Forest Meteorology, 200*, 135–143.

Hochman, Z., & Horan, H. (2018). Causes of wheat yield gaps and opportunities to advance the water-limited yield frontier in Australia. *Field Crops Research, 228*, 20–30.

Hochman, Z., & Waldner, F. (2020). Simplicity on the far side of complexity: optimizing nitrogen for wheat in increasingly variable rainfall environments. *Environmental Research Letters, 15*(11), 114060.

Jaenisch, B. R., Silva, A. D., DeWolf, E., Ruiz-Diaz, D. A., & Lollato, R. P. (2019). Plant population and fungicide economically reduced winter wheat yield gap in Kansas. *Agronomy Journal, 111*(2), 650–665.

Jiao, X. Q., He, G., Cui, Z. L., Shen, J. B., & Zhang, F. S. (2018). Agri-environment policy for grain production in China: Toward sustainable intensification. *China Agricultural Economic Review, 10*(1), 78–92.

Kalra, N., Chakraborty, D., Kumar, P. R., Jolly, M., & Sharma, P. K. (2007). An approach to bridging yield gaps, combining response to water and other resource inputs for wheat in northern India, using research trials and farmers' fields data. *Agricultural Water Management, 93*(1–2), 54–64.

Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., Huth, N. I., Hargreaves, J. N. G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J. P., Silburn, M., Wang, E., Brown, S., Bristow, K. L., Asseng, S., et al. (2003). An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy, 18*(3–4), 267–288.

Kersebaum, K. C., & Nendel, C. (2014). Site-specific impacts of climate change on wheat production across regions of Germany using different CO_2 response functions. *European Journal of Agronomy, 52*, 22–32.

Khaliq, T., Gaydon, D. S., Ahmad, M. U. D., Cheema, M. J. M., & Gull, U. (2019). Analyzing crop yield gaps and their causes using cropping systems modelling-A case study of the Punjab rice-wheat system, Pakistan. *Field Crops Research, 232*, 119–130.

Kong, X. B. (2014). China must protect high-quality arable land. *Nature, 506*(7486), 7.

Lambin, E. F., & Meyfroidt, P. (2011). Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences of the United States of America, 108*(9), 3465–3472.

Li, J., Wang, L. X., Shao, M. A., & Fang, T. L. (2001). Simulation of wheat potential productivity on Loess Plateau region of China. *Journal of Natural Resources, 16*(2), 161–165. In Chinese with English abstract.

Li, K. N., Yang, X. G., Liu, Z. J., Zhang, T. Y., Lu, S., & Liu, Y. (2014). Low yield gap of winter wheat in the North China Plain. *European Journal of Agronomy, 59*, 1–12.

Li, X. M., Xun, C. X., & Li, K. Y. (1999). Effect of water and fertilizer on economic properties of winter wheat in Loess Plateau galley regions. *Chinese Journal of Applied Ecology, 10*(3), 309–311. In Chinese with English abstract.

Li, Y. S., Guo, M. H., & Dong, D. X. (1991). *Water-yield potentiality of arid crop and water-fertilizer-yield relationship in Weibei Arid Plateau. Efficient ecological and economic system in Wangdong watershed of Changwu county.* Scientific and Technical Documents Publishing House. In Chinese with English abstract.

Li, Y., Li, W. P., & Li, X. F. (2010). Identification and analysis of drought resistance of different winter wheat cultivars. *Agricultural Research in the Arid Areas, 28*(2), 17–21. In Chinese with English abstract.

Li, Z. P., Song, M. D., Feng, H., & Zhao, Y. (2016). Within-season yield prediction with different nitrogen inputs under rain-fed condition using CERES-Wheat model in the northwest of China. *Journal of the Science of Food and Agriculture, 96*(8), 2906–2916.

Li, Z., Zhang, Q., Yang, Q., Yang, X., Li, J. C., Cui, S., & Shen, Y. Y. (2017). Yield, water productivity and economic return of dryland wheat in the Loess Plateau in response to conservation tillage practices. *Journal of Agricultural Science, 155*(8), 1–15.

Lian, H. D., Qin, C., & He, Z. (2020). A synergistic increase in water and nitrogen use efficiencies in winter wheat cultivars released between the 1940s and the 2010s for cultivation in the drylands of the shaanxi Province in China? *Agricultural Water Management, 240*, 106308.

Licker, R., Johnston, M., Foley, J. A., Barford, C., Kucharik, C. J., Monfreda, C., & Ramankutty, N. (2010). Mind the gap: How do climate and agricultural management explain the "yield gap" of croplands around the world? *Global Ecology and Biogeography, 19*(6), 769–782.

Liu, L., Zhu, Y., Tang, L., Cao, W., & Wang, E. (2013). Impacts of climate changes, soil nutrients, variety types and management practices on rice yield in East China: A case study in the Taihu region. *Field Crops Research, 149*, 40–48.

Liu, S. W., Lin, F., Wu, S., Ji, C., Sun, Y., Jin, Y. G., Li, S. Q., Li, Z. F., & Zou, J. W. (2017). A meta-analysis of fertilizer-induced soil NO and combined NO+N2O emissions. *Global Change Biology, 23*(6), 2520–2532.

Liu, Z. T., Yin, Y. L., Pan, J. X., Ying, H., Lu, D. J., Batchelor, W. D., Ma, W. Q., & Cui, Z. L. (2019). Yield gap analysis of county level irrigated wheat in Hebei Province, China. *Agronomy Journal, 111*(5), 2245–2254.

Lobell, D. B., & Asner, G. P. (2003). Climate and management contributions to recent trends in US agricultural yields. *Science, 299*(5609), 1032–1032.

Lollato, R. P., & Edwards, J. T. (2015). Maximum attainable winter wheat yield andresource use efficiency in the southern Great Plains. *Crop Science, 55*, 2863–2876.

Lollato, R. P., Edwards, J. T., & Ochsner, T. E. (2017). Meteorological limits to winter wheat productivity in the US southern Great Plains. *Field Crops Research, 203*, 212–226.

Lollato, R. P., Ruiz Diaz, D. A., DeWolf, E., Knapp, M., Peterson, D. E., & Fritz, A. K. (2019a). Agronomic practices for reducing wheat yield gaps: A quantitative appraisal of progressive producers. *Crop Science, 59*(1), 333–350.

Lollato, R. P., Figueiredo, B. M., Dhillon, J. S., Arnall, D. B., & Raun, W. R. (2019b). Wheat grain yield and grain-nitrogen relationships as affected by N, P, and K fertilization: A synthesis of long-term experiments. *Field Crops Research, 236*, 42–57.

Lollato, R. P., Jaenisch, B. R., & Silva, S. R. (2021). Genotype-specific nitrogen uptake dynamics and fertilizer management explain contrasting wheat protein concentration. *Crop Science, 61*(3), 2048–2066.

Lu, Y. Q., Liu, Y. X., Zhou, F. B., Zhang, Z. M., Jian, Z. H., & Wang, W. J. (2019). Effect of different water supplies on nitrogen accumulation distribution and yield in wheat. *Acta Agriculturae Borealioccidentalis Sinica, 20*(11), 1760–1768. In Chinese with English abstract.

McCown, R. L., Hammer, G. L., Hargreaves, J. N. G., Holzworth, D. P., & Freebairn, D. M. (1996). APSIM: A novel software system for model development, model testing and simulation in agricultural systems research. *Agricultural Systems, 50*(3), 255–271.

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., & Foley, J. A. (2012). Closing yield gaps through nutrient and water management. *Nature, 490*(7419), 254–257.

Munaro, L. B., Hefley, T. J., DeWolf, E., Haley, S., Fritz, A. K., Zhang, G., Haag, A. J., Schlegel, A. J., Edwards, J. T., Marburger, D., Alderman, P., Jones-Diamond, S. M., Johnson, J., Lingenfelser, J. E., Unêda-Trevisoli, S. H., & Lollato, R. P. (2020). Exploring long-term variety performance trials to improve environment-specific genotype× management recommendations: A case-study for winter wheat. *Field Crops Research, 255*, 1078.

Nielsen, D. C., & Halvorson, A. D. (1991). Nitrogen fertility influence on water stress and yield of winter wheat. *Agronomy Journal, 83*(6), 1065–1070.

Nyombi, K. (2019). Soil data importance in guiding maize intensification and yield gap estimations in East Africa. *Archives of Agronomy and Soil Science, 65*(6), 809–821.

Olesen, J. E., & Bindi, M. (2002). Consequences of climate change for European agricultural productivity, land use and policy. *European Journal of Agronomy, 16*(4), 239–262.

Pathak, H., Ladha, J. K., Aggarwal, P. K., Peng, S., Das, S., Singh, Y., Singh, B., Kamra, S. K., Mishra, B., Sastri, A., Aggarwal, H. P., Das, D. K., & Gupta, R. K. (2003). Trends of climatic potential and on-farm yields of rice and wheat in the Indo-Gangetic Plains. *Field Crops Research, 80*(3), 223–234.

Patrignani, A., Lollato, R. P., Ochsner, T. E., Godsey, C. B., & Edwards, J. T. (2014). Yield gap and production gap of rainfed winter wheat in the southern Great Plains. *Agronomy Journal, 106*(4), 1329–1339.

Pradhan, P., Fischer, G., van Velthuizen, H., Reusser, D. E., & Kropp, J. P. (2015). Closing yield gaps: how sustainable can we be? *PLoS ONE, 10*(6), e0129487.

Rabbinge, R. (1993). The ecological background of food-production. *Ciba Foundation Symposia, 177*, 2–29.

Ru, X. Y., Li, G., Chen, G. P., Zhang, T. S., & Yan, L. J. (2019). Regulation effects of water and nitrogen on wheat yield and biomass in different precipitation years. *Acta Agronomica Sinica, 45*(11), 1725–1734. In Chinese with English abstract.

Schierhorn, F., Mueller, D., Prishchepov, A. V., Fararnarzi, M., & Salmann, A. (2014). The potential of Russia to increase its wheat production through cropland expansion and intensification. *Global Food Security-Agriculture Policy Economics and Environment, 3*(3–4), 133–141.

Schils, R., Olesen, J. E., Kersebaum, K. C., Rijk, B., Oberforster, M., Kalyada, V., Khitrykau, M., Gobin, A., Kirchev, H., Manolova, V., Manolov, I., Trnka, M., Hlavinka, P., Palosuo, T., Peltonen-Sainio, P., Jauhiainen, L., Lorgeou, J., Marrou, H., Danalatos, N., et al. (2018). Cereal yield gaps across Europe. *European Journal of Agronomy, 101*, 109–120.

Shewry, P. R., & Hey, S. J. (2015). The contribution of wheat to human diet and health. *Food and Energy Security, 4*(3), 178–202.

Shi, W. X. (2008). The wheat variety Xifeng Symbol's seed hereditary foundation and its breeding objectives and countermeasures for rain-fed land in east Gansu Province. *Agricultural Research in the Arid Areas, 26*(4), 180–195. In Chinese with English abstract.

Silva, J. V., Tenreiro, T. R., Spätjens, L., Anten, N. P., van Ittersum, M. K., & Reidsma, P. (2020). Can big data explain yield variability and water productivity in intensive cropping systems? *Field Crops Research, 255*, 107828.

Sun, S., Yang, X. G., Lin, X. M., Sassenrath, G. F., & Li, K. N. (2018). Winter wheat yield gaps and patterns in china. *Agronomy Journal, 110*(1), 319–330.

van Herwaarden, A. F., Farquhar, G. D., Angus, J. F., Richards, R. A., & Howe, G. N. (1998). "Haying-off", the negative grain yield response of dryland wheat to nitrogen fertiliser-I. Biomass, grain yield, and water use. *Australian Journal of Agricultural Research, 49*(7), 1067–1081.

van Ittersum, M. K., Cassman, K. G., Grassini, P., Wolf, J., Tittonell, P., & Hochman, Z. (2013). Yield gap analysis with local to global relevance: A review. *Field Crops Research, 143*, 4–17.

van Wart, J., van Bussel, L. G. J., Wolf, J., Licker, R., Grassini, P., Nelson, A., Boogaard, H., Gerber, J., Mueller, N. D., Claessens, L., van Ittersum, M. K., & Cassman, K. G. (2013). Use of agroclimatic zones to upscale simulated crop yield potential. *Field Crops Research, 143*, 44–55.

Wang, E. L., Xu, J. H., & Smith, C. J. (2008). Value of historical climate knowledge, SOI-based seasonal climate forecasting and stored soil moisture at sowing in crop nitrogen management in south eastern Australia. *Agricultural and Forest Meteorology, 148*(11), 1743–1753.

Wardlaw, I. F. (1994). The effect of high-temperature on kernel development in wheat-variability related to preheading and postanthesis conditions. *Australian Journal of Plant Physiology, 21*, 731–739.

Xu, J. T., Wang, X. Y., Ding, Y. B., Mu, Q., Cai, H. J., Ma, C. G., & Saddique, Q. (2020). Effects of irrigation and nitrogen fertilization management on crop yields and long-term dynamic characteristics of water and nitrogen transport at deep soil depths. *Soil and Tillage Research, 198*, 104536.

Xu, Y., Wang, L. L., Chen, W., Li, H. B., & Deng, X. P. (2013). Effect of different nitrogen levels on grain-filling characteristics and yield of two dryland wheat cultivars for superior and interior grain. *Journal of Triticeae Crops, 33*(3), 489–494. In Chinese with English abstract.

Yu, Q. (1998). Simulation of the physiological responses of C-3 plant leaves to environmental factors by a model which combines stomatal conductance, photosynthesis and transpiration. *Acta Botanica Sinica, 40*(8), 740–754.

Zhai, B. N., & Li, S. X. (2006). Study on the key and sensitive stage of winter wheat responses to water and nitrogen coordination. *Agricultural Sciences in China, 5*(1), 50–56.

Zhang, Y., Hao, M., Pang, Y., & Fan, H. (2009). Study on evolution of species traits and quality characters of Changwu brand in dryland of the Loess. *Acta Agriculturae Boreali-Occidentalis Sinica, 18*(1), 65–70. In Chinese with English abstract.

Zhou, D., Yu, Q., Li, A., & Li, J. (2020). Effect of nitrogen application rate on winter wheat yield and grain quality in Weibei dryland. *Journal of Triticeae Crops, 40*(7), 818–825. In Chinese with English abstract.

Zhu, Z. L., & Chen, D. L. (2002). Nitrogen fertilizer use in China: Contributions to food production, impacts on the environment and best management strategies. *Nutrient Cycling in Agroecosystems, 63*(2–3), 117–127.

Zu, Q., Mi, C. R., Liu, D. L., He, L., Kuang, Z. M., Fang, Q. X., Ramp, D., Li, L., Wang, B., Chen, Y. L., Li, J., Jin, N., & Yu, Q. (2018). Spatio-temporal distribution of sugarcane potential yields and yield gaps in Southern China. *European Journal of Agronomy, 92*, 72–83.