To be or not to be: Prospects for rice self-sufficiency in China

Nanyan Deng[1], Patricio Grassini[2], Haishun Yang[2], Jianliang Huang[1], Kenneth G. Cassman[2], Shaobing Peng[1*]

[1] National Key Laboratory of Crop Genetic Improvement, 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, Hubei 430070, China.

[2] Department of Agronomy and Horticulture, University of Nebraska-Lincoln, PO Box 830915, Lincoln, Nebraska 68583-0915, USA.

[*]To whom correspondence should be addressed. E-mail: speng@mail.hzau.edu.cn

Abstract:

China produces 28% of global rice supply and is currently self-sufficient despite a massive rural to urban demographic transition that drives intense competition for land and water resources. At issue is whether to remain self-sufficient, which depends on the potential to raise yields on existing rice land. Here we report the first high-resolution spatial analysis of rice production potential in China and evaluate scenarios to 2030. We find that China is likely to remain self-sufficient in rice assuming current yield and consumption trajectories and no reduction in production area. Focusing research and development on rice systems and regions with the largest potential to close yield gaps, as identified in this study, provides greatest opportunity to remain self-sufficient, even with reduced rice area.

Main Text:

China must make strategic decisions about how to ensure food security for 1.4 billion people, and those decisions will have a large impact on global agriculture and land use. Currently self-sufficient in rice production, China's most important food crop, annual production of about 206 million metric tons (MMT) represents 28% of global rice supply[1,2]. At issue is whether agricultural policy should target continued self-sufficiency in rice or accept becoming a major rice importer. Resolution of this issue will markedly influence global rice markets because reliance on imports for just 10% of China's rice consumption represents more than 35% of all internationally traded rice based on 2013-2015 global export statistics[3].

Current self-sufficiency has been achieved by raising rice yields more than 50% since 1980 with an 11% reduction in harvested rice area. But the rate of rice yield growth has slowed markedly in recent years[4], and prime farmland and water for irrigation are becoming increasingly scarce as the rural to urban demographic shift drives fierce competition for both land and water[5,6]. Given the prognosis for little increase, or even a reduction, in rice production area, making an informed decision about whether to pursue continued self-sufficiency depends on the potential for increasing yields on existing rice area. Yield gap analysis provides the means for estimating this untapped production potential by estimating the difference (i.e. gap) between current farm yields and the potential yield that can be achieved when yield losses from nutrient deficiencies, pests and diseases are minimized[7].

Robust estimation of rice yield gaps in China is complicated by the large variation in production systems and climates in which rice is grown, from warm sub-tropics at 18° N latitude to cool temperate climates at 50° N. Potential yield is a location-specific property because it depends on the local weather and the annual crop rotation sequence. In the irrigated systems that dominate rice production in China, location-specific factors governing potential yield include length of growing season, determined by temperature regime, and the amount of light intercepted by the leaf canopy during the crop growth period, determined by incident solar radiation, leaf area development and persistence[8]. Hence, accurate yield gap estimation requires good quality, long-term weather records and data on current crop yields and management practices with adequate spatial resolution to support simulation of potential yield across the large environmental variation that characterizes Chinese rice production[9]. To date it has not been possible to perform such a high-resolution analysis due to lack of both a spatially explicit dataset on rice production systems across such a wide range of environments, and a suitable upscaling technique for aggregating results to a national scale.

To fill this void, we report the first spatially explicit yield gap analysis of Chinese rice production using primary data and scaling methods recently developed for the Global Yield Gap Atlas (www.yieldgap.org)[9,10]. From this yield gap analysis, we evaluate future scenario options based on estimated rice production capacity on current Chinese rice area and identify specific regions and rice production systems that deserve highest priority for research and development investments to achieve greatest rice production on a limited supply of prime farm land.

The geography of Chinese rice production has undergone enormous changes over the past 35 years. Whereas double-rice systems (i.e. two rice crops per year planted and harvested in the same field) that dominate in the warm climates of south and central-south coastal regions accounted for 66% of total harvested rice area in the 1980s, they currently represent less than 40% (Fig. 1). In contrast, area given to single-rice systems (i.e. one rice crop per year on a given field) in cooler climates of central and northern regions has increased steadily although this expansion did not overcome the reduction in double-rice area. Hence, total harvested rice area has decreased by about 3.6 million hectares (Mha) since 1980. The main reasons for decrease in double-rice were: (i) rapid urbanization in south and central-south coastal regions and associated conversion of rice land to housing, industry, and supporting infrastructure, and (ii) decreased rural labor availability and rising labor costs leading to lower net income than for single-rice systems, which require less labor[11]. Taken together, trends in production area and yields have resulted in dominance of single-rice systems, which now account for more than 65% of national rice production (Fig. 1).

To achieve the required level of spatial resolution for robust estimation of rice yield gaps requires primary data for at least 10 years of daily weather records, digital maps of current rice production area and associated rice yields, and the dominant rice cropping systems and management practices at 50 locations representing 16 climate zones[9,10]. Because both single- and double-rice systems are prevalent at some of these locations, a total of 847 simulations of rice yield potential were required using a well-validated rice simulation model (details on calibration and validation provided in Supplemental Materials). These location-specific estimates were then scaled up, based on the proportion of national rice area represented by each location and rice cropping system, to give national estimates of yield potential and current farm yield of 9.8 and 6.8 metric tons per ha (t ha^{-1}), respectively, and a national average yield gap of 3.0 t ha^{-1}. Hence, current national average rice yield represents 69% of potential yield, which is approaching the 75-80% of the potential yield threshold at which farm yields typically stagnate at regional to national scales due to diminishing returns from further investment in yield-enhancing technologies and inputs[12].

Evaluating yields by climate zone identifies large differences in potential yield among regions and rice cropping systems. For example, estimated potential yields ranged from 8.6 to

10.8 t ha^{-1} across climate zones and rice systems, while current farm yields varied from 5.2 to 8.8 t ha^{-1} (Fig. 2). Farm yields were highest in central regions for both single- and double-rice systems. Year-to-year variability in potential yield was small for both systems as indicated by a coefficient of variation (CV) of 8%, which is typical of the high yield stability found in grain production systems with a reliable supply of irrigation water[13]. In double-rice systems, potential yields of early- and late-rice crops were similar, with a national average of 9.0 t ha^{-1} for both crops. Although national potential yield of single-rice was 14% greater than that of double-rice (10.3 versus 9.0 t ha^{-1}), total annual potential yield from double-rice was 18 t ha^{-1} because two crops are produced each year from the same field.

Larger spatial variation in current farm yields (CV = 14%) than in potential yields (CV = 8%) resulted in a wide range of yield gaps, from 18% to 41% of potential yield across the 16 climate zones evaluated. Current national farm yields for single-rice (7.4 t ha^{-1}) and per season double-rice (5.9 t ha^{-1}) were 72% and 66% of the potential yields estimated for each system, respectively. Hence, yield gaps of single-rice systems are very close to the 75-80% of potential yield threshold at which farm yields tend to stagnate, whereas yield gaps in double-rice systems are considerably below this threshold.

Assuming the *exploitable* yield gap is estimated by the difference between current farm yield and 80% of potential yield (hereafter called the attainable yield ceiling), exploitable yield gaps for each of the two crops in double-rice systems are 44% greater than for single-rice (1.3 versus 0.9 t ha^{-1}, Table 1). Annual total per hectare increase in rice production from closing exploitable yield gaps would be three-fold greater for double-rice than for single-rice (2.6 versus 0.9 t ha^{-1}). Correcting for the larger current production area of single-rice gives a total potential increase in rice production of about 16 MMT from double-rice and 15 MMT from single-rice with closure of exploitable yield gaps on all current rice area (Fig. 3a). Taken together, a scenario of closing exploitable yield gaps on existing rice area would increase national rice production by 15% (+31 MMT, Table 1) compared to current rice production of 206 MMT (average of 2013-2015)[1].

But achieving yields that are 80% of yield potential requires large inputs of fertilizer nutrients and aggressive use of pest control measures to minimize yield losses caused by diseases, insects, and weeds. Precise timing of these inputs with regard to stage of crop development is also required, which means greater investment in labor and expertise to monitor crop status and make tactical modifications to field management during the growing season in response to weather and expected yield levels. Such intensive management may not be economically justifiable if marginal costs of the additional inputs, labor, equipment, and decision-support tools do not cover expected returns, which appears to be the case in California where irrigated rice yields have stagnated at 76% of yield potential[14]. Hence, if the attainable yield ceiling for profitable rice production is only 75% of yield potential, increased production capacity would be 8% of current production (+16 MMT, Fig. 3a). Although climate change will have an impact on rice yield potential and regional production potential as evaluated in these scenarios, the magnitude of climate change by 2030 is projected to be relatively small compared to the impact during the second half of this century[15].

To evaluate plausible future scenarios, we use a projected total rice demand of 217 MMT by 2030 based on the average of three studies[16-18]. In the four scenarios evaluated, we assume that total rice production area remains constant to 2030, which is consistent with recent trends for double-rice systems (Fig. 1), and also for central and northern provinces where single-rice systems prevail (justification for this assumption in supplementary materials and associated Extended Data Fig. 5). Scenario 1 assumes farm yields remain at current levels to 2030.

Scenarios 2 and 3 assume that current modest growth rates in rice yields (Extended Data Fig. 4) continue to 2030 and impose an attainable yield ceiling of either 80% (scenario 2) or 75% (scenario 3) of potential yield (Table 1). Scenario 4 is the same as scenario 3 but with higher growth rate in yields of double-rice systems to be equivalent to the yield growth rate of single rice, which is modest compared to much faster growth rates experienced during the 1970s and 1980s.

Import of 11 MMT would be required to meet projected 2030 rice demand under scenario 1, whereas scenario 2 with an attainable yield ceiling 80% of yield potential results in a 7 MMT surplus (Table 1), which is equivalent to 11% of current global rice trade. But given concerns about the substantial environmental pollution associated with current intensive crop production practices[19], a scenario with a 75% attainable yield ceiling is perhaps more appropriate because it would require less fertilizer input and less aggressive pest control measures. Under this less intensive production scenario, China would be nearly self-sufficient with a modest annual import requirement of 2 MMT. Strategic investment in provinces and rice systems with greatest yield gaps, however, could produce a small surplus even with the more conservative attainable yield ceiling. For example, greatest yield gaps are found in double-rice systems in general (Fig. 2), and in some provinces where single-rice dominates. Indeed, seven of the seventeen provinces in which rice is a major crop account for 78% of the potential increase in rice supply if all rice farmers achieved yields that reach the attainable yield ceiling of 80% of yield potential (Fig. 3b). Hence, a focus on increasing yields of double-rice systems in general, and in the three single-rice provinces where yield gaps are relatively large, would likely provide greatest return on investments in research and development to raise rice production. Moreover, current annual growth rate in yield of double-rice is only 60% that of single-rice (0.03 versus 0.05 t ha^{-1} year^{-1}, Extended Data Fig. 4) while magnitude of the yield gap is considerably larger for double-rice than for single-rice. Taken together, the larger yield gap and slower yield growth rate suggests greater potential to accelerate yield growth of double-rice, assuming targeted investment in that goal. Raising the rate of yield growth of double-rice to that of single-rice would lead to a rice production surplus of 2 MMT by 2030 with a conservative attainable yield ceiling 75% of yield potential.

That small changes in projected Chinese rice production have large impact on global rice trade highlights the need for accurate estimates of potential production on existing rice area. Hence, the spatial resolution of our yield gap analysis by climate zone, province, and cropping system is essential to adequately inform policies and strategic plans for food security and land use. For this reason our analysis: (i) distinguishes between the two major rice cropping systems, (ii) utilizes a rice simulation model that has been rigorously validated for ability to estimate yield potential across the major rice-growing regions in China (supplementary materials, Extended Data Fig. 3), (iii) relies on at least 10 years of measured weather data (supplementary materials, Extended Data Fig. 1), and (iv) employs a "bottom-up" scaling protocol validated for capacity to reproduce crop performance across large variation in climate[9,10]. In contrast, previous studies have used a "top-down" spatial framework based on meso-scale grids (roughly 100 km^2) into which weather and current crop yield data obtained from databases at much coarser scale are "interpolated" into this smaller grid size. Likewise, these previous studies do not provide estimates of potential yield as distinguished by different rice cropping systems. In these top-down studies, yield potential is estimated by either the 90th percentile of current farm yields[20], or by a generic crop model not specific for rice and therefore not validated for ability to estimate rice yield potential across the wide variation of rice-growing environments in China[21].

Comparison of estimates using our bottom up approach with those from the top down approach of Global Agro-Ecological Zone protocols (GAEZ)[21] shows a modest difference in national potential production of 17 MMT by 2030, which represents 8% of current national production, and a relatively large fraction (27%) of current global rice trade (documentation of comparison provided in supplemental materials and Extended Data Table 3). And while estimates of national potential yield by the two approaches are also in relatively close agreement (10.5 t ha^{-1} for GAEZ versus 9.8 t ha^{-1} as reported here), potential production estimates at the provincial level (Fig. 3b) and the estimates of yield potential and yield gap at climate zone scale (Extended Data Fig. 6) differ markedly; For example, in two of the provinces GAEZ potential production estimates are well below current rice production (2013-2015 average). Moreover, in five climate zones in central and southern China, representing 43% of total Chinese rice production, GAEZ estimates a yield potential 18% greater than reported here, and in the two northernmost rice-growing climate zones the GAEZ estimate is 22% less than our estimate (based on data shown in Extended Data Fig. 6). Hence, the relatively close agreement in potential yield estimates at national scale occurs by chance and masks large differences in estimates at finer spatial scales. Such large differences at provincial and climate zone scales between the two approaches would result in very different research and development priorities that seek to focus investments on regions and cropping systems with greatest opportunities for increasing rice production.

Crop price supports and other types of subsidies to promote self-sufficiency in food production are not considered sound agricultural policy due to high costs, market distortions, and reduced incentives for innovation and efficiencies[22]. In contrast, Clapp[23] argues that populous countries like China may benefit from maintaining self-sufficiency or near self-sufficiency, in production of their primary staple food crops. Hence, for a country like China, reliance on imports for even a small portion of total rice demand represents such a large fraction of global rice trade that pressure from Chinese rice purchases can influence global rice prices in ways that might lead to higher food prices and reduced access, not only for China but also for other countries that import rice. Such pressures are of particular concern in years when global rice supply falls short due to major drought or flooding in rice exporting countries. The good news is that the scenarios evaluated in this study indicate that China has substantial flexibility to maintain self-sufficiency in rice without increasing cropland area devoted to rice production. Indeed, by strategic targeting of investments in research and development it may be possible to maintain self-sufficiency with a net reduction in rice cropland area, especially if the rate of yield gain can be accelerated in double-rice systems.

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Materials and Methods

Protocols for yield gap assessment and spatial upscaling. For irrigated crops such as rice in China, the yield gap represents the difference between current farm yields and the yield potential when the crop is grown without limitations from nutrient deficiencies, insect pests, or diseases[7]. To estimate yield gaps we followed protocols developed by the Global Yield Gap Atlas, which utilizes primary, location-specific data to the extent possible[9] and a robust upscaling framework to estimate yield gap at larger levels of spatial aggregation such as climate zones (CZ), regions, and national scales[10]. These protocols have been rigorously evaluated for their ability to estimate yield gaps using Australian rainfed wheat as a test case[24]. All underpinning data are available on the Global Yield Gap Atlas (GYGA) website (http://www.yieldgap.org/). The GYGA protocols are based on a climate zonation scheme developed by van Wart et al.[25] that is delineated by three variables: (i) growing degree days, which determine the potential length of the crop growing season, (ii) annual aridity index, which provides an estimate of water supply as the ratio between rainfall and potential evapotranspiration, and (iii) temperature seasonality, which distinguishes between temperate and tropical climates. One hundred and twenty-seven CZ are delineated in China using this climate zonation scheme.

Briefly, a digital map of rice crop area distribution (SPAM map, with 10 x 10 km grid-cell resolution)[26] was superimposed on the CZ map to identify weather stations located in areas with greatest density of rice production area (Extended Data Fig. 1). Buffer zones of 100-km radius surrounding each weather station, were clipped following van Bussel et al.[10], so that their borders fall within the same CZ. Weather stations were selected in sequence starting with the station and associated buffer zone with largest rice area and continuing until ca. 50% of national rice area was covered by the selected weather station buffer zones. Earlier work has shown that inclusion of additional weather stations to achieve greater coverage of rice area does not improve national estimates of yield gap[27]. Selected weather stations are hereafter referred to as reference weather stations (RWS). Following this approach, 50 RWS were selected containing 48% of national harvested rice area within their associated buffer zones. The 50 RWS are located in 16 CZ, which together contain 85% of national rice area (Extended Data Fig. 1). Details about selected RWS locations and the dominant rice cropping system within each RWS buffer zone are provided in Extended Data Table 1.

Simulating rice potential yield. The ORYZA model has been widely used to simulate yields of different rice cultivars across a wide range of climatic conditions in Asia, Africa and USA[14,28,29]. We used the most recent version of this model, ORYZA v3[30]. Because potential yield is a location-specific property, ORYZA v3 requires input data for each RWS, including long-term daily weather records and crop management practices. Rice cultivar specification and associated cultivar-specific parameters are also required to run the simulation model to adequately represent crop phenology, biomass production and dry matter partitioning amongst different plant organs (roots, leaves, stems, panicles, and seeds).

(i) Weather data

Simulation of annual potential yield and temporal variability in potential yield due to year-to-year variation in weather using the ORYZA v3 model requires daily weather records for maximum and minimum temperature, wind speed, relative humidity, precipitation, and solar radiation. For irrigated cropping systems, 10 years of weather data are sufficient for robust estimation of weather-related temporal variation in potential yield[7]. We obtained daily weather data for 11 years (2004-2014) for all weather variables (except solar radiation) from the National Meteorological Information Center of the China Meteorological Administration. We obtained solar radiation data from the NASA-POWER database (http://power.larc.nasa.gov/). Previous studies have shown that crop yield simulations based on NASA-POWER solar radiation are in close agreement with simulations based on ground-measured radiation across a wide range of environments and regions[31].

(ii) Crop management data

Crop management data required for simulation of potential yield include sowing date, plant density (i.e., number of plants per unit of ground area), and phenological durations of dominant cultivars. For each RWS and associated buffer zone, we obtained information about the predominant rice cultivars and current yield from local experimental data, and publications reporting agronomic field research conducted at those sites. The selected RWS were grouped into six regions according to CZ and dominant cultivar characteristics following Duan et al.[32,33], and management practices within the same region were assumed to be similar (Extended Data Fig. 2). For example, single-rice systems dominate in the northeast, north, central and southwest regions, while double-rice systems dominate in the central and south regions. In each region, one widely planted rice cultivar was used for single-crop systems, while two cultivars were used for double-rice systems, one for the early and the other for the late cropping season.

(iii) Derivation of cultivar-specific parameters, calibration and validation of the ORYZA v3 model

Cultivar-specific parameters were derived following standard procedures for the ORYZA v3 model[30], and related information is provided in Extended Data Table 2. Parameterization of crop characteristics was obtained by two utility programs in ORYZA v3 model called ***drate(v2).exe*** and ***param(v2).exe***. The ***drate(v2).exe*** was used to determine the phenology development rate by using the phenological stages and growth duration of local dominant cultivars. The

param(v2).exe was used to estimate crop parameters such as assimilate partitioning among organs, leaf area index, and specific leaf area at different phenological stages of local dominant cultivars.

We calibrated the model and evaluated it over a subset of RWS that reflect the variation in rice cropping systems and climates across rice growing regions in China. Calibration utilized data from both our own high-yield field studies conducted in central China, and from data published by others based on field experiments in other regions in which rice was grown without limitations from nutrients, water supply, or pests. Further details about model calibration and validation can be found in Extended Data Table 2.

Since ORYZA v3 was developed for tropical areas, the model was calibrated in the present study to account for the climate conditions and dominant cultivars grown in China. For cultivars used in southern China, for example, the maximum temperature at which phenological development rate falls to zero was increased from 42 ºC as the default value in ORYZA v3 to 42.6 ºC and the optimal temperature for growth and development from 30 ºC to 31.2 ºC; for cultivars used in northern China, cold tolerant days was extended from 5 days to 10 days within the optimal rice growth range[34].

Agreement between simulated and observed variables was assessed by the coefficient of determination *(r^2)*, root mean square error (*RMSE)* and *RMSE* expressed as percentage of the observed mean (*$RMSE_n$*), which were calculated as follows:

$$r^2 = \left(\frac{n(\sum xy)-(\sum x)(\sum y)}{[n\sum x^2-(\sum x)^2][n\sum y^2-(\sum y)^2]}\right)^2 \qquad (1)$$

$$RMSE = [(\sum(x-y)^2/n)]^{0.5} \qquad (2)$$

$$RMSE_n = [(\sum(x-y)^2/n)]^{0.5} / M_{mean} \times 100\% \qquad (3)$$

where x and y represent the simulated and observed values, and n represents the number of paired values. r^2 close to 1 and *RMSE* and $RMSE_n$ close to 0 indicate a good agreement between simulated and observed values.

The validation indicated that the calibrated ORYZA v3 model adequately reproduced measured rice yields across a wide range of production environments in China (Extended Data Fig. 3). Measured grain yields across experiments ranged from 7.7 to 14.5 t ha^{-1} and were in close agreement with simulated values after model calibration as indicated by relatively low *RMSE* of 0.84 t ha^{-1}, which is less than 10% of the mean measured yield (Extended Data Fig. 3). Likewise, aboveground dry matter and growth duration (from emergence to physiological maturity) were in close agreement as indicated by the low *RMSE* of 0.61 t ha^{-1} for shoot biomass and 8 d for growth duration. High r^2 (0.90) between measured and simulated yields, indicates little bias in simulated yields over the entire range of measured values, which gives confidence that the calibrated ORYZA v3 model is robust at reproducing potential yield across the wide range of climates and rice cropping systems in China.

Current farm yield and yield gaps. Current farm yields for the most recent 2-5 years were retrieved from official statistical records and online statistics in national and provincial bureaus for each of the counties in which the selected RWS is located. However, county-level farm yield data are not accurate for a number of reasons, and the magnitude of inaccuracy varies across counties and is difficult to predict[35,36]. In contrast, provincial level farm yield data are more reliable and accurate because a combination of different methods are used, including remote sensing and ground trothing[37]. Hence, using county-level data without adjustment to be consistent with the provincial-level yield data gives inaccurate yield gap estimates when results are aggregated to larger spatial scales. To adjust county-level yield data in a province, we increased or decreased farm yields by an equivalent percentage so that the weighted average farm yields across all RWS within that province equaled the provincial official average yield. However, we did not adjust farm yield of counties in provinces for which there was little difference (within ± 5%) between the official provincial farm yield and the upscaled provincial farm yields following GYGA protocols.

The dominant cropping system (single- or double-rice) was identified for each RWS buffer zone and used as the basis for simulating potential yields and for estimating yield gaps. In some parts of central China and in northern provinces, only a single-rice crop is grown each year because the growing season is too short for double-rice. Hence, the yield gap for each RWS where a single-rice crop is grown was calculated as the difference between the single-rice potential yield and the current farm yield. In south and some parts of central China, farmers practice a double-rice cropping system. However, county level data provide only the average yield for the two crops. But the area of early- and late-season rice crops is almost identical at 19% and 20% of total rice area, respectively, based on the estimates from[1]. We therefore simulated yields of early and late-rice crops separately, and used the average potential yield of the two crops to calculate yield gaps for each RWS where double-rice systems dominate.

To upscale potential yield, current farm yield, and yield gap estimates from RWS to larger spatial scales, weighted averages for each variable were calculated by the proportional contribution of rice area within each spatial unit contributing to the spatially aggregated value at the CZ or national scale[10].

Estimating rice production potential. Current farm yields tend to stagnate when they reach 75-80% of potential yield (called the attainable yield ceiling) due to diminishing returns from investment in additional production inputs and effort as yields approach the potential yield ceiling[12,14,27]. Hence, prospects for increasing rice production at any spatial scale are best indicated by the “exploitable” portion of the yield gap, which is the difference between current farm yields and 75% or 80% of potential yields estimated at the CZ and national scales. All else equal, achieving yields that are 80% of potential yield requires greater input of nutrients and more aggressive pest control measures than production at 75% of potential yield. Given concerns about the substantial environmental pollution associated with current intensive crop production practices[19], scenarios with either an 80% or 75% attainable yield ceiling were evaluated. Additional exploitable production potential of single- versus double-rice systems were estimated by the difference between 75% or 80% of potential yield and current farm yields for each rice cropping system over the total national production area.

Future Scenarios. Rice production scenarios to 2030 were evaluated based on the following assumptions:

(i) Yield would stagnate at current levels to 2030 or follow current trajectories based on regression of national rice yields versus year for single- and double-rice (Extended Data Fig. 4).

(ii) The amount of cropland devoted to rice production remains unchanged at the level of 2011-2014 average. This assumption is consistent with current trajectories based on the fitted trends of observed harvested area (Extended Data Fig. 4). We plotted harvested area and yield against year (1985-2014) for different rice cropping systems by linear function or by a linear-segment piecewise function using SigmaPlot 10.0 (Systat. Software, Inc., San Jose California USA), as shown in Extended Data Fig. 4.

Linear function:

$$y = at + \mathrm{b} \qquad (4)$$

where t is year, y is single-rice harvested area or single-, double-rice yield.

Two-linear-segments piecewise function:

$$t_1 = \min\ (t), \text{ which is the year 1985} \tag{5}$$

$$t_2 = \max\ (t), \text{ which is the year 2014} \tag{6}$$

$$y = \begin{cases} \frac{a(T_1-t)+b(t-t_1)}{T_1-t_1}, & t_1 \le t \le T_1 \\ \frac{b(t_2-t)+c(t-T_1)}{t_2-T_1}, & T_1 \le t \le t_2 \end{cases} \tag{7}$$

where *t* is year, *y* is total- or double-rice harvested area, and T_1 is the breakpoint year. The r^2 for the linear regressions of total-, single- and double-rice harvested area are 0.73, 0.88 and 0.93, and the r^2 for the linear regressions of single- and double-rice yield are 0.78 and 0.71. All estimated parameters were significant (Student's t-test, $P < 0.0001$).

The linear regression for single-rice yield:

$$\mathrm{y} = 0.0488\ t - 90.788 \tag{8}$$

The linear regression for double-rice yield:

$$\mathrm{y} = 0.0263\ t - 47.255 \tag{9}$$

(iii) While a similar regression for single-rice area shows a continued linear increase through 2015, disaggregation of these data by province shows that most of the recent increase occurred in Heilongjiang province, and to a lesser extent in Jilin province while rice production area in remaining single-rice provinces has remained constant or even decreased in recent years (Extended Data Fig. 5). Moreover, recent government policies have advocated for reduced rice area in Heilongjiang.

(iv) Total rice demand in 2030 is 217 MMT, which represents the average of three recent studies[16-18] compared with current rice production of 206 MMT (average of 2013-2015)[1].

(v) An attainable yield ceiling of either 80% or 75% of potential rice yield.

Comparison of yield differences by GAEZ and GYGA methods. Global Agro-Ecological Zones Model version 3.0 (GAEZ v3.0)[21] was used for comparison of yield gap analyses. We selected GAEZ for comparison because the potential crop production data layer is being used to evaluate future scenarios of agricultural production in several studies (e.g.[38,39]). Compared to the GYGA up-scaling method, a down-scaling method is used in GAEZ v3.0 such that both weather and agricultural crop production data (e.g. current yields and crop production area) from much coarser spatial scales are "interpolated" into 5 arc-minute grid cells (roughly 100 km^2). National estimates are then estimated by aggregation of data from all grids in which there is rice production area. In contrast to our GYGA approach, which utilized provincial-level data on proportion of rice area under either single- or double-rice systems to estimate area of each system within RWS station buffer zones, GAEZ assigned one rice cropping system to each 5 arc-minute grid cell by matching growth cycle and temperature requirements of rice with time available for crop growth[21].

In GAEZ the "Agro-climatic attainable yields with high input level" data layer is defined as potential climatic yield with optimal management practices ($Yp_{\_GAEZ}$), which is the proxy for potential yield as estimated using GYGA methodology ($Yp_{\_GYGA}$). The map of Agro-climatic attainable yields with high input level for irrigated rice (map) was downloaded on May 26th, 2018 from GAEZ website: http://gaez.fao.org/.

We calculated $Yp_{\_GAEZ}$ at CZ, province and country levels and compared them with $Yp_{\_GYGA}$ at those same levels of spatial upscaling using the following approach. First, each GAEZ grid cell (5 arc-min) in $Yp_{\_GYGA}$ map was superimposed with the irrigated rice harvested area from the SPAM map[26] to assign a harvested rice area to each grid cell. Second, each grid cell was assigned to a GYGA CZ based on the CZ map. The two processes were performed in ArcGIS 10.2. Weighted Yp values based on harvested area were then estimated at the CZ, province and at the country level. Potential yield in GAEZ was calculated:

$$Y_p = \frac{\sum_{i=1}^{n} Y_{pi} \times ha_i}{\sum_{i=1}^{n} ha_i} \qquad (10)$$

where Yp is potential yield, and ha is harvested area. For Yp at CZ level, *i* is a grid cell and n is the number of grid cells within a CZ. For Yp at province level, *i* is a grid cell and n is the number of grid cells within a province. For single-rice Yp, *i* is a CZ and n is the number of CZ within single-rice system. For double-rice Yp, *i* is a CZ and n is the number of CZ within double-rice system. For Yp at country level, *i* is a cropping system and n is the number of cropping systems within a country. Yg in GAEZ (Ya as a percent of Yp) was calculated:

$$Y_{g\_GAEZ}\,(\%) = \frac{Y_{a\_GYGA}}{Y_{p\_GAEZ}} \times 100\% \qquad (11)$$

where Ya in GYGA was used to calculate Yg for GAEZ because the Ya in GAEZ is outdated (from year 2000).

Data availability. All data is available in the manuscript or the supplementary materials.

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Table 1 │ Yields and production of single- and double-rice systems in China, and total national production under four scenarios projected to 2030.

Scenarios*	Rice system	Yield ($t\ ha^{-1}$)	Production (MMT)	Total production (MMT)	Total production compared with demand in 2030 (217 MMT) (MMT)
S1[*]	Single-rice	7.4	135.4	206	-11
	Double-rice	5.9	71.0		
S2, 80% Yp ceiling	Single-rice	8.3	150.5	224	7
	Double-rice	6.1	73.6		
S3, 75% Yp ceiling	Single-rice	7.8	141.2	215	-2
	Double-rice	6.1	73.6		
S4, 75% Yp ceiling	Single-rice	7.8	141.2	219	2
	Double-rice	6.5	77.9		

[*] S1: Farm yields stagnate at current levels to 2030. S2 and S3: Rates of yield gain follow current trajectories based on regression of national rice yields versus year since 1985 to present for single- and double-rice to 2030 (Extended Data Fig. 4) and an attainable yield ceiling that is 80% (S2) or 75% (S3) of potential yield (Yp). S4: Rates of yield gain in double-rice systems increase to the current yield growth rate of single-rice (an increase from 0.03 $t\ ha^{-1}\ year^{-1}$ to 0.05 $t\ ha^{-1}\ year^{-1}$) and an attainable yield ceiling that is 75% of Yp. In all four scenarios there is no change in rice production area for each rice system, which is consistent with recent land use trends as explained in the text.

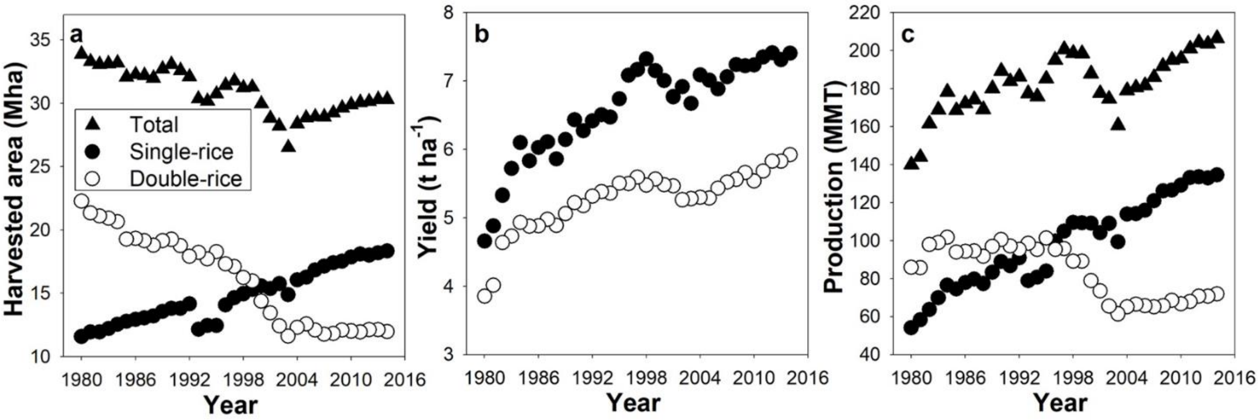


Fig. 1 | Rice production trends in China. Trends in harvested rice area (**a**), rice yield (**b**) and total production (**c**) for single- and double-rice cropping systems during the past 35 years (1980-2014) in China. Note that the yield for double-rice is on a per-harvested area basis so that total annual yield is twice the values shown. Data were obtained from[1].

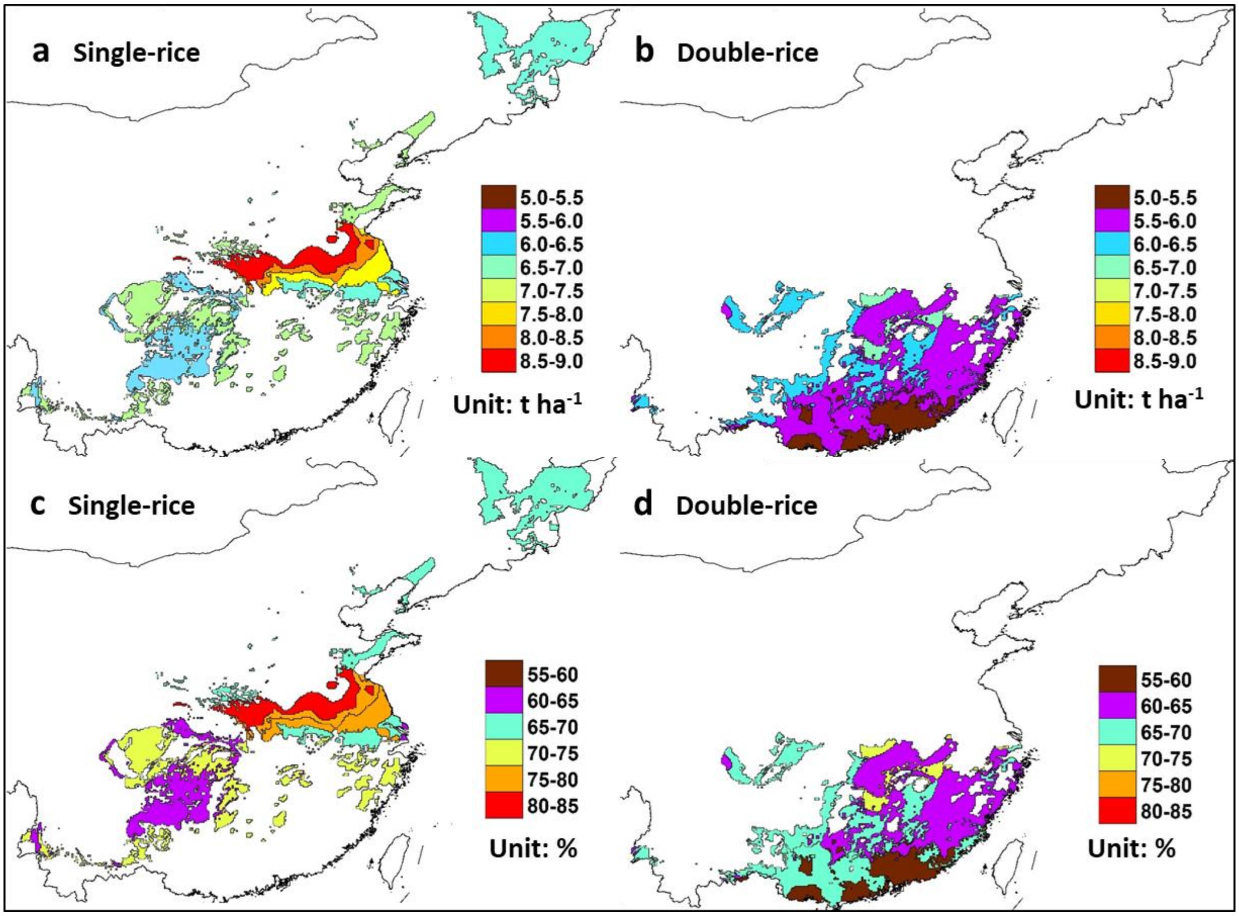


Fig. 2 │ Current farm yields and yield gap in China. Current farm yields as absolute values (**a**, **b**) or as a percentage of potential yields (**c**, **d**). All values are reported on a per-harvest basis and are mapped at the climate zone spatial scale. Note that there may be several climate zones within areas showing the similar current farm yield, and thus having the same color in these figures.

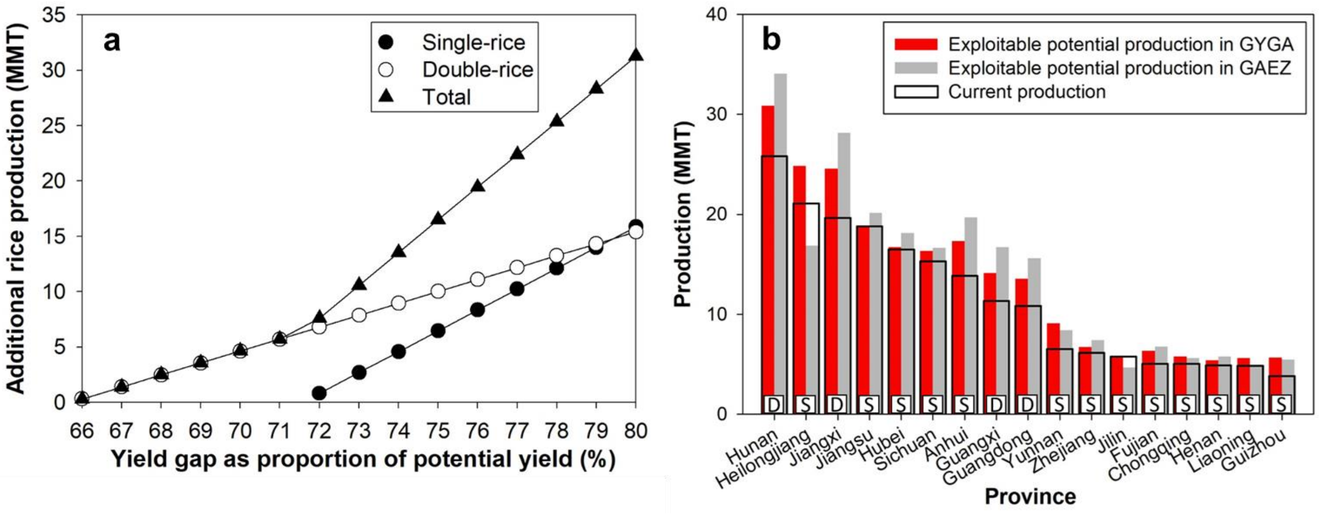
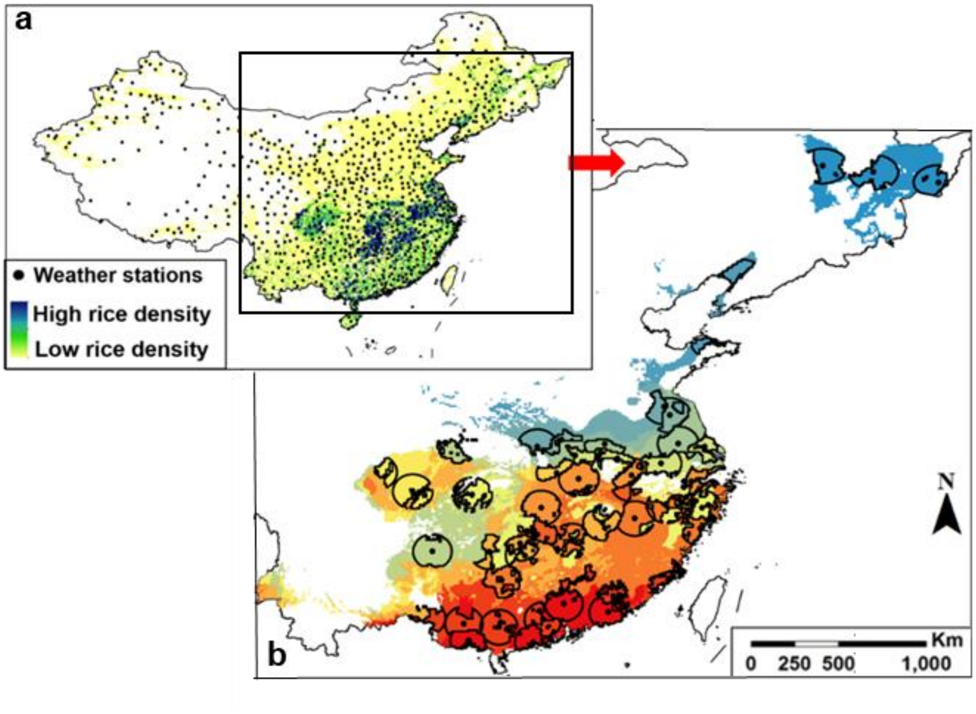
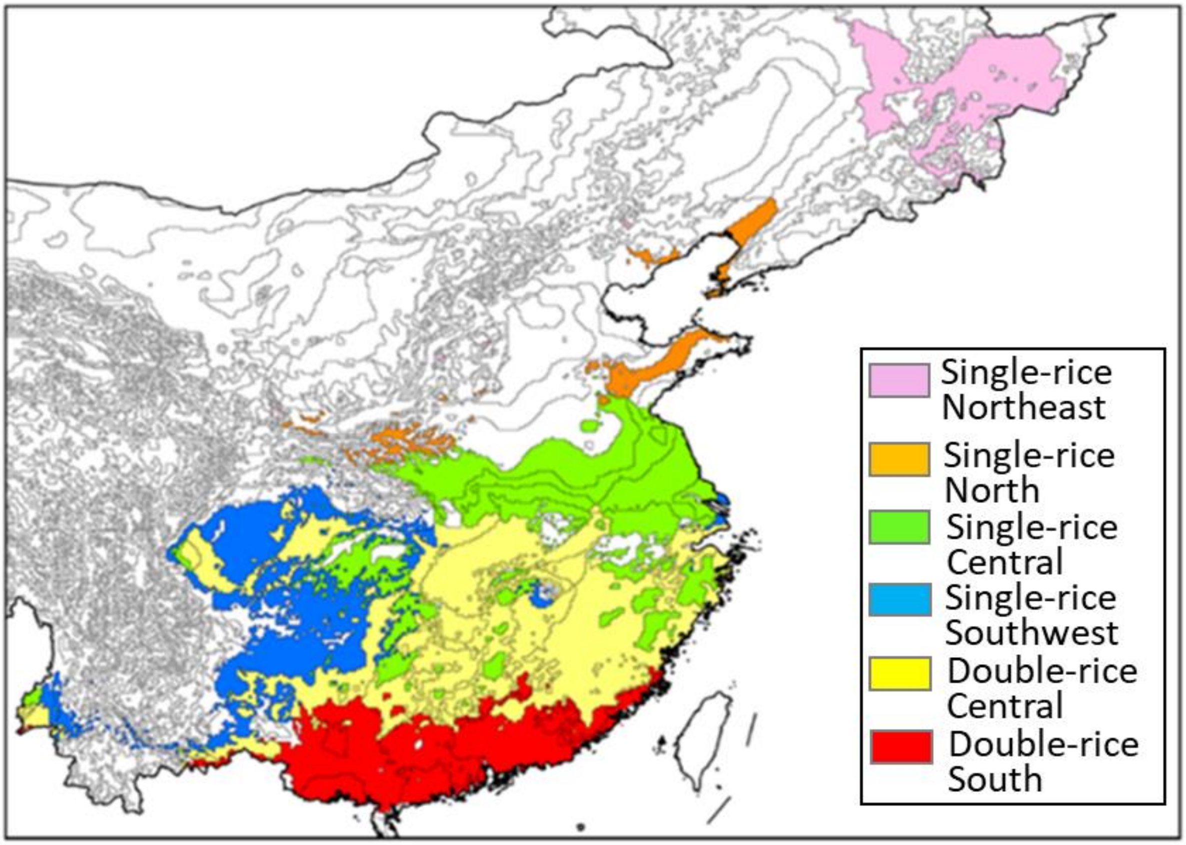


Fig. 3│Rice production in different cropping systems and provinces. a, additional rice production resulting from yield gap closure (expressed as % of potential yield) in single- and double-rice systems assuming no change in harvested area for each system and a maximum attainable yield ceiling that is 80% of potential yield. **b**, current annual rice production and exploitable potential production for each major rice growing province as estimated using protocols developed by the Global Yield Gap Atlas (GYGA) or by the Global Agro-Ecological Zones Model version 3.0 (GAEZ v3.0). Capital letters at bottom of each province production bar designate provinces in which double- (D) or single-rice (S) dominate. Exploitable potential production for each province is calculated as the product of provincial average rice planting area of 2013-2015 and the attainable yield whereby all rice farmers achieve yields that are 80% of yield potential. The current production for each province is based on 2013-2015 average.

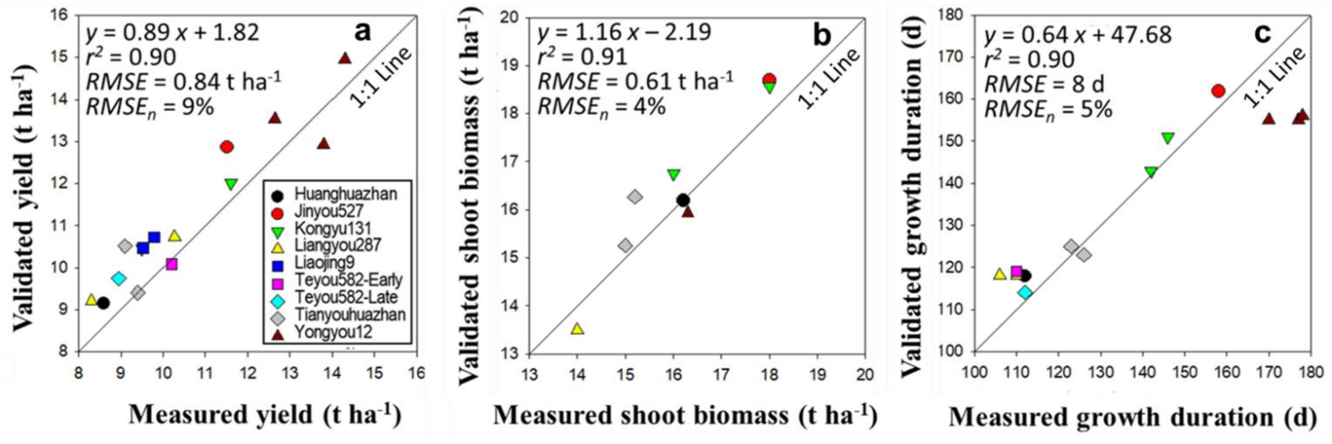
Supplementary Information



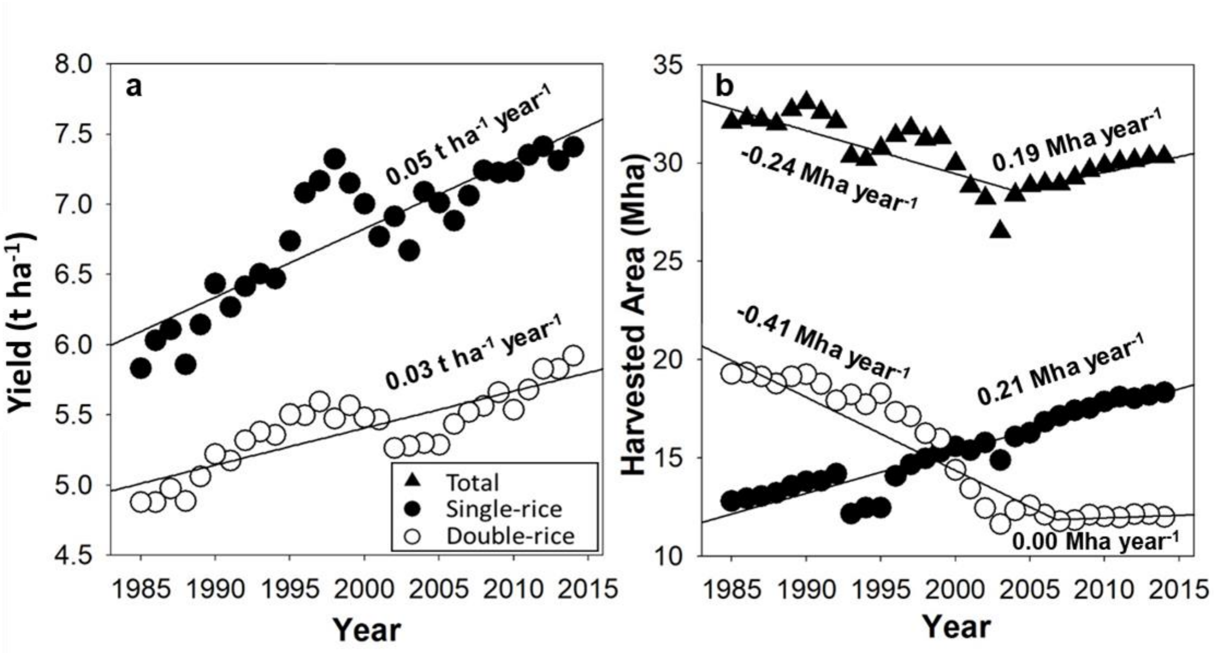
Extended Data Fig. 1 │ Selected reference weather stations (RWS) and climate zones (CZ). **a**, Locations of 875 weather stations (dots) from the China Meteorological Administration weather database (National Meteorological Information Center, http://data.cma.cn), and rice harvested area density (SPAM map)[26]. **b**, Selected RWS (black dots), borders of RWS buffers (black lines), and CZ (different colors) in China. In total, 50 RWS were selected in northeast, north, central, and south China, accounting for 48% of national rice harvested area within RWS buffer zones. The 50 selected RWS are located in 16 CZ, which, in turn, account for 85% of national rice harvested area.



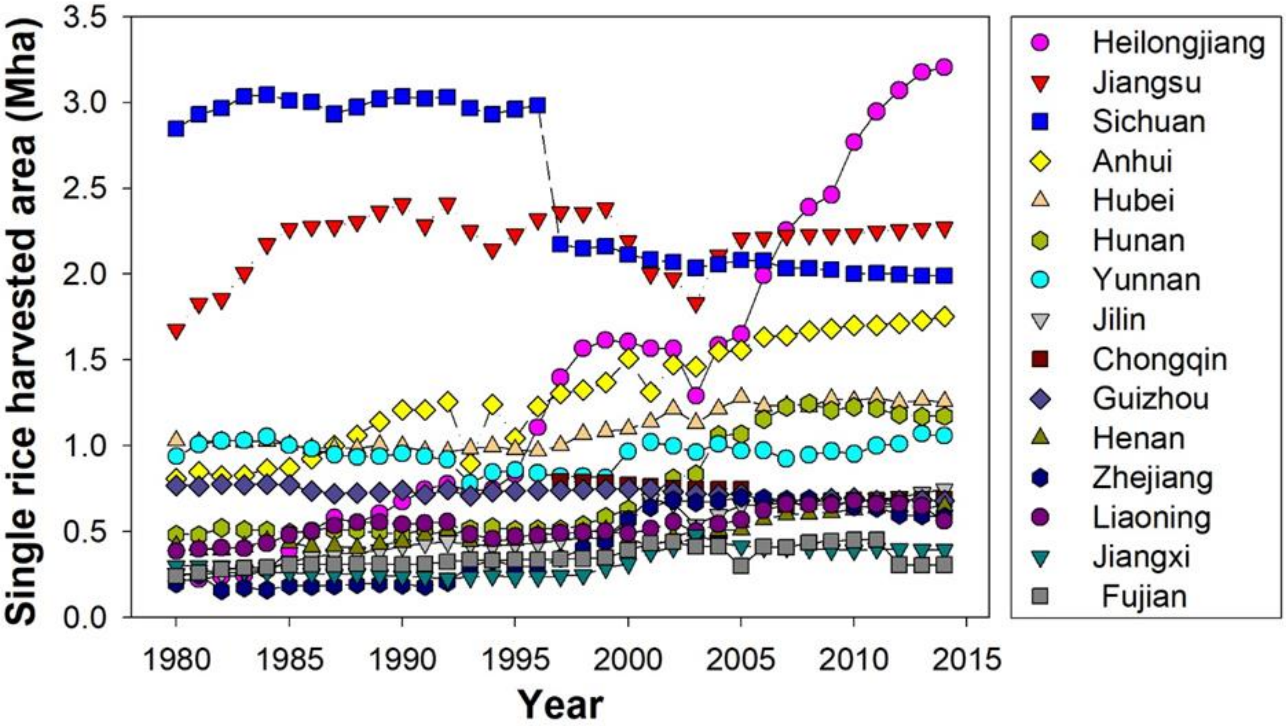
Extended Data Fig. 2 | Six rice production regions and dominant rice cropping system in each region. For the purpose of simulating yield potential, crop management practices, including rice cropping system, cultivar and sowing date, are considered to be similar within each region, which may contain from 1 to 5 climate zones.



Extended Data Fig. 3 │ ORYZA v3 model validation. Comparison of validated versus measured grain yield (**a**), shoot biomass (**b**) and growth duration (**c**) by using calibrated ORYZA v3 model. Growth duration corresponding to the time period from emergence to physiological maturity. Symbols with same colors represent the same cultivar grown in different years.

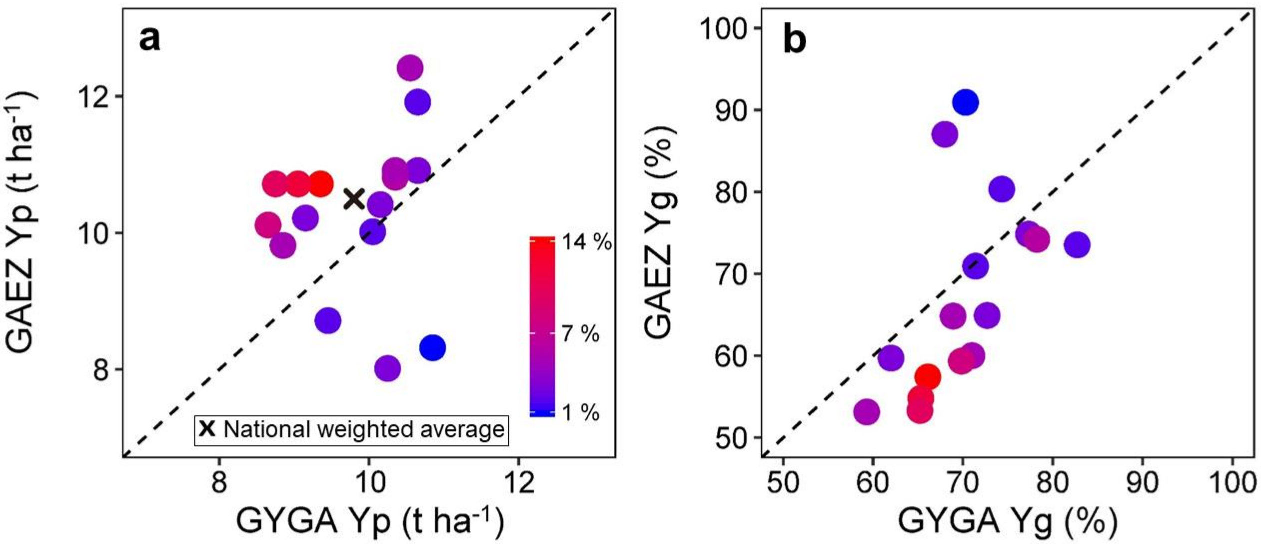


Extended Data Fig. 4 │ Trends in national average rice yield (a) and harvested area (b) in China. The data were disaggregated by total- (single and double), single- and double-rice crop production systems. Note that yields for double-rice are the average for the two rice crops grown each year in the same field so that total rice output per hectare is twice the values shown. Data were obtained from[1].



Extended Data Fig. 5│Trends in rice harvested area of single-rice by province since 1980.

Data were obtained from[1].



Extended Data Fig. 6 │ Comparison between GYGA and GAEZ. Comparison of (**a**) Yp and (**b**) Yg (Ya/Yp %) between GYGA and GAEZ at CZ level by weighting irrigated rice harvested area based on the SPAM map. Each observation represents one of the 16 major rice-growing CZs, and the different symbol colors represent the percentage of national rice harvested area contained within each CZ.

Extended Data Table 1 │Location, elevation, and cropping system for the reference weather stations (RWS) used in this study.

Station ID	RWS location (County, Province)	Longitude (º)	Latitude (º)	Elevation (m)	Cropping system*
1	Xiangfan, Hubei	112.2	32.0	70	Single-rice
2	Muyang, Jiangsu	118.8	34.1	9	Single-rice
3	Tongbai, Henan	113.4	32.4	149	Single-rice
4	Huaiyin, Jiangsu	119.0	33.7	15	Single-rice
5	Gushi, Henan	115.7	32.2	58	Single-rice
6	Dantu, Jiangsu	119.5	32.2	29	Single-rice
7	Dawu, Hubei	114.1	31.6	72	Single-rice
8	Nantong, Jiangsu	120.9	32.0	6	Single-rice
9	Huoshan, Anhui	116.3	31.4	73	Single-rice
10	Wuhu, Anhui	118.6	31.2	20	Single-rice
11	Qianjiang, Chongqing	108.8	29.5	609	Single-rice
12	Chengbu, Hunan	111.5	26.4	476	Single-rice
13	Xianju, Zhejiang	120.7	28.9	52	Single-rice
14	Wanyuan, Sichuan	108.0	32.1	674	Single-rice
15	Guiyang, Guizhou	106.7	26.6	1074	Single-rice
16	Wenjiang, Sichuan	103.8	30.7	541	Single-rice
17	Dazu, Chongqing	105.7	29.7	394	Single-rice
18	Jingan, Jiangxi	115.4	28.9	80	Single-rice
19	Haicheng, Liaoning	122.7	40.9	27	Single-rice
20	Fushan, Shandong	121.3	37.5	34	Single-rice
21	Suihua, Heilongjiang	127.0	46.6	180	Single-rice
22	Yilan, Heilongjiang	129.6	46.3	101	Single-rice
23	Hulin, Heilongjiang	133.0	45.8	104	Single-rice
24	Tianmen, Hubei	113.2	30.7	35	Double-rice
25	Jingzhou, Hunan	109.7	26.6	321	Double-rice
26	Shaoyang, Hunan	111.3	27.0	278	Double-rice
27	Cixi, Zhejiang	121.3	30.2	8	Double-rice
28	Jinhua, Zhejiang	119.7	29.1	65	Double-rice
29	Zhangshu, Jiangxi	115.6	28.1	30	Double-rice
30	Jiangxia, Hubei	114.3	30.4	38	Double-rice
31	Yuanjiang, Hunan	112.4	28.9	36	Double-rice
32	Anqing, Anhui	117.1	30.5	20	Double-rice
33	Hangzhou, Zhejiang	120.2	30.2	43	Double-rice
34	Lianhua, Jiangxi	114.0	27.1	181	Double-rice
35	Guilin, Guangxi	110.3	25.1	172	Double-rice
36	Guixi, Jiangxi	117.2	28.3	52	Double-rice
37	Quzhou, Zhejiang	118.9	29.0	67	Double-rice
38	Ruian, Zhejiang	120.6	27.8	10	Double-rice
39	Shuangfeng, Hunan	112.2	27.5	98	Double-rice
40	Dongzhi, Anhui	117.0	30.1	23	Double-rice
41	Nanxiong, Guangdong	114.3	25.1	135	Double-rice
42	Xianyou, Fujian	118.7	25.4	77	Double-rice
43	Meixian, Guangdong	116.1	24.3	89	Double-rice
44	Gaoyao, Guangdong	112.5	23.1	12	Double-rice
45	Nanning, Guangxi	108.4	22.8	74	Double-rice
46	Yulin, Guangxi	110.2	22.7	85	Double-rice
47	Fogang, Guangdong	113.5	23.9	68	Double-rice
48	Jiexi, Guangdong	115.8	23.4	42	Double-rice
49	Qinzhou, Guangxi	108.6	22.0	6	Double-rice
50	Yangjiang, Guangdong	112.0	21.9	22	Double-rice

*Dominant rice cropping system within the buffer zone surrounding each RWS, with either one (single-) or two (double-) rice crops per year, depending on length of growing season. The dominant cropping system (single- or double-rice) was identified for each RWS buffer zone and used as the basis for simulation of potential yield and estimation of yield gaps.

Extended Data Table 2 │ Crop management information for each of the six rice-production regions and the source of this information, and modifications to key parameters based on calibration of the ORYZA v3 model.

Rice system	Region	Sowing date	Cultivar	Growth duration[*] (d)	Modification in ORYZA v3	References
Single-rice	Northeast	15-April	Kongyu 131	130-145	Cold tolerant days (10 d)	40-42
Single-rice	North	15-April	Liaojing9	150-160	Cold tolerant days (10 d)	41-44
Single-rice	Central	10-May	Huanghuazhan; Yongyou12	115-125; 150-170	Max & Optimal temperature for development (42.6/31.2ºC)	Experimental data (2012-2013) from Wuxue, Hubei province, China; 45-49
Single-rice	Southwest	5-March; 20-April	Jinyou 527	155-170	Cold tolerant days (10 d)	50-51
Double-rice	Central	20-March; 20-June	Liangyou287; Tianyouhuazhan	115-130; 115-135	Max & Optimal temperature for development (42.6/31.2ºC)	Experimental data (2012-2014) from Wuxue, Hubei province, China 52-54
Double-rice	South	10-March; 15-July	Teyou582; Teyou582	115-135; 105-120	Max & Optimal temperature for development (42.6/31.2 ºC)	55-56

[*] Growth duration: days from emergence to physiological maturity.

Extended Data Table 3 | Estimated potential total production in 2030 if all rice farmers achieved yields that were 80% of potential attainable production as estimated by protocols developed by the Global Yield Gap Atlas (GYGA) or by the Global Agro-Ecological Zones Model version 3.0 (GAEZ v3.0).

Method	Total production in 2030 (MMT)	Increase over current production (206 MMT) (MMT)	Increase over production demand in 2030 (217 MMT) (MMT)
GYGA	237	31	20
GAEZ	254	48	37