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Can China get out of soy dilemma? A yield gap analysis of soybean in China

Yucheng Wang¹ · Xiaoxia Ling¹ · Chunmei Ma² · Changyan Liu³ · Wei Zhang⁴ · Jianliang Huang¹ · Shaobing Peng¹ · Nanyan Deng¹

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Abstract

China is the largest soybean-consuming country in the world, but its self-sufficiency rate (SSR) of 16% is very low and it therefore has to heavily rely on imports. To solve the soybean dilemma in China, it is necessary to examine the maximum amount of soybean that could be grown on the land currently used, how much land could reasonably be used to expand soybean acreage, and whether China could sustainably increase soybean self-sufficiency to reduce the risks of import reliance. To answer these questions, our paper presents a high-resolution spatial analysis of potential soybean production in China using primary data of weather and crop production practices that govern this potential. We employed a “bottom-up” scaling protocol to estimate gaps between potential yield with optimal management and current yields in three major soybean-planting regions, namely, Northeast China, Central China, and South China. We found that current soybean yield gap (Yg) in China is 49% and 45% of potential yield under irrigated and rainfed cropping systems, respectively. By closing the yield gap, Northeast China could provide additional soybean production equivalent to 32% of the current national total. Our results show that SSR could only be increased to 21–23% in 2030 by Yg closure alone but could be increased to a maximum of 52% by combining Yg closure and a reasonable area expansion. Even so, at least 61.08 million tons of soybean accounting for 38% of global soybean trade would still need to be imported to meet future domestic demand. We discuss strategies for soybean production increase based on Yg closure in the most valuable areas and cropland expansion in a sustainable manner in order to increase SSR as well as lessen the import pressure on the global market.

Keywords Soybean · Potential yield · Yield gap · Self-sufficiency rate · Maize-soybean intercropping system

Yucheng Wang and Xiaoxia Ling contributed equally to this work.

✉ Nanyan Deng
nydeng@mail.hzau.edu.cn

- ¹ National Key Laboratory of Crop Genetic Improvement, Hubei Hongshan Laboratory, MARA Key Laboratory of Crop Ecophysiology and Farming System in the Middle Reaches of the Yangtze River, College of Plant Science and Technology, Huazhong Agricultural University, Wuhan 430070, Hubei, China
- ² College of Agricultural, Northeast Agricultural University, Harbin 150030, Heilongjiang, China
- ³ Institute of Food Crops, Hubei Academy of Agricultural Sciences, Wuhan 430072, Hubei, China
- ⁴ Soybean Research Institute, Jilin Academy of Agricultural Science, Changchun 130033, Jilin, China

1 Introduction

Soybean (*Glycine max* (L.) Merrill) is an important crop for China with an annual domestic demand of 117 million tons (Mt), of which 13% is consumed as food and 84% is processed into soybean meal and edible oil (CAOC 2021; USDA 2022). The demand for soybean meal and oil has been increasing greatly in the last two decades in China (Fig. 1a) due to the increase in people's income accompanied by a dietary change and the rapid development of animal husbandry (Gale et al. 2019; Zhao et al. 2021a). Currently, domestic soybean production only meets ca. 16% of national demand, and the rest depends on imports from other countries, mainly the USA, Brazil, and Argentina (Gale et al. 2019). Due to the high price linkage coefficient (0.92) between domestic and international soybean prices, farmers' income is greatly affected by the fluctuation in the global soybean market, especially under the climate change

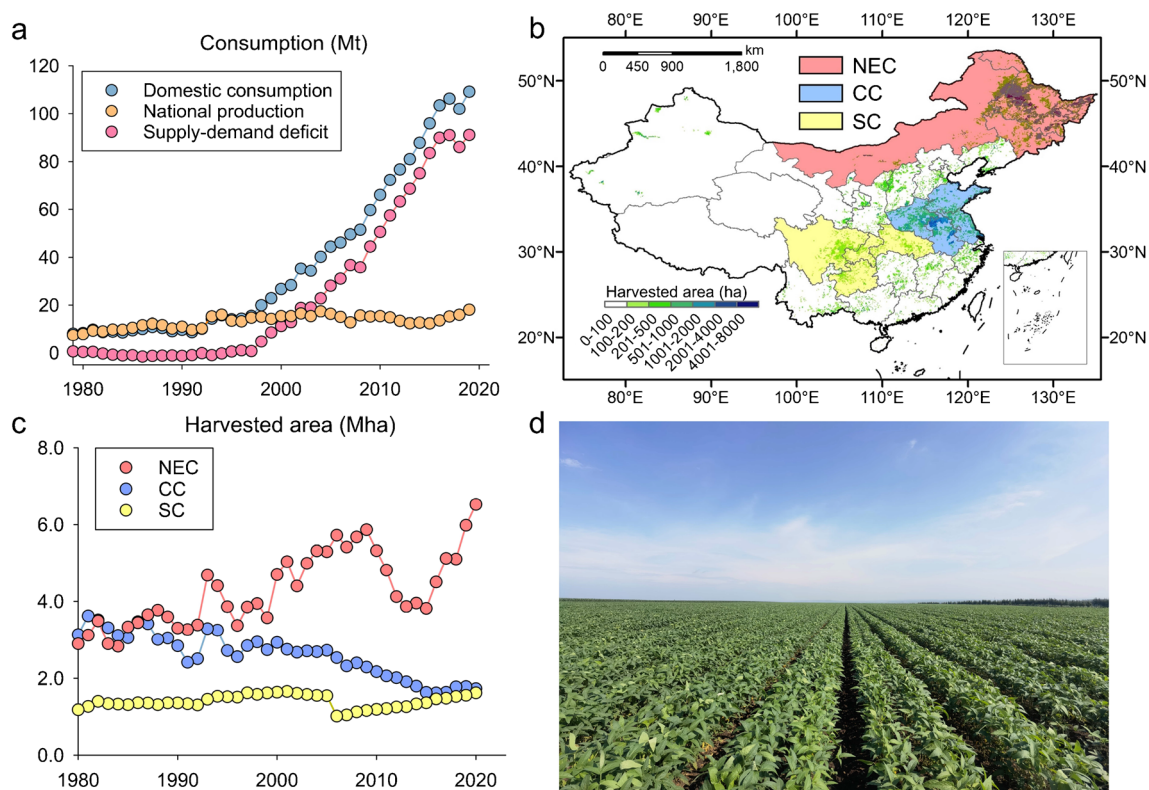


Fig. 1 Information on soybean production system in China. **a** Soybean production and consumption (Mt) in China. **b** Major soybean planting regions and provinces in China. **c** Historical changes in soybean area (Mha) in three major soybean planting regions, namely,

Northeast China (NEC), Central China (CC), and South China (SC). **d** Soybean was planted in one of our experimental sites in Heihe, Heilongjiang Province, as an example.

environment (Bhattarai et al. 2017; CAAS 2022). Generally, China's annual soybean imports have accounted for approximately 60% of global soybean trade in recent years already (USDA 2022). However, it is projected by the China Agricultural Outlook Committee (CAOC) that China's soybean consumption is increasing at a fast speed and will increase continuously by ca. 9% in 2030 (CAOC 2021).

The heavy dependence on soybean imports has threatened China's edible oil security in recent years, and the Chinese government has issued several policies to increase national soybean production and ensure soybean market stability since 2016. For example, a *National Planting Structure Adjustment Plan* was released, and a soybean target price policy was implemented (MARA 2016). As a result, soybean area has been increasing rapidly (Fig. 1c), especially in Northeast China with plain terrain and high mechanical rate (Fig. 1d at the experimental site was shown as an example). With a 71% soybean area increase through area transformation from the low-yielding paddy fields that have excessively consumed groundwater resources since 2016, the area dedicated to soybean in Northeast China currently accounts for 65% of the country's level (NBSC 2022). However, the rapid expansion of soybean areas has also caused many problems

such as intensified water stress and drought frequency (Li et al. 2022; Zhao et al. 2022), and the cultivation system in Northeast China is becoming increasingly vulnerable. The other two major soybean-growing regions only account for 35% of soybean area, namely, Central China and Southern China, due to the mountainous and hilly topography which lacks smaller machines and irrigation intrastation (Iqbal et al. 2019), resulting in a slow area expansion and difficulty in production increase (Fig. 1, Fig. S1). Multiple policies have been released to promote an innovative intercropping system for soybean production increases in Central China and South China (MARA 2019). However, it remains largely unclear to what extent soybean production could be increased and where would be the most valuable regions for R&D investment by implementing these policies and measures. It is therefore vital for the edible oil security in China to determine whether the country can get out of this dilemma and increase its self-sufficiency rate (SSR).

In this study, we conducted a soybean yield gap (Yg) study at different spatial levels to identify the areas with large potential for further production increase in China. Yield gap represents the difference between yield potential (Yp) and current farm yield (Ya). The analysis of Yg provides insights into

where the most valuable areas for yield increase are on existing cropland and informs research prioritization with adequate spatial resolution and agronomic relevance (van Wart et al. 2013c; Cassman and Grassini 2020). Yield potential is defined as the highest yield with optimal management practices in a given region, which is only determined by local climate conditions without the impact of biotic or abiotic stresses (Evans and Fischer 1999). For a rainfed cropping system, the potential yield is defined as water-limited potential yield (Yw) with the impact of water (van Ittersum et al. 2013). Many studies have evaluated soybean Yg in major soybean-producing countries such as the USA (10–30% of Yp), Brazil (42% of Yw), Argentina (32% of Yw), and India (54% of Yw and 67% of Yp) (Bhatia et al. 2008; Grassini et al. 2015a; Merlos et al. 2015; Sentelhas et al. 2015). Few studies on soybean Yg have been performed in China. Liu et al. (2021) reported a large soybean Yg of 52% of Yp in China based on county-level data aggregation and a maximum SSR of 45% by Yg closure and area expansion from the shifting of maize area. A recent study has shown the different Yp limitations in the three major soybean regions which should have different yield increase strategies (Wu et al. 2023). More studies are needed on the evaluation of Yg at different spatial levels, such as agricultural zones and specific areas to explicitly explore the potential for soybean production increase in China.

Global Yield Gap Atlas protocol (GYGA, www.yieldgap.org) was used for Yg evaluation, which has been widely used at large spatial scales (Monzon et al. 2021; Wang et al. 2022; Huang et al. 2023). It is a bottom-up upscaling approach that includes agronomic climate zone (CZ) classification, reference weather station (RWS) selection, crop modeling, and data collection with strict data quality control (Grassini et al. 2015b; van Bussel et al. 2015; van Wart et al. 2013c). In China, although more than 95% of the soybean area in Northeast China is rainfed, only 50% and 67% of soybean areas in Central China and South China are rainfed, respectively (Yu et al. 2020), which means that the importance of irrigation to production increases is also worth studying. In this study, a spatially explicit yield gap analysis at different levels following GYGA protocols was conducted in China to evaluate the Yp, Yw, Ya, and Yg of soybean at the climate zone, regional, and country levels; investigate exploitable production at the regional and country levels; identify the areas with great potential for further production increases; and evaluate future soybean SSR under reasonable scenarios.

2 Materials and methods

2.1 Data source and quality control

Daily weather data of 836 weather stations covering all over China from 2010–2019 (Fig. 2a) were provided by China

Meteorological Administration (CMA 2022) including maximum temperature, minimum temperature, and precipitation. Radiation data were obtained from NASA POWER Data Access Viewer (NASA 2022). It was proven that radiation data from NASA POWER in combination with the meteorological data on the ground were suitable for model simulation (van Wart et al. 2013a; White et al. 2011). The weather data were processed to exclude outliers and fill in missing data following the GYGA protocols (Grassini et al. 2015b; van Wart et al. 2013b). Soil data for model simulation were from the Global High-Resolution Soil Profile Database, including soil properties and hydraulic properties such as soil bulk density, texture, organic carbon, pH, saturated hydraulic conductivity, field capacity, and wilting point (Han et al. 2015; Komarek et al. 2018). The data of actual soybean area and yield were from the national and municipal bureau of statistics (NBSC 2013–2020). The soybean harvested area map was from spatial production allocation model (SPAM) of the latest version SPAM 2010 (Yu et al. 2020; IFPRI 2019). The SPAM 2010 is widely used worldwide by using a cross-entropy approach to make plausible estimates of both rainfed and irrigated crop distribution within the data of crop production, cropland, population density, etc.

2.2 Adjustment of soybean area

Soybean area in Northeast China from SPAM 2010 was adjusted based on municipal data from NBSC because of the shifts of major soybean areas within Northeast China in the last decade, which could not be well depicted by SPAM 2010 with the data from 2009 to 2011. In brief, soybean area in Northeast China at the municipal level was aggregated by using the NBSC data from 2018 to 2020 and compared with the area in SPAM 2010. The ratio of changes was calculated to adjust the area in SPAM 2010 as follows:

$$A_{CZ} = \sum_{i=1}^n A_{STAT_i} / A_{SPAM_i} \times A_{City_i} \quad (1)$$

where A_{CZ} indicates the adjusted area in a CZ; n indicates the number of cities that have a spatial intersection within a CZ; A_{STAT} indicates the statistical soybean area in NBSC and A_{SPAM} indicates the gridded soybean area in SPAM 2010 of a city; A_{City} indicates the gridded soybean area in SPAM 2010 where city and CZ have a spatial intersection. More details of area adjustment can be found in Fig. S2.

2.3 Selection of reference weather station

Based on the GYGA protocol, for RWS selection, CZs were used first to distinguish the regions with similar climate conditions by considering harvested area of major food crops and the matrix of three categorical variables: 10

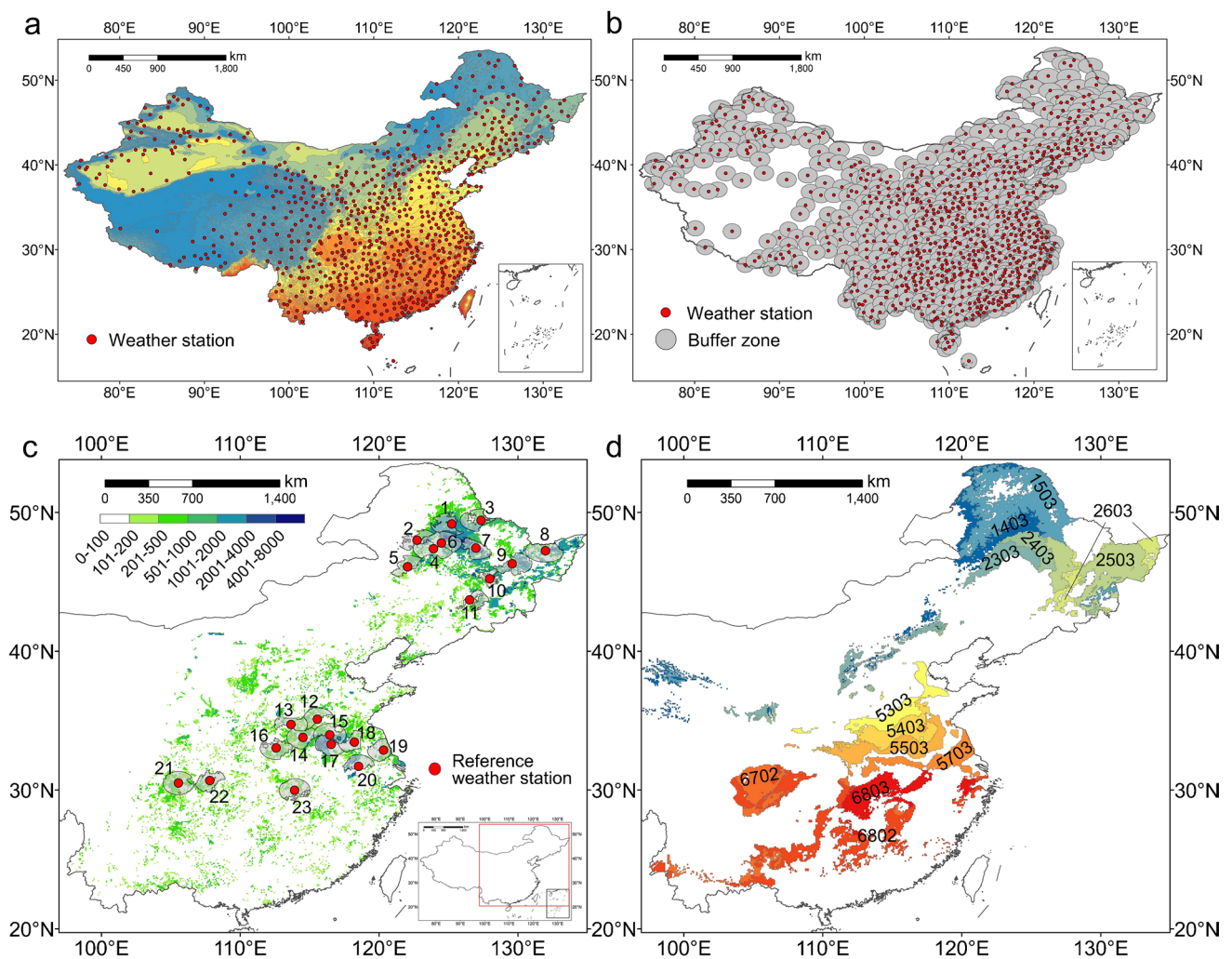


Fig. 2 Reference weather station (RWS) selection. **a** 836 weather stations (red dots) and 139 climate zones (CZ, different colors) in China. **b** The 100 km buffer zones of 836 weather stations (round gray circles).

c Selected RWSs (red dots) with clipped buffer zones (irregular gray circles). **d** Distribution of selected CZs with different colors.

degrees of growing degree days with base temperature of 0°C, 10 degrees of aridity index (annual total precipitation divided by annual total potential evapotranspiration), and 3 degrees of temperature seasonality (the standard deviation of monthly average temperature). More details about CZ classification can be found in van Wart et al. (2013c). In total, China was divided into 139 CZs (Fig. 2a). After CZ classification, a 100 km radius buffer zone was created for 836 weather stations and was subsequently clipped by the CZ border (Fig. 2b). Then, the soybean area in each clipped buffer zone was calculated and ranked from the largest to the smallest, and the buffer zones with the largest crop area were selected as RWSs until the summed soybean area reached ca. 50% of the national soybean area. If the distance between the two adjacent RWSs within one CZ was less than 180 km, one of them was removed. More details can be found in van Bussel et al. (2015) and GYGA website (www.yieldgap.org).

As a result, a total of 23 RWSs were selected, covering 43% of total soybean area, and the RWSs were distributed in 13 CZs, accounting for 74% of total soybean area (Fig. 2c, d). The selection was slightly less than 50% due to the sparse distribution of soybean areas in South China with small area buffer zones (Fig. 2c).

2.4 Potential yield simulation

For Yp simulation, CROPGRO-Soybean model embedded in the Decision Support System for Agrotechnology Transfer (DSSAT, v4.7) was used in this study, which has been used widely for soybean growth simulation and management practice improvement worldwide (Bebeley et al. 2022; da Silva et al. 2021; Guo et al. 2023; Mulazzani et al. 2022; Perondi et al. 2022). In this model, soil, plant, and soil-plant-atmosphere systems were simulated on a

daily basis (Boote et al. 1998; Jones et al. 2003). To simulate Yp, CROPGRO-Soybean model was first calibrated and validated based on crop data of phenology, biomass, and grain yield from multiyear or multilocation high-yielding experiments conducted in major soybean regions (Table 1). Crop data from one year or one location were used for calibration, and the data from the other year or location of the same experiment were used for validation. Management practices followed the high-yielding experiments, which were set according to local high-yielding management practices with dominant cultivars, sufficient water and fertilizer supply, and strict control of pests, diseases, and weeds by major soybean research institutes and universities in China. The data we used for calibration and validation for each variety are from one high-yielding experiment with a dominant local variety over two years or two sites.

For model calibration and validation, the trial-and-error method and the generalized likelihood uncertainty estimation (GLUE) method were used to calibrate crop parameters. The GLUE method has been widely used for model calibration in previous studies, and desirable calibration results could be achieved by setting a large prior distribution (He et al. 2010; Jones et al. 2011). Specifically, trial-and-error was used first to narrow down the ranges of phenology-related parameters of each local dominant cultivar. Then, the parameter coefficients were optimized by GLUE based on soybean growth duration. After that, crop growth parameters were calibrated by biomass in different stages and grain yield following similar processes. The information on crop parameters used in calibration and the calibrated parameter coefficients are shown in Table S2–4. Model performance was evaluated using three coefficients, namely, the coefficients of determination (R^2), root mean square error ($RMSE$), and normalized $RMSE$ ($nRMSE$). The coefficients of $RMSE$ and $nRMSE$ are usually used to evaluate the difference between simulated and measured values. These three coefficients were calculated as follows:

$$R^2 = \left[\frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}} \right]^2 \quad (2)$$

$$RMSE = \sqrt{\sum (y_i - x_i)^2 / n} \quad (3)$$

$$nRMSE = \frac{RMSE}{\bar{y}} \times 100\% \quad (4)$$

where y_i and x_i are the simulated value and measured value, respectively; \bar{y} and \bar{x} are the average of simulated value and measured value, respectively; and n indicates the amount of data. The $RMSE$ and $nRMSE$ values are close to 0 and the R^2 value is close to 1, representing better model performance.

After calibration, Yp and Yw in each RWS of 10 years (2010–2019) were simulated by calibrated crop model. Considering the variations in soil properties in an RWS, we combined the gridded soil data from Global High-Resolution Soil Profile Database and harvested area from SPAM 2010 to select the reference soil type (Han et al. 2015). Specifically, we selected 2–3 grids with the largest soybean area in an RWS and used the related soil data in the selected 2–3 grids as identical soil types for an RWS. We simulated Yp and Yw by each selected soil type and used the average results to represent the evaluated results of an RWS (details for soil type selection can be seen in Fig. S3).

2.5 Yield gap evaluation

The representative Ya of RWS was weighted by Ya of 3–5 counties in the RWS with the largest soybean area, and average Ya was calculated as follows:

$$Y_{a_RWS} = \frac{\sum_{i=1}^n Y_{a_county_i} \times A_{county_i}}{\sum_i A_{county_i}} \quad (5)$$

Table 1 Information on high-yielding experiments in universities and institutes in China.

Cultivar (full name)	Location (city, province)	Longitude, latitude	Year	Sowing date	Growth duration days	University/institute
HH43 (Heihe 43)	Nenjiang, Heilongjiang	45.77°N, 126.93°E	2018	5/4	148	Northeast Agricultural University
			2019	5/8	148	
DS7 (Dongsheng 7)	Hailun, Heilongjiang	47.67°N, 126.88°E	2018	5/8	144	Northeast Institute of Geography and Agroecology, CAS
			2019	5/3	150	
JY86 (Jiyu 86)	Gongzhuling, Jilin	43.52°N, 124.81°E	2017	4/28	159	Jilin Academy of Agricultural Sciences
			2018	4/26	156	
XD18 (Xudou 18)	Xuzhou, Jiangsu	34.17°N, 117.17°E	2019	6/21	97	Nanjing Agricultural University
	Chuzhou, Anhui	32.32°N, 118.30°E	2019	6/18	96	Nanjing Agricultural University

where Y_{a_county} indicates Y_a and A_{county} indicates the soybean area of selected counties within an RWS.

The Y_g and Y_g of Y_p (%) were calculated as follows:

$$Y_g = Y_p - Y_a \quad (6)$$

$$Y_g \text{ of } Y_p(\%) = (Y_p - Y_a)/Y_p \times 100\% \quad (7)$$

Here, we used Y_g under an irrigated system as an example, and Y_g under rainfed system was calculated by replacing Y_p with Y_w . In addition, it is important to investigate the effect of water stress on yield reduction in different regions since China's soybean is mostly rainfed. In our study, the water limitation index (WLI) was used to evaluate water stress (van Loon et al. 2018). WLI was calculated as follows:

$$WLI = (Y_p - Y_w)/Y_p \times 100\% \quad (8)$$

2.6 Upscaling

Based on GYGA protocols, results were upscaled from RWS level to CZ, regional, and country levels by a bottom-up upscaling method. Here, we use Y_p as an example, as well as Y_w and Y_a .

$$Y_{p_CZ} = \frac{\sum_{i=1}^n Y_{p_RWS_i} \times A_{RWS \text{ buffer zone}_i}}{\sum_{i=1}^n A_{RWS \text{ buffer zone}_i}} \quad (9)$$

$$Y_{p_region} = \frac{\sum_{i=1}^n Y_{p_CZ_i} \times A_{CZ_i}}{\sum_{i=1}^n A_{CZ_i}} \quad (10)$$

$$Y_{p_country} = \frac{\sum_{i=1}^n Y_{p_CZ_i} \times A_{CZ_i}}{\sum_{i=1}^n A_{CZ_i}} \quad (11)$$

where Y_{p_CZ} , Y_{p_region} , and $Y_{p_country}$ indicate yield potentials at CZ, regional, and country levels, respectively. RWS represents reference weather station; CZ is climate zone. A represents soybean area.

2.7 Evaluation of production gap

Previous studies have shown that increasing Y_a to 80% of Y_p is feasible while a continuous increase in Y_a is not cost-effective due to the high production input (Grassini et al. 2011; Lobell et al. 2009). Therefore, 80% of Y_p is defined as exploitable yield (van Ittersum et al. 2013). Exploitable production was defined as the production on current soybean land when Y_a reached 80% of Y_p . The exploitable production and production gap of each region were evaluated based

on upscaled yield and statistical area and were calculated as follows:

$$\text{Exploitable production} = 80\% \times Y_p \times \text{Area} \quad (12)$$

$$\text{Production gap} = (80\% \times Y_p - Y_a) \times \text{Area} \quad (13)$$

where Y_p and Y_a are upscaled yield potential and actual yield at regional level, respectively. Area represents soybean area in different regions. The annual average Y_a and area data from 2017 to 2019 were collected from NBSC.

2.8 Future scenarios

With the support of government policies, it is promising for further soybean area expansion in China. An estimation from CAOC of potential soybean area expansion of 0.66 million hectares (Mha) in Northeast China would be possible by the transformation of other types of arable land (CAOC 2021; MARA 2019). For Central China and South China, the government support policy for the implementation of maize-soybean intercropping system in the two regions provides a positive way for soybean area expansion by multiple cropping. Therefore, the potentially soybean expanding area would be the maize area of 15.95 Mha in Central China and 6.60 Mha in South China (NBSC 2018–2020). However, since soybean yield in an intercropping system would be different from that under sole crop planting, we collected soybean yields in many experiments that had treatments of both single soybean yield and soybean yield in a maize-soybean intercropping system in Central China and South China from published studies (Liu et al. 2018; Li et al. 2020; Rahman et al. 2017; Yang et al. 2015a, 2017). Based on these studies, we calculated the lower and upper limits of 40% and 120% of soybean Y_a within a maize-soybean intercropping system and evaluated the maximum room for national soybean production increase if soybean would be intercropped with maize in all the maize planting areas in Central China and South China.

Our study evaluated the SSR of soybeans in China in 2030 based on four scenarios. Current status (CS) assumed future soybean production would remain at current level based on the assumption that both soybean yield and area were not expected to increase further. Scenario 1 (S1) assumed an increase in future soybean production solely through Y_g closure to 80% of Y_p while maintaining the current soybean area. Scenario 2 (S2) assumed the potentially expanding soybean area of 0.66 Mha in Northeast China, 15.95 Mha in Central China, and 6.60 Mha in South China. Under S2, soybean yield was defined as 40–120% of Y_a as a single crop. For scenario 3 (S3),

soybean production increase in China was evaluated by combining Yg closure on current soybean area in S1 and Yg closure on potentially expanding area in S2. Specifically, for Northeast China, Yg would be close to 80% of Yp with 0.66 Mha area expansion. For Central China and South China, Yg would be close to 80% of Yp in the current soybean area, and area expansion would be 15.95 Mha for Central China and 6.60 Mha for South China, while the soybean yield in those areas was 40–120% of Ya rather than a yield close to 80% of Yp due to the yield penalty in intercropping. The SSR was calculated as the national production under each scenario divided by consumption in 2030 of 127 Mt forecasted by CAOC (2021).

3 Results

3.1 Soybean area adjustment in Northeast China

The soybean area in Northeast China decreased from 2010 to 2015 and has increased rapidly since 2016 after new policy implementation (Fig. 1c). Compared with SPAM 2010, although the overall soybean area increase was only 0.19 Mha in Northeast China, our results showed that the area expansion was mainly in the north of Northeast China in CZ 1403 and 1503, which have increased by 82% (0.34 Mha) and 84% (0.43 Mha), respectively (Fig. 3). Soybean area has decreased by 2–31% in other CZs in Northeast China, especially the CZ 2053 in the southern part, which decreased by 31% (0.39 Mha). Therefore, it is necessary to adjust soybean area of each CZ in Northeast China in SPAM 2010 to accurately locate major soybean-growing regions and estimate the regional and national Yp at present. The remaining regions had moderate changes in soybean area so we did not adjust those regions.

3.2 Model calibration and validation

Model calibration and validation results are shown in Fig. 4 by comparison between simulated and measured data of growth period, aboveground biomass, and yield at maturity. It was found that the simulated and measured data have good agreement in calibration as small *nRMSEs* of 2%, 13%, and 3% were observed for growth period, aboveground biomass, and yield, respectively, and R^2 values were above 0.96 for these parameters. The validation results also showed good agreement between measured and simulated data as small *nRMSEs* of 3%, 16%, and 9% were observed for growth period, aboveground biomass, and yield, respectively, and the R^2 values were above 0.92

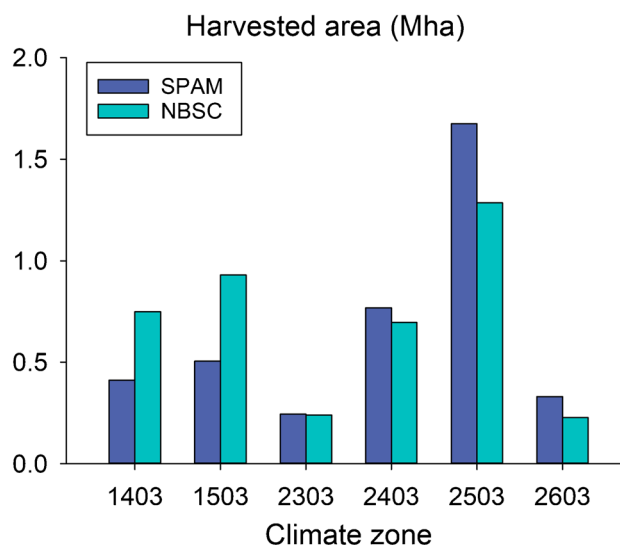


Fig. 3 Changes in soybean area in different climate zones (CZ) in Northeast China. The blue bars represent soybean harvested area from SPAM map 2010 (average of 2009–2011), and green bars represent soybean area from NBSC (average of 2018–2020).

for the three parameters. In conclusion, the above results of model calibration and validation indicated that CROP-GRO-Soybean model was suitable for simulating soybean growth process and Yp in a wide range of soybean-growing regions in China.

3.3 Yield potential and yield gap

3.3.1 Climate zone level

The upscaled results at CZ level showed that there were significant variations within the three soybean regions (Fig. 5). The locations of CZs can be found in Fig. 2d. For Northeast China, the highest Yp and Yw were both found in CZ 2603 located in the south of Northeast China mainly located in southeastern Heilongjiang Province (hereafter as Heilongjiang). The lowest Yp and Yw were found in CZ 1503 located in the north of Northeast China mainly in northwestern Heilongjiang and northeastern Nei Mongol Autonomous Region (hereafter as Nei Mongol). The highest Ya was found in CZ 1403 located in northeastern Nei Mongol, with the smallest Yg of Yp (36%) and Yg of Yw (34%). The highest Yg of Yw (51%) and Yg of Yp (58%) were in CZ 2503 and CZ 2303, respectively, and both CZs were in the south of Northeast China located in southern Heilongjiang. For Central China, the Yp and Yw among CZs had small variations. The highest Yp and Yw and lowest Ya were found in CZ 5503 in the south of Central China mainly located in northwestern Jiangsu, northern Anhui, and southern Henan provinces, resulting in the largest Yg of Yp (65%) and Yg of Yw (60%) with

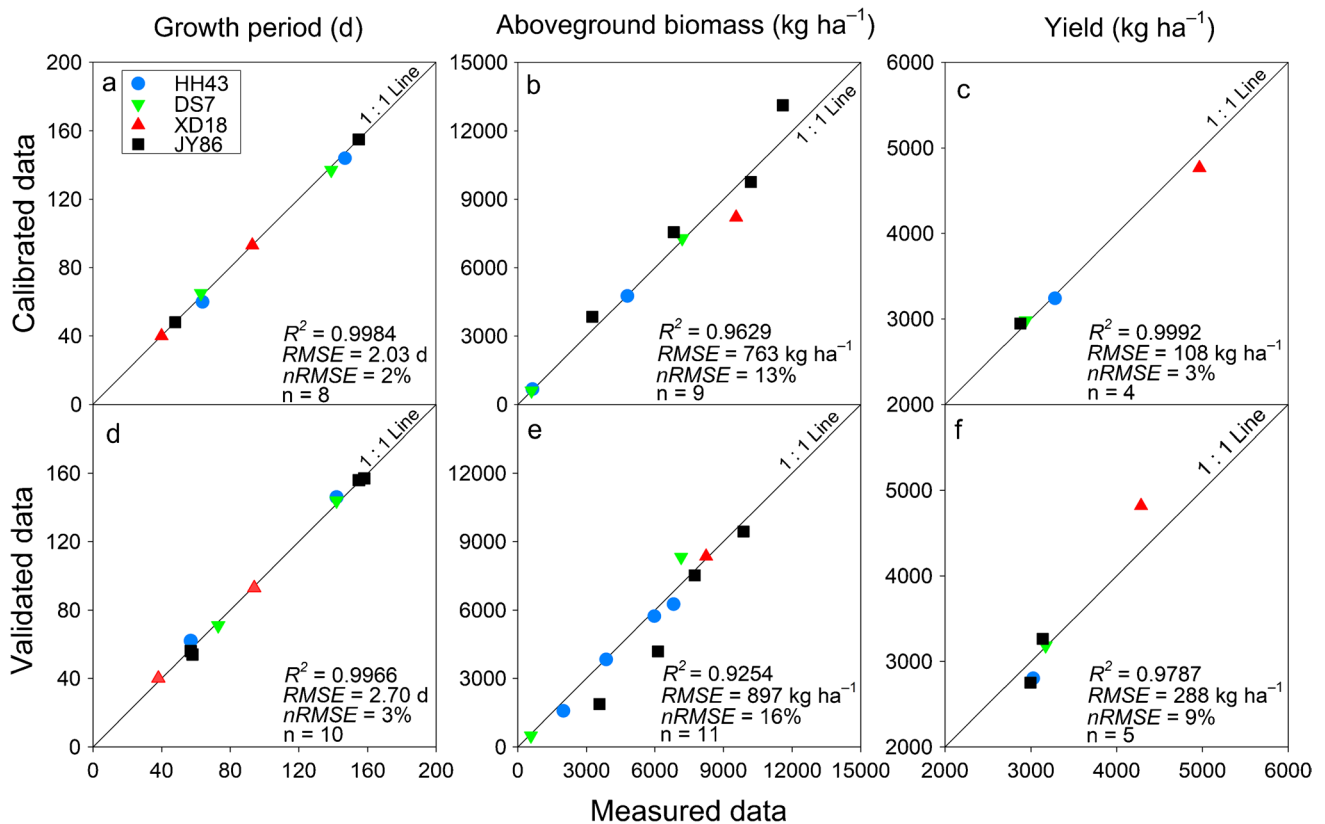


Fig. 4 Model calibration and validation results. Comparison between simulated and measured data of the growth period, aboveground biomass, and yield for model calibration (a–c) and validation (d–f).

large potential for further yield increase. The Ya of CZ 5303 in the north of Central China located in northern Henan and western Shandong provinces was the highest at 2875 kg ha⁻¹, with the smallest Yg of Yp (39%) and Yg of Yw (27%). For South China, the highest Yp and Yw were both found in CZ 6803 located in the north of South China in southeastern Hubei and northeastern Hunan, resulting in the largest Yg of Yp (46%) and Yg of Yw (24%). The highest Ya was found in CZ 6702 located in the east of South China mainly in Sichuan, with the lowest Yg of Yp (31%) and Yg of Yw (8%).

3.3.2 Regional and national level

After upscaling the results from CZ to the regional level, the highest Yp of 4677 kg ha⁻¹ and Yw of 3994 kg ha⁻¹ were found in Central China, which were 18–27% and 11–41% higher than the two other regions, respectively (Table 2). South China had the highest Ya (2352 kg ha⁻¹) among the three regions, and it was 23% and 14% higher than that in Northeast China and Central China, respectively. The Yg of Yw in Northeast China and Central

China were both over 47%, indicating a large potential to increase yield. However, Yg of Yw in South China was only 17%. The upscaled results showed that the national soybean Yp, Yw, and Ya were 3933, 3619, and 1987 kg ha⁻¹, respectively, resulting in a Yg of Yp of 49% and a Yg of Yw of 45%.

3.4 Water limitation index

In this study, we found that WLI of Northeast China, Central China, and South China was 2%, 15%, and 29%, respectively, and it was positively correlated with interannual variation in Yw (Fig. 6a). The WLI of CZs in South China was higher than 25%, while that in Northeast China (except for CZ 2303) was less than 3% (Fig. 5f). Water limitation index in South China was the highest with a large coefficient of variation (CV) of approximately 40% for Yw. The ranges of CV of Yw in Northeast China and Central China were 6–30% and 16–29%, respectively. The results showed that the CV of Yw was negatively correlated with Yw in Central China and South China, while there was no relationship in Northeast China except for CZ 2303 (Fig. 6b).

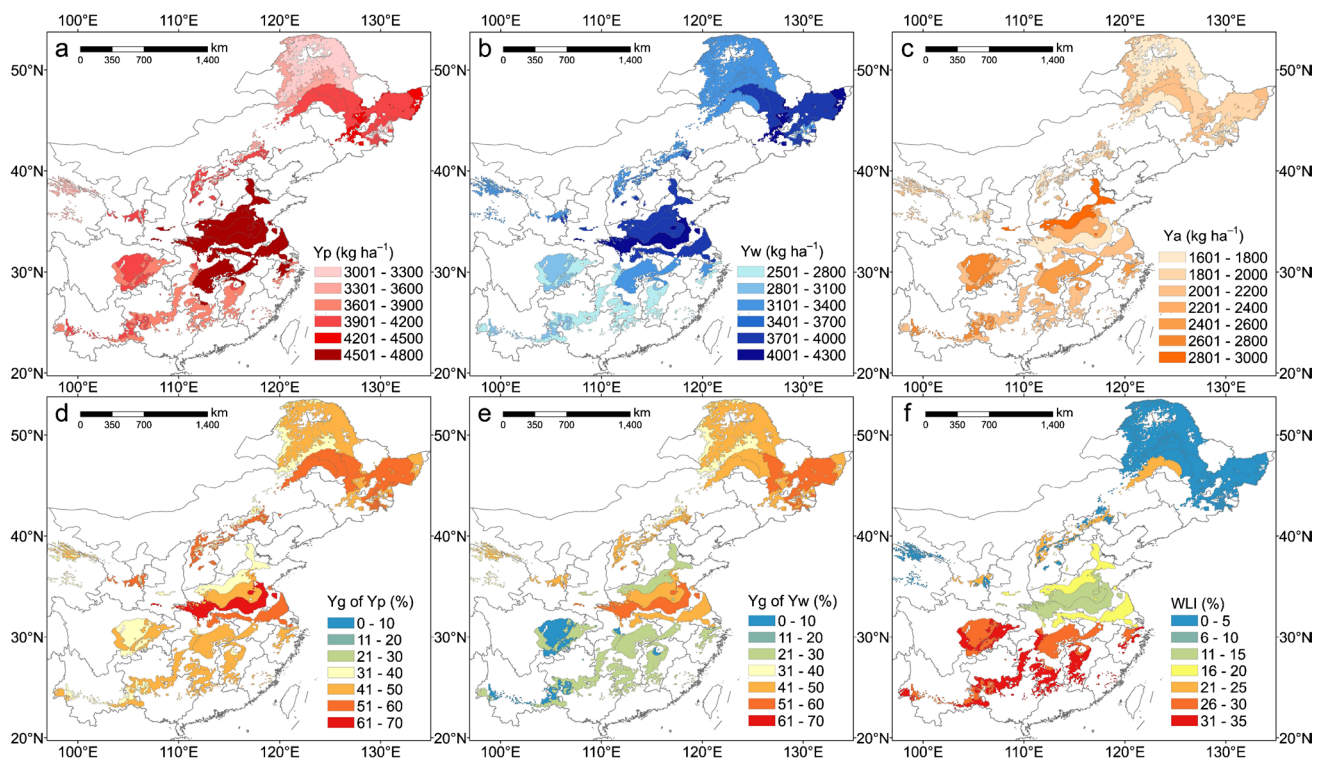


Fig. 5 Potential yield under irrigated (Yp, **a**) and rainfed (Yw, **b**) systems, current farm yield (Ya, **c**), yield gap under irrigated (Yg of Yp, **d**) and rainfed (Yg of Yw, **e**) systems, and water limitation index (WLI, **f**) at climate zone level.

3.5 Production gap

By Yg closure to 80% of Yw, soybean production in China could increase by at least 8.07 Mt (Table 3), of which Northeast China would provide an additional production of 5.67 Mt, followed by Central China (2.01 Mt). However, under rainfed system, there was no room for production increase in South China since its Ya had already reached the yield ceiling of exploitable yield, namely, 80% of Yw. However, since the WLI was the highest in South China and 67% of soybean area was rainfed, irrigation could be an efficient way to further increase Ya. In total, our results indicated that irrigation could provide an additional production of 2.69 Mt nationally, of which Northeast China, Central China, and

South China could provide 0.43, 0.96, and 1.30 Mt of additional production, respectively.

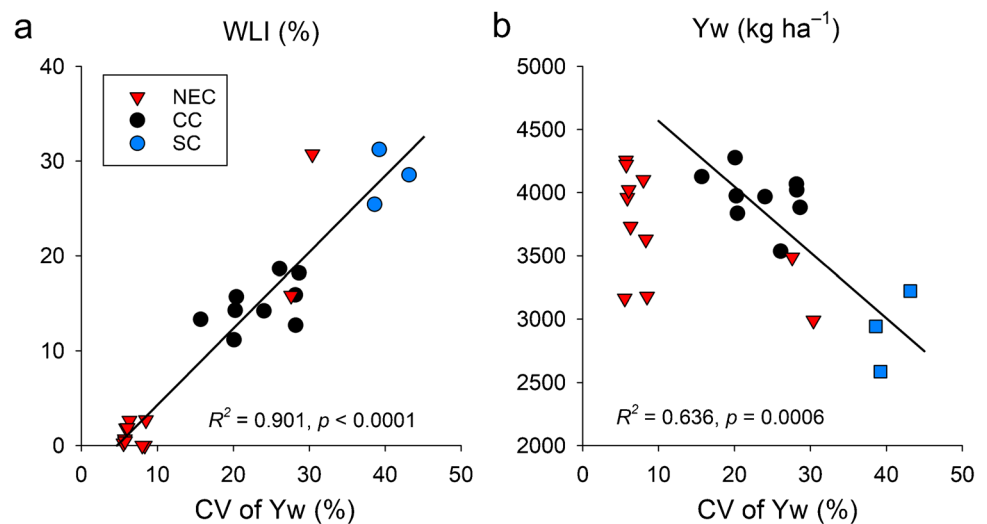
3.6 Scenarios

Additional production and SSR in 2030 were further evaluated under different scenarios (Fig. 7). Figure 7a shows the previously reported land equivalent ratio (the ratio of intercropping crop yield to monocropping yield at the same density) for both soybean and maize in maize-soybean intercropping system. Our results showed that if soybean area and yield were the same as current level (CS), SSR would slightly decrease from 16% to 15% with the consumption increase in 2030. By Yg closure to 80% Yw and Yp on current soybean area (S1), additional production of 7.68–10.37 Mt would be achieved, and SSR would be increased to 21–23%, which was still much lower than soybean import amount (117 Mt). By soybean area expansion in Northeast China and adopting maize-soybean intercropping system in South China and Central China (S2), the total soybean production could be increased to 37.54–55.56 Mt (the range was due to the assumption that soybean yield ranged from 40% to 120% of Ya in maize-soybean intercropping system), and SSR could reach 30–44%. By combining Yg closure and area expansion to exploitable yield (S3), the total soybean

Table 2 Potential yield (Yp), actual yield (Ya), and yield gap (Yg) of soybean in main soybean-growing regions in China. NEC Northeast China, CC Central China, SC South China.

Region	Yp (kg ha ⁻¹)	Yw (kg ha ⁻¹)	Ya (kg ha ⁻¹)	Yg of Yp (%)	Yg of Yw (%)
NEC	3696	3606	1918	48	47
CC	4677	3994	2057	56	48
SC	3971	2830	2352	41	17

Fig. 6 The correlation between coefficient of variation (CV) of Yw and WLI (a) and between CV of Yw and Yw (b) in different regions. WLI water limited index. The CV of Yw was the annual variation of simulated Yw within 10 years.



production increase would reach 47.90–65.92 Mt, and the maximum SSR would be 38–52%, revealing that at least 61.08 Mt of soybean accounted for 38% of world soybean trade would still be imported to meet the domestic demand.

4 Discussion

It is important for China to increase soybean production and SSR to lower import reliance and better address unexpected changes such as COVID-19 and natural disasters, as well as trade barriers (Wu et al. 2020; Yang et al. 2015b; Yao et al. 2020). In this study, we evaluated Yp, Yw, and Yg at different levels to investigate the production gap by CROPGRO-Soybean model simulation and a “bottom-up” upscaling method based on the data from high-yielding experiments in typical soybean-growing regions in China. We acknowledge that the current study with only one model for the simulation

has some limitations and uncertainties compared with multiple model simulations (Li et al. 2015; Paleari et al. 2022). Besides, for the calibration and validation process, more detailed data in Northeast China and Central China were used, while fewer data points were used in South China, where soybean research infrastructure is relatively poor. However, as this model has been widely used for soybean simulation (Bebeley et al. 2022; da Silva et al. 2021; Guo et al. 2023; Mulazzani et al. 2022; Perondi et al. 2022; Rizzo et al. 2022) and has shown good performance compared with other soybean models (Sun et al. 2022), and the data we collected from experimental sites and varieties were selected strictly to represent typical soybean-growing regions in China following local high-yielding management practices, we believe the model and data we used are robust for the simulation of Yp in current soybean system. More models and process data in South China are needed for the wide application of our results in the future. Our results showed that national soybean yield only reached 55% of Yw and 51% of Yp, indicating a large room for soybean yield increase. Because Northeast China, Central China, and South China are three major soybean-growing regions in China that are usually used for regional policymaking and R&D investment by government and researchers, we discussed the differences in Yg and production increase within each region and the sustainable ways for further soybean production improvement.

Northeast China is the most important soybean production region in China. Our results showed that an additional 32% of national production at maximum could be provided by Yg closure alone in Northeast China with low water stress (WLI of 2%). In terms of production increase, the north and south of Northeast China have large difference. Soybean area has increased by over 80% in the north of Northeast

Table 3 Current soybean production and production gap in main soybean-growing regions in China. NEC Northeast China, CC Central China, SC South China. Current production was calculated as soybean area multiplied by regional actual yield (NBSC, 2018–2020). Production gap was calculated as exploitable production (the additional production when yield reaches 80% of potential yield) minus current production.

Region	Harvested area (Mha)	Current production (Mt)	Production gap (Mt)	
			Rainfed	Irrigated
NEC	5.87	11.26	5.67	6.10
CC	1.76	3.63	2.01	2.97
SC	1.57	3.69	0.00	1.30

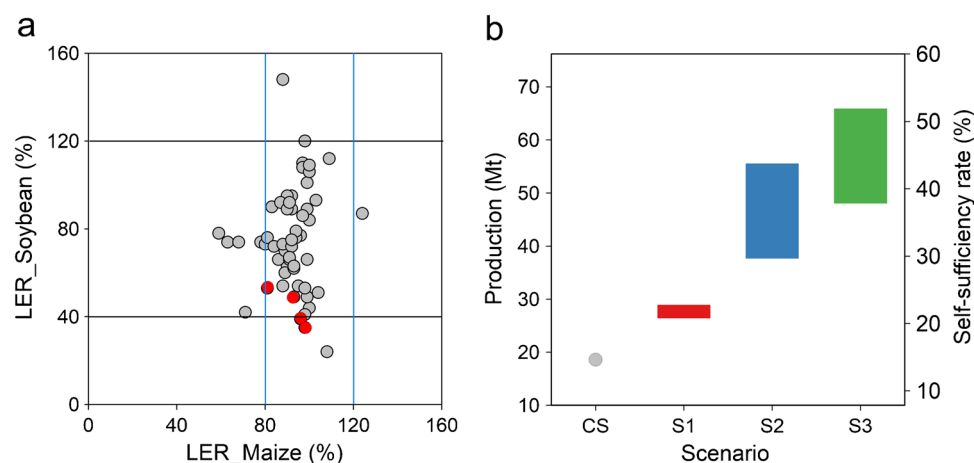


Fig. 7 Additional production increase and self-sufficiency rate (SSR) of soybean under different scenarios in 2030. **a** Land equivalent ratio (LER) of soybean and maize. The LER is calculated as the maize or soybean yield from intercropping system to the yield from a single crop. Red and gray dots represent experiments conducted in Central China and South China, respectively. Data are from previous research

China (especially in CZ 1403 in northwestern Heilongjiang and northeastern Nei Mongol) with a higher Y_a than in the rest of Northeast China mainly caused by the introduction of soybean subsidies and a high mechanical rate in the north (Yang et al. 2019; CAMI 2018). However, the Y_w was the lowest in the north of Northeast China which was largely due to the limited heat resources at high latitudes (Zhao et al. 2023; Wu et al. 2023), resulting in the smallest Y_g . However, it was noticeable that Y_w in the north of Northeast China is promising to increase under future global warming conditions with the northward shift of crop planting boundaries and larger spring-sowing window (He et al. 2020; Li et al. 2021; Liu and Dai 2020). Except for the north of Northeast China, the remaining areas had a high Y_g of 46–58% especially in southernmost Heilongjiang and eastern Jilin Province, which was caused by many existing problems such as long-term continuous cropping, unreasonable intercropping, lack of high potential cultivars, and poor management practices (Li et al. 2010; Liu et al. 2012; Zhen et al. 2012). Some possible solutions have been proposed in previous studies such as breeding disease-resistant and high-yield varieties, converting single cropping system into rotation system, establishing conservation tillage systems, and increasing planting density (Chen et al. 2011; Liu and Herbert 2002; Liu et al. 2008; Jin et al. 2010).

Currently, the contribution of Central China and South China to national soybean production is quite low. However, production increases in Central China and South China are of great importance for alleviating the ecological pressure of soybean production in Northeast China. For Central China with the highest Y_p and large Y_g (56% of Y_p), an additional production of 2.82 Mt could be provided by Y_g closure on

articles. **b** Production increase and SSR under four scenarios: CS, current status; S1, soybean production increase by yield gap closure to 80% of potential yield on current soybean area; S2, soybean production increase by potentially expanding soybean area in three regions; S3, soybean production increase by combining Y_g closure in S1 on the current area and in S2 on potentially expanding area.

the current soybean area. The highest Y_p was found in Central China among three regions which might due to the plentiful heat and light resources with an affordable water supply (Meng et al. 2013; Sun et al. 2018). Meanwhile, Y_g was also large in this region, especially in the south of Central China (CZ 5503), which is one of the most important grain producers in China mainly including northern Anhui, southern Henan, and northwestern Jiangsu provinces (Zhang et al. 2019). In addition to local soil conditions that limit land productivity such as waterlogging and salinization (Shi et al. 2021; Xiao et al. 2019), there are also many shortcomings in cultivation technology in Central China such as the lack of special harvesters with suitable varieties for mechanical soybean harvest, resulting in high yield loss during mechanical harvesting process (Ni et al. 2019). In addition, the difficulties in dealing with the residue from winter crops also largely limit soybean growth and yield (Yan et al. 2017). Hence, further yield gap closure is promising if more attention could be paid to those regions by improving soil conditions and optimizing cultivation technologies, especially the practices during harvest process.

Soybean yield in South China had little room for further increase under rainfed system with the highest WLI of 25–31%. Interestingly, during modeling process, we found that although the total rainfall was sufficient in South China, the rainfall in critical soybean growth periods such as flowering to grain filling stage in some years was inadequate, thus posing water stress to crop growth (data not shown). Lv (2015) also found soybean water shortages in South China with mountainous and hilly areas in autumn. Besides, the soybean yield was restricted by many factors such as varieties, topography, planting patterns (Wu et al. 2023). With

optimized management practices under irrigation system, Ya in South China was supposed to increase further with higher yield stability due to the close relationship between WLI and CV of Yw (Fig. 6). However, it is not the priority to develop due to the high cost of the development of related technology and infrastructure in this region.

Maximum soybean production could meet only 21–23% of SSR by Yg closure alone and reach more than 50% of SSR by combining with reasonable area expansion in China, and soybean imports would decrease from 60% to 38% of current global soybean trade at maximum. Hence, area expansion is vital for higher SSR and edible oil safety in the future. However, due to the lower economic returns of planting soybean and the difficulties of developing soybean-special harvesters and related cultivation technologies, farmers have been less motivated to plant soybeans than other crops in recent years (CAMI 2018; Liu et al. 2021; Ren et al. 2021; Wu et al. 2023). Maize-soybean intercropping is a good choice for soybean area expansion, but it usually has yield penalties for both crops. Based on the yields we collected from studies conducted in maize-soybean intercropping system, soybean yield could be decreased by as much as 60%. However, with innovative cultivation technology, soybean yield in intercropping system could be similar to that in monoculture system and even increase to 120% (Fig. 7a), such as by using optimized fertilizer management and planting structure with planting in wide and narrow rows (Liu et al. 2018; Yang et al. 2015a, 2017; Chen et al. 2017). It is important to note that the implementation of innovative technology and an increase in soybean yield in farmers' fields are still huge challenges. However, the government's strong support for this intercropping system with more R&D investment makes it promising to popularize on a larger scale (State Council 2023; <https://ngx.net.cn/ztzl/ddym>). In addition, more soybean area expansion is still needed to increase SSR in China. Some innovative cropping systems for area expansion, e.g. transforming other low-yielding cropland into soybean and developing agroforestry such as planting with fruit trees are also promising for further soybean production increases (Liu et al. 2020; Liu et al. 2021; Liu and Zhang 2022; Zhao et al. 2021b).

5 Conclusion

To understand current and exploitable soybean production in China, we conducted a detailed spatial Yg analysis at different levels throughout China and found a Yg of 49% of Yp and 45% of Yw, which revealed that large room existed for soybean yield increase at the national level. Although the north of Northeast China has the largest soybean area, Yg is hard to close further due to low Yp compared with

other regions. Yield gap closure in the south of Northeast China (including southern Heilongjiang and northern Jilin provinces) and in the south of Central China (including northern Anhui, northwestern Jiangsu, and southern Henan provinces) is important under rainfed systems, while more irrigation in South China is needed for further yield increases. Scenarios in this study indicate that SSR could be increased from 15% to 23% by Yg closure alone and could reach a maximum of 52% in 2030 by combining Yg closure and reasonable area expansion. Therefore, to increase SSR to a higher level, more arable land and agricultural innovation technologies are still needed to increase soybean production.

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Authors' contributions Conceptualization: JH, SP, ND. Experiment conduction: CM, CL, WZ. Data collection: ND. Data analysis: YW, ND. Visualization: YW. Writing original draft: YW, XL. Review and editing: YW, XL, JH, SP, ND. Review and suggestion: CM, CL, WZ. Supervision: SP, ND. Funding: ND.

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Data availability The datasets generated during and/or analyzed during the current study are not publicly available due to privacy reasons but are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

References

- Bebeley JF, Kamara AY, Jibrin JM, Akinseye FM, Tofa AI, Adam AM, Kamai N, Solomon R (2022) Evaluation and application of the CROPGRO-soybean model for determining optimum sowing windows of soybean in the Nigeria savannas. *Sci Rep* 12:6747. <https://doi.org/10.1038/s41598-022-10505-4>
- Bhatia VS, Singh P, Wani SP, Chauhan GS, Rao AVRK, Mishra AK, Srinivas K (2008) Analysis of potential yields and yield gaps of rainfed soybean in India using CROPGRO-Soybean model. *Agr*

- Forest Meteorol 148(8):1252–1265. <https://doi.org/10.1016/j.agrformet.2008.03.004>
- Bhattarai MD, Secchi S, Schoof J (2017) Projecting corn and soybeans yields under climate change in a Corn Belt watershed. *Agr Syst* 152:90–99. <https://doi.org/10.1016/j.agry.2016.12.013>
- Boote KJ, Jones JW, Hoogenboom G, Pickering NB (1998) The CROPGRO model for grain legumes. In: Tsuji GY, Hoogenboom G, Thornton PK (eds) *Understanding Options for Agricultural Production*. Springer Netherlands, Dordrecht, pp 99–128. https://doi.org/10.1007/978-94-017-3624-4_6
- CAAS, Chinese Academy of Agricultural Sciences (2022) China agricultural industry development report. <https://www.caas.cn/xwzx/mtbd/321338.html>. Accessed 1 Jul 2022
- CAMI, China Machinery Industry Yearbook Editorial Committee (2018) China agricultural machinery industry yearbook. China Machine Press, Beijing, China
- CAOC, Chinses Agriculture Outlook Committee (2021) China agriculture outlook report (2021–2030). China Agricultural Science and Technology Press, Beijing, China
- Cassman KG, Grassini P (2020) A global perspective on sustainable intensification research. *Nat Sustain* 3(4):262–268. <https://doi.org/10.1038/s41893-020-0507-8>
- Chen Y, Liu S, Li H, Li X, Song C, Cruse RM, Zhang X (2011) Effects of conservation tillage on corn and soybean yield in the humid continental climate region of Northeast China. *Soil Tillage Res* 115–116:56–61. <https://doi.org/10.1016/j.still.2011.06.007>
- Chen P, Du Q, Liu X, Zhou L, Hussain S, Lei L, Song C, Wang X, Liu W, Yang F, Shu K, Liu J, Du J, Yang W, Yong T (2017) Effects of reduced nitrogen inputs on crop yield and nitrogen use efficiency in a long-term maize-soybean relay strip intercropping system. *PLoS One* 12(9):e0184503. <https://doi.org/10.1371/journal.pone.0184503>
- CMA, China Meteorological Administration. China Surface climate data daily value dataset V3.0. http://data.cma.cn/data/cdcdetail/dataCode/SURF_CLI_CHN_MUL_DAY_V3.0.html. Accessed 1 Mar 2022
- da Silva EHF, Boote KJ, Hoogenboom G, Gonçalves AO, Junior ASA, Marin FR (2021) Performance of the CSM-CROPGRO-soybean in simulating soybean growth and development and the soil water balance for a tropical environment. *Agric Water Manag* 252:106929. <https://doi.org/10.1016/j.agwat.2021.106929>
- Evans LT, Fischer RA (1999) Yield potential: its definition, measurement, and significance. *Crop Sci* 39(6):1544–1551. <https://doi.org/10.2135/cropsci1999.3961544x>
- Gale F, Valdes C, Ash M (2019) Interdependence of China, United States, and Brazil in soybean trade. USDA, Economic Research Service. <https://www.ers.usda.gov/webdocs/outlooks/93390/ocs-19f-01.pdf>. Accessed 1 Feb 2022
- Grassini P, Thorburn J, Burr C, Cassman KG (2011) High-yield irrigated maize in the Western U.S. Corn Belt: I. On-farm yield, yield potential, and impact of agronomic practices. *Field Crop Res* 120(1):142–150. <https://doi.org/10.1016/j.fcr.2010.09.012>
- Grassini P, Torrión JA, Yang HS, Rees J, Andersen D, Cassman KG, Specht JE (2015a) Soybean yield gaps and water productivity in the western U.S. Corn Belt. *Field Crop Res* 179:150–163. <https://doi.org/10.1016/j.fcr.2015.04.015>
- Grassini P, van Bussel LGJ, Van Wart J, Wolf J, Claessens L, Yang H, Boogaard H, de Groot H, van Ittersum MK, Cassman KG (2015b) How good is good enough? Data requirements for reliable crop yield simulations and yield-gap analysis. *Field Crop Res* 177:49–63. <https://doi.org/10.1016/j.fcr.2015.03.004>
- Guo S, Zhang Z, Zhang F, Yang X (2023) Optimizing cultivars and agricultural management practices can enhance soybean yield in Northeast China. *Sci Total Environ* 857:159456. <https://doi.org/10.1016/j.scitotenv.2022.159456>
- Han E, Ines A, Koo J (2015) Global high-resolution soil profile database for crop modeling applications. *Harv Dataverse*. <https://doi.org/10.7910/DVN/1PEEY0>
- He J, Jones JW, Graham WD, Dukes MD (2010) Influence of likelihood function choice for estimating crop model parameters using the generalized likelihood uncertainty estimation method. *Agr Syst* 103(5):256–264. <https://doi.org/10.1016/j.agry.2010.01.006>
- He L, Jin N, Yu Q (2020) Impacts of climate change and crop management practices on soybean phenology changes in China. *Sci Total Environ* 707:135638. <https://doi.org/10.1016/j.scitotenv.2019.135638>
- Huang J, Cao X, Kuai J, Cheng H, Zuo Q, Du H, Peng S, Huang J, Deng N (2023) Evaluation of production capacity for rice-rape-seed cropping system in China. *Field Crop Res* 293:108842. <https://doi.org/10.1016/j.fcr.2023.108842>
- IFPRI, International Food Policy Research Institute (2019) Global spatially-disaggregated crop production statistics data for 2010 version 2.0. *Harvard Dataverse*, V4. 10.7910/DVN/PRFF8V
- Iqbal N, Hussain S, Ahamed Z, Yang F, Wang X, Liu W, Yong T, Du J, Shu K, Yang W, Liu J (2019) Comparative analysis of maize-soybean strip intercropping systems: a review. *Plant Prod Sci* 22(2):131–142. <https://doi.org/10.1080/1343943X.2018.1541137>
- Jin J, Liu X, Wang G, Mi L, Shen Z, Chen X, Herbert SJ (2010) Agronomic and physiological contributions to the yield improvement of soybean cultivars released from 1950 to 2006 in Northeast China. *Field Crop Res* 115(1):116–123. <https://doi.org/10.1016/j.fcr.2009.10.016>
- Jones JW, Hoogenboom G, Porter CH, Boote KJ, Batchelor WD, Hunt LA, Wilkens PW, Singh U, Gijsman AJ, Ritchie JT (2003) The DSSAT cropping system model. *Eur J Agron* 18(3):235–265. [https://doi.org/10.1016/S1161-0301\(02\)00107-7](https://doi.org/10.1016/S1161-0301(02)00107-7)
- Jones JW, He J, Boote KJ, Wilkens P, Porter CH, Hu Z (2011) Estimating DSSAT cropping system cultivar-specific parameters using Bayesian techniques. In: *Methods of Introducing System Models into Agricultural Research*. pp 365–393. <https://doi.org/10.2134/advagricsystmodel2.c13>
- Komarek AM, Koo J, Wood-Sichra U, You L (2018) Spatially-explicit effects of seed and fertilizer intensification for maize in Tanzania. *Land Use Policy* 78:158–165. <https://doi.org/10.1016/j.landusepol.2018.06.033>
- Li C, Li X, Kong W, Wu Y, Wang J (2010) Effect of monoculture soybean on soil microbial community in the Northeast China. *Plant Soil* 330(1):423–433. <https://doi.org/10.1007/s11104-009-0216-6>
- Li T, Hasegawa T, Yin X, Zhu Y, Boote K, Adam M, Bregaglio S, Buis S, Confalonieri R, Fumoto T, Gaydon D, Marcaida M III, Nakagawa H, Oriol P, Ruane AC, Ruget F, Singh B, Singh U, Tang L, Tao F, Wilkens P, Yoshida H, Zhang Z, Bouman B (2015) Uncertainties in predicting rice yield by current crop models under a wide range of climatic conditions. *Glob Change Biol* 21:1328–1341. <https://doi.org/10.1111/gcb.12758>
- Li S, Evers JB, van der Werf W, Wang R, Xu Z, Guo Y, Li B, Ma Y (2020) Plant architectural responses in simultaneous maize/soybean strip intercropping do not lead to a yield advantage. *Ann Appl Biol* 177(2):195–210. <https://doi.org/10.1111/aab.12610>
- Li Z, Zhan C, Hu S, Ning L, Wu L, Guo H (2021) Yield effects of irrigated acreage change under climate change in China. *TCSAE* 37(19):94–104 ((in Chinese))
- Li L, Li X, Zheng X, Li X, Jiang T, Ju H, Wan X (2022) The effects of declining soil moisture levels on suitable maize cultivation areas in Northeast China. *J Hydrol* 608:127636. <https://doi.org/10.1016/j.jhydrol.2022.127636>
- Liu Y, Dai L (2020) Modelling the impacts of climate change and crop management measures on soybean phenology in China. *J Clean Prod* 262:121271. <https://doi.org/10.1016/j.jclepro.2020.121271>
- Liu X, Herbert SJ (2002) Fifteen years of research examining cultivation of continuous soybean in northeast China: a review. *Field*

- Crop Res 79(1):1–7. [https://doi.org/10.1016/S0378-4290\(02\)00042-4](https://doi.org/10.1016/S0378-4290(02)00042-4)
- Liu J, Zhang G (2022) Analysis and countermeasures of high temperature and drought disaster in intercropping of fruit trees in Sichuan province. *Sichuan Agric Sci Tech* 10:12–23 ((in Chinese))
- Liu X, Jin J, Wang G, Herbert SJ (2008) Soybean yield physiology and development of high-yielding practices in Northeast China. *Field Crop Res* 105(3):157–171. <https://doi.org/10.1016/j.fcr.2007.09.003>
- Liu X, Li Y, Han B, Zhang Q, Zhou K, Zhang X, Hashemi M (2012) Yield response of continuous soybean to one-season crop disturbance in a previous continuous soybean field in Northeast China. *Field Crop Res* 138:52–56. <https://doi.org/10.1016/j.fcr.2012.09.012>
- Liu X, Rahman T, Song C, Yang F, Su B, Cui L, Bu W, Yang W (2018) Relationships among light distribution, radiation use efficiency and land equivalent ratio in maize-soybean strip intercropping. *Field Crop Res* 224:91–101. <https://doi.org/10.1016/j.fcr.2018.05.010>
- Liu S, Zhang M, Feng F, Tian Z (2020) Toward a “green revolution” for soybean. *Mol Plant* 13(5):688–697. <https://doi.org/10.1016/j.molp.2020.03.002>
- Liu Z, Ying H, Chen M, Bai J, Xue Y, Yin Y, Batchelor WD, Yang Y, Bai Z, Du M, Guo Y, Zhang Q, Cui Z, Zhang F, Dou Z (2021) Optimization of China’s maize and soy production can ensure feed sufficiency at lower nitrogen and carbon footprints. *Nat Food* 2(6):426–433. <https://doi.org/10.1038/s43016-021-00300-1>
- Lobell DB, Cassman KG, Field CB (2009) Crop yield gaps: their importance, magnitudes, and causes. *Annu Rev Environ Resour* 34:179–204. <https://doi.org/10.1146/annurev.envIRON.04.1008.093740>
- Lv M (2015) Effects of absorbent polymer on yield and growth of autumn planting soybean. *Chin Agric Sci Bull* 31(12):57–61 ((in Chinese))
- MARA, Ministry of Agricultural and Rural Affairs of the People’s Republic of China (2016) National structure adjustment plan for crop farming (2016–2020). http://www.gov.cn/xinwen/2016-04/28/content_5068722.htm. Accessed in 1 Mar 2022
- MARA, Ministry of Agricultural and Rural Affairs of the People’s Republic of China (2019) Implementation plan of soybean revitalization plan. https://www.moa.gov.cn/nybg/2019/0201903/201905/t20190525_6315395.htm. Accessed in 1 Mar 2022
- Meng Q, Hou P, Liang W, Chen X, Cui Z, Zhang F (2013) Understanding production potentials and yield gaps in intensive maize production in China. *Field Crop Res* 143:91–97. <https://doi.org/10.1016/j.fcr.2012.09.023>
- Merlos FA, Monzon JP, Mercu JL, Taboada M, Andrade FH, Hall AJ, Jobbagy E, Cassman KG, Grassini P (2015) Potential for crop production increase in Argentina through closure of existing yield gaps. *Field Crop Res* 184:145–154. <https://doi.org/10.1016/j.fcr.2015.10.001>
- Monzon JP, Slingerland MA, Rahutomo S, Agus F, Oberthür T, Andrade JF, Couëdel A, Rattalino Edreira JI, Hekman W, van den Beuken R, Hidayat F, Pradiko I, Purwantomo DKG, Donough CR, Sugianto H, Lim YL, Farrell T, Grassini P (2021) Fostering a climate-smart intensification for oil palm. *Nat Sustain* 4:595–601. <https://doi.org/10.1038/s41893-021-00700-y>
- Mulazzani RP, Gubiani PI, Zanon AJ, Drescher MS, Schenato RB, Girardello VC (2022) Impact of soil compaction on 30-year soybean yield simulated with CROPGRO-DSSAT. *Agr Syst* 203:103523. <https://doi.org/10.1016/j.agry.2022.103523>
- NASA, NASA prediction of worldwide energy resources data access viewer. <https://power.larc.nasa.gov/data-access-viewer>. Accessed 1 Mar 2022
- NBSC, National bureau of statistics of the People’s Republic of China (2013–2020) China Statistical Yearbook. China Statistics Press, Beijing, China
- NBSC, National Bureau of Statistics. <https://data.stats.gov.cn/index.htm>. Accessed 1 Feb 2022
- Ni Y, Jin C, Chen M, Wang T, Li Z, Yuan W (2019) Research progress on mechanized production technology and equipment of soybean in China. *J Chin Agric Mech* 40(12):17–25. <https://doi.org/10.13733/j.jcam.issn.2095-5553.2019.12.04>. ((in Chinese))
- Paleari L, Li T, Yang Y, Wilson LT, Hasegawa T, Boote KJ, Buis S, Hoogenboom G, Gao Y, Movedi E, Ruget F, Singh U, Stöckle CO, Tang L, Wallach D, Zhu Y, Confalonieri R (2022) A trait-based model ensemble approach to design rice plant types for future climate. *Glob Change Biol* 28:2689–2710. <https://doi.org/10.1111/gcb.16087>
- Perondi D, Boote K, De Souza Nôia Júnior R, Mulvaney M, Iboyi J, Fraisse C (2022) Assessment of soybean yield variability in the southeastern U.S. with the calibration of genetic coefficients from variety trials using CROPGRO-Soybean. *Agron J* 114:1100–1114. <https://doi.org/10.1002/agj.2.20995>
- Rahman T, Ye L, Liu X, Iqbal N, Du J, Gao R, Liu W, Yang F, Yang W (2017) Water use efficiency and water distribution response to different planting patterns in maize-soybean relay strip intercropping systems. *Exp Agric* 53(2):159–177. <https://doi.org/10.1017/S0014479716000260>
- Ren D, Yang H, Zhou L, Yang Y, Liu W, Hao X, Pan P (2021) The land-water-food-environment nexus in the context of China’s soybean import. *Adv Water Resour* 151:103892. <https://doi.org/10.1016/j.advwatres.2021.103892>
- Rizzo G, Mazzilli SR, Ernst O, Baethgen WE, Berger AG (2022) Season-specific management strategies for rainfed soybean in the South American Pampas based on a seasonal precipitation forecast. *Agr Syst* 196:103331. <https://doi.org/10.1016/j.agry.2021.103331>
- Sentelhas PC, Battisti R, CÂMara GMS, Farias JRB, Hampf AC, Nendel C (2015) The soybean yield gap in Brazil – magnitude, causes and possible solutions for sustainable production. *J Agric Sci* 153(8):1394–1411. <https://doi.org/10.1017/S0021859615000313>
- Shi W, Wang M, Liu Y (2021) Crop yield and production responses to climate disasters in China. *Sci Total Environ* 750:141147. <https://doi.org/10.1016/j.scitotenv.2020.141147>
- State Council (2023) Opinions on opinions of completing the key work of comprehensively promoting rural revitalization in 2023. http://www.gov.cn/zhengce/2023-02/13/content_5741370.htm. Accessed in 1 Feb 2023
- Sun S, Yang X, Lin X, Sassenrath GF, Li K (2018) Winter wheat yield gaps and patterns in China. *Crop Econ Prod Manga* 110(1):319–330. <https://doi.org/10.2134/agronj2017.07.0417>
- Sun W, Fleisher D, Timlin D, Li S, Wang Z, Beegum S, Reddy V (2022) Evaluation of models for simulating soybean growth and climate sensitivity in the U.S. Mississippi Delta. *Eur J Agron* 140:126610. <https://doi.org/10.1016/j.eja.2022.126610>
- USDA, US Department of Agriculture National Foreign Agricultural Service (2020) Oilseeds: world markets and trade. Version November 2022, United States Department of Agriculture, Washington, DC, USA
- van Bussel LGJ, Grassini P, Van Wart J, Wolf J, Claessens L, Yang H, Boogaard H, de Groot H, Saito K, Cassman KG, van Ittersum MK (2015) From field to atlas: upscaling of location-specific yield gap estimates. *Field Crop Res* 177:98–108. <https://doi.org/10.1016/j.fcr.2015.03.005>
- van Ittersum MK, Cassman KG, Grassini P, Wolf J, Tittonell P, Hochman Z (2013) Yield gap analysis with local to global relevance-a review. *Field Crop Res* 143:4–17. <https://doi.org/10.1016/j.fcr.2012.09.009>

- van Loon MP, Deng N, Grassini P, Rattalino Edreira JI, Wolde-meskel E, Baijukya F, Marrou H, van Ittersum MK (2018) Prospect for increasing grain legume crop production in East Africa. *Eur J Agron* 101:140–148. <https://doi.org/10.1016/j.eja.2018.09.004>
- van Wart J, Grassini P, Cassman KG (2013a) Impact of derived global weather data on simulated crop yields. *Glob Change Biol* 19(12):3822–3834. <https://doi.org/10.1111/gcb.12302>
- van Wart J, Kersebaum KC, Peng S, Milner M, Cassman KG (2013b) Estimating crop yield potential at regional to national scales. *Field Crop Res* 143:34–43. <https://doi.org/10.1016/j.fcr.2012.11.018>
- van Wart J, van Bussel LGJ, Wolf J, Licker R, Grassini P, Nelson A, Boogaard H, Gerber J, Mueller ND, Claessens L, van Ittersum MK, Cassman KG (2013c) Use of agro-climatic zones to upscale simulated crop yield potential. *Field Crop Res* 143:44–55. <https://doi.org/10.1016/j.fcr.2012.11.023>
- Wang Y, Peng S, Huang J, Zhang Y, Feng L, Zhao W, Qi H, Zhou G, Deng N (2022) Prospects for cotton self-sufficiency in China by closing yield gaps. *Eur J Agron* 133:126437. <https://doi.org/10.1016/j.eja.2021.126437>
- White JW, Hoogenboom G, Wilkens PW, Stackhouse PW Jr, Hoel JM (2011) Evaluation of satellite-based, modeled-derived daily solar radiation data for the continental United States. *Agron J* 103(4):1242–1251. <https://doi.org/10.2134/agronj2011.0038>
- Wu F, Geng Y, Zhang Y, Ji C, Chen Y, Sun L, Xie W, Ali T, Fujita T (2020) Assessing sustainability of soybean supply in China: evidence from provincial production and trade data. *J Clean Prod* 244:119006. <https://doi.org/10.1016/j.jclepro.2019.119006>
- Wu Y, Wang E, Gong W, Xu L, Zhao Z, He D, Yang F, Wang X, Yong T, Liu J, Pu T, Yan Y, Yang W (2023) Soybean yield variations and the potential of intercropping to increase production in China. *Field Crop Res* 291:108771. <https://doi.org/10.1016/j.fcr.2022.108771>
- Xiao Y, Zhao G, Li T, Zhou X, Li J (2019) Soil salinization of cultivated land in Shandong Province, China—dynamics during the past 40 years. *Land Degrad Dev* 30:426–436. <https://doi.org/10.1002/ldr.3236>
- Yan X, He X, Zhang Q, Sun H, Kou C (2017) Varieties (lines) screening of summer soybeans suitable for no-tillage straw mulching precise sowing cultivation way. *Soy Sci* 36(6):879–886 ((in Chinese))
- Yang F, Wang X, Liao D, Lu F, Gao R, Liu W, Yong T, Wu X, Du J, Liu J, Yang W (2015) Yield response to different planting geometries in maize-soybean relay strip intercropping systems. *Agron J* 107(1):296–304. <https://doi.org/10.2134/agronj14.0263>
- Yang X, Liu Y, Bai W, Liu B (2015b) Evaluation of the crop insurance management for soybean risk of natural disasters in Jilin Province, China. *Nat Hazards* 76(1):587–599. <https://doi.org/10.1007/s11069-014-1510-z>
- Yang F, Liao D, Fan Y, Gao R, Wu X, Rahman T, Yong T, Liu W, Liu J, Du J, Shu K, Wang X, Yang W (2017) Effect of narrow-row planting patterns on crop competitive and economic advantage in maize-soybean relay strip intercropping system. *Plant Prod Sci* 20(1):1–11. <https://doi.org/10.1080/1343943X.2016.1224553>
- Yang L, Wang L, Huang J, Mansaray LR, Mijiti R (2019) Monitoring policy-driven crop area adjustments in northeast China using Landsat-8 imagery. *Int J Appl Earth Obs* 82:101892. <https://doi.org/10.1016/j.jag.2019.06.002>
- Yao H, Zuo X, Zuo D, Lin H, Huang X, Zang C (2020) Study on soybean potential productivity and food security in China under the influence of COVID-19 outbreak. *Geogr and Sustain* 1(2):163–171. <https://doi.org/10.1016/j.geosus.2020.06.002>
- Yu Q, You L, Wood-Sichra U, Ru Y, Joglekar AKB, Fritz S, Xiong W, Lu M, Wu W, Yang P (2020) A cultivated planet in 2010 – part 2: the global gridded agricultural-production maps. *Earth Syst Sci Data* 12(4):3545–3572. <https://doi.org/10.5194/essd-12-3545-2020>
- Zhang T, Xu W, Lin X, Yan H, Ma M, He Z (2019) Assessment of heavy metals pollution of soybean grains in North Anhui of China. *Sci Total Environ* 646:914–922. <https://doi.org/10.1016/j.scitoenv.2018.07.335>
- Zhao H, Chang J, Havlík P, van Dijk M, Valin H, Janssens C, Ma L, Bai Z, Herrero M, Smith P, Obersteiner M (2021a) China's future food demand and its implications for trade and environment. *Nat Sustain* 4(12):1042–1051. <https://doi.org/10.1038/s41893-021-00784-6>
- Zhao J, Wang C, Shi X, Bo X, Li S, Shang M, Chen F, Chu Q (2021) Modeling climatically suitable areas for soybean and their shifts across China. *Agr Syst* 192:103205. <https://doi.org/10.1016/j.agsy.2021.103205>
- Zhao J, Han T, Wang C, Shi X, Wang K, Zhao M, Chen F, Chu Q (2022) Assessing variation and driving factors of the county-scale water footprint for soybean production in China. *Agric Water Manag* 263:107469. <https://doi.org/10.1016/j.agwat.2022.107469>
- Zhao J, Wang Y, Zhao M, Wang K, Li S, Gao Z, Shi X, Chu Q (2023) Prospects for soybean production increase by closing yield gaps in the Northeast Farming Region China. *Field Crop Res* 293:108843. <https://doi.org/10.1016/j.fcr.2023.108843>
- Zhen X, Zhang B, Kou H (2012) Main problems and development countermeasures of soybean production in Northeast China. *Heilongjiang Agr Sci* 2:146–149 ((in Chinese))

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