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

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17 **Abstract:**

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

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40 **Main Text:**

41 China must make strategic decisions about how to ensure food security for 1.4 billion
42 people, and those decisions will have a large impact on global agriculture and land use. Currently
43 self-sufficient in rice production, China's most important food crop, annual production of about
44 206 million metric tons (MMT) represents 28% of global rice supply^{1,2}. At issue is whether
45 agricultural policy should target continued self-sufficiency in rice or accept becoming a major
46 rice importer. Resolution of this issue will markedly influence global rice markets because
47 reliance on imports for just 10% of China's rice consumption represents more than 35% of all
48 internationally traded rice based on 2013-2015 global export statistics³.

49 Current self-sufficiency has been achieved by raising rice yields more than 50% since 1980
50 with an 11% reduction in harvested rice area. But the rate of rice yield growth has slowed
51 markedly in recent years⁴, and prime farmland and water for irrigation are becoming increasingly
52 scarce as the rural to urban demographic shift drives fierce competition for both land and
53 water^{5,6}. Given the prognosis for little increase, or even a reduction, in rice production area,
54 making an informed decision about whether to pursue continued self-sufficiency depends on the
55 potential for increasing yields on existing rice area. Yield gap analysis provides the means for
56 estimating this untapped production potential by estimating the difference (i.e. gap) between
57 current farm yields and the potential yield that can be achieved when yield losses from nutrient
58 deficiencies, pests and diseases are minimized⁷.

59 Robust estimation of rice yield gaps in China is complicated by the large variation in
60 production systems and climates in which rice is grown, from warm sub-tropics at 18° N latitude
61 to cool temperate climates at 50° N. Potential yield is a location-specific property because it
62 depends on the local weather and the annual crop rotation sequence. In the irrigated systems that

63 dominate rice production in China, location-specific factors governing potential yield include
64 length of growing season, determined by temperature regime, and the amount of light intercepted
65 by the leaf canopy during the crop growth period, determined by incident solar radiation, leaf
66 area development and persistence⁸. Hence, accurate yield gap estimation requires good quality,
67 long-term weather records and data on current crop yields and management practices with
68 adequate spatial resolution to support simulation of potential yield across the large environmental
69 variation that characterizes Chinese rice production⁹. To date it has not been possible to perform
70 such a high-resolution analysis due to lack of both a spatially explicit dataset on rice production
71 systems across such a wide range of environments, and a suitable upscaling technique for
72 aggregating results to a national scale.

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

79 The geography of Chinese rice production has undergone enormous changes over the past 35
80 years. Whereas double-rice systems (i.e. two rice crops per year planted and harvested in the
81 same field) that dominate in the warm climates of south and central-south coastal regions
82 accounted for 66% of total harvested rice area in the 1980s, they currently represent less than
83 40% (Fig. 1). In contrast, area given to single-rice systems (i.e. one rice crop per year on a given
84 field) in cooler climates of central and northern regions has increased steadily although this
85 expansion did not overcome the reduction in double-rice area. Hence, total harvested rice area

86 has decreased by about 3.6 million hectares (Mha) since 1980. The main reasons for decrease in
87 double-rice were: (i) rapid urbanization in south and central-south coastal regions and associated
88 conversion of rice land to housing, industry, and supporting infrastructure, and (ii) decreased
89 rural labor availability and rising labor costs leading to lower net income than for single-rice
90 systems, which require less labor¹¹. Taken together, trends in production area and yields have
91 resulted in dominance of single-rice systems, which now account for more than 65% of national
92 rice production (Fig. 1).

93 To achieve the required level of spatial resolution for robust estimation of rice yield gaps
94 requires primary data for at least 10 years of daily weather records, digital maps of current rice
95 production area and associated rice yields, and the dominant rice cropping systems and
96 management practices at 50 locations representing 16 climate zones^{9,10}. Because both single- and
97 double-rice systems are prevalent at some of these locations, a total of 847 simulations of rice
98 yield potential were required using a well-validated rice simulation model (details on calibration
99 and validation provided in Supplemental Materials). These location-specific estimates were then
100 scaled up, based on the proportion of national rice area represented by each location and rice
101 cropping system, to give national estimates of yield potential and current farm yield of 9.8 and
102 6.8 metric tons per ha ($t\ ha^{-1}$), respectively, and a national average yield gap of $3.0\ t\ ha^{-1}$. Hence,
103 current national average rice yield represents 69% of potential yield, which is approaching the
104 75-80% of the potential yield threshold at which farm yields typically stagnate at regional to
105 national scales due to diminishing returns from further investment in yield-enhancing
106 technologies and inputs¹².

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

109 10.8 t ha⁻¹ across climate zones and rice systems, while current farm yields varied from 5.2 to 8.8
110 t ha⁻¹ (Fig. 2). Farm yields were highest in central regions for both single- and double-rice
111 systems. Year-to-year variability in potential yield was small for both systems as indicated by a
112 coefficient of variation (CV) of 8%, which is typical of the high yield stability found in grain
113 production systems with a reliable supply of irrigation water¹³. In double-rice systems, potential
114 yields of early- and late-rice crops were similar, with a national average of 9.0 t ha⁻¹ for both
115 crops. Although national potential yield of single-rice was 14% greater than that of double-rice
116 (10.3 versus 9.0 t ha⁻¹), total annual potential yield from double-rice was 18 t ha⁻¹ because two
117 crops are produced each year from the same field.

118 Larger spatial variation in current farm yields (CV = 14%) than in potential yields (CV =
119 8%) resulted in a wide range of yield gaps, from 18% to 41% of potential yield across the 16
120 climate zones evaluated. Current national farm yields for single-rice (7.4 t ha⁻¹) and per season
121 double-rice (5.9 t ha⁻¹) were 72% and 66% of the potential yields estimated for each system,
122 respectively. Hence, yield gaps of single-rice systems are very close to the 75-80% of potential
123 yield threshold at which farm yields tend to stagnate, whereas yield gaps in double-rice systems
124 are considerably below this threshold.

125 Assuming the *exploitable* yield gap is estimated by the difference between current farm yield
126 and 80% of potential yield (hereafter called the attainable yield ceiling), exploitable yield gaps
127 for each of the two crops in double-rice systems are 44% greater than for single-rice (1.3 versus
128 0.9 t ha⁻¹, Table 1). Annual total per hectare increase in rice production from closing exploitable
129 yield gaps would be three-fold greater for double-rice than for single-rice (2.6 versus 0.9 t ha⁻¹).
130 Correcting for the larger current production area of single-rice gives a total potential increase in
131 rice production of about 16 MMT from double-rice and 15 MMT from single-rice with closure of

132 exploitable yield gaps on all current rice area (Fig. 3a). Taken together, a scenario of closing
133 exploitable yield gaps on existing rice area would increase national rice production by 15% (+31
134 MMT, Table 1) compared to current rice production of 206 MMT (average of 2013-2015)¹.

135 But achieving yields that are 80% of yield potential requires large inputs of fertilizer
136 nutrients and aggressive use of pest control measures to minimize yield losses caused by
137 diseases, insects, and weeds. Precise timing of these inputs with regard to stage of crop
138 development is also required, which means greater investment in labor and expertise to monitor
139 crop status and make tactical modifications to field management during the growing season in
140 response to weather and expected yield levels. Such intensive management may not be
141 economically justifiable if marginal costs of the additional inputs, labor, equipment, and
142 decision-support tools do not cover expected returns, which appears to be the case in California
143 where irrigated rice yields have stagnated at 76% of yield potential¹⁴. Hence, if the attainable
144 yield ceiling for profitable rice production is only 75% of yield potential, increased production
145 capacity would be 8% of current production (+16 MMT, Fig. 3a). Although climate change will
146 have an impact on rice yield potential and regional production potential as evaluated in these
147 scenarios, the magnitude of climate change by 2030 is projected to be relatively small compared
148 to the impact during the second half of this century¹⁵.

149 To evaluate plausible future scenarios, we use a projected total rice demand of 217 MMT by
150 2030 based on the average of three studies¹⁶⁻¹⁸. In the four scenarios evaluated, we assume that
151 total rice production area remains constant to 2030, which is consistent with recent trends for
152 double-rice systems (Fig. 1), and also for central and northern provinces where single-rice
153 systems prevail (justification for this assumption in supplementary materials and associated
154 Extended Data Fig. 5). Scenario 1 assumes farm yields remain at current levels to 2030.

155 Scenarios 2 and 3 assume that current modest growth rates in rice yields (Extended Data Fig. 4)
156 continue to 2030 and impose an attainable yield ceiling of either 80% (scenario 2) or 75%
157 (scenario 3) of potential yield (Table 1). Scenario 4 is the same as scenario 3 but with higher
158 growth rate in yields of double-rice systems to be equivalent to the yield growth rate of single
159 rice, which is modest compared to much faster growth rates experienced during the 1970s and
160 1980s.

161 Import of 11 MMT would be required to meet projected 2030 rice demand under scenario 1,
162 whereas scenario 2 with an attainable yield ceiling 80% of yield potential results in a 7 MMT
163 surplus (Table 1), which is equivalent to 11% of current global rice trade. But given concerns
164 about the substantial environmental pollution associated with current intensive crop production
165 practices¹⁹, a scenario with a 75% attainable yield ceiling is perhaps more appropriate because it
166 would require less fertilizer input and less aggressive pest control measures. Under this less
167 intensive production scenario, China would be nearly self-sufficient with a modest annual import
168 requirement of 2 MMT. Strategic investment in provinces and rice systems with greatest yield
169 gaps, however, could produce a small surplus even with the more conservative attainable yield
170 ceiling. For example, greatest yield gaps are found in double-rice systems in general (Fig. 2), and
171 in some provinces where single-rice dominates. Indeed, seven of the seventeen provinces in
172 which rice is a major crop account for 78% of the potential increase in rice supply if all rice
173 farmers achieved yields that reach the attainable yield ceiling of 80% of yield potential (Fig. 3b).
174 Hence, a focus on increasing yields of double-rice systems in general, and in the three single-rice
175 provinces where yield gaps are relatively large, would likely provide greatest return on
176 investments in research and development to raise rice production. Moreover, current annual
177 growth rate in yield of double-rice is only 60% that of single-rice (0.03 versus 0.05 t ha⁻¹ year⁻¹,

178 Extended Data Fig. 4) while magnitude of the yield gap is considerably larger for double-rice
179 than for single-rice. Taken together, the larger yield gap and slower yield growth rate suggests
180 greater potential to accelerate yield growth of double-rice, assuming targeted investment in that
181 goal. Raising the rate of yield growth of double-rice to that of single-rice would lead to a rice
182 production surplus of 2 MMT by 2030 with a conservative attainable yield ceiling 75% of yield
183 potential.

184 That small changes in projected Chinese rice production have large impact on global rice
185 trade highlights the need for accurate estimates of potential production on existing rice area.
186 Hence, the spatial resolution of our yield gap analysis by climate zone, province, and cropping
187 system is essential to adequately inform policies and strategic plans for food security and land
188 use. For this reason our analysis: (i) distinguishes between the two major rice cropping systems,
189 (ii) utilizes a rice simulation model that has been rigorously validated for ability to estimate yield
190 potential across the major rice-growing regions in China (supplementary materials, Extended
191 Data Fig. 3), (iii) relies on at least 10 years of measured weather data (supplementary materials,
192 Extended Data Fig. 1), and (iv) employs a “bottom-up” scaling protocol validated for capacity to
193 reproduce crop performance across large variation in climate^{9,10}. In contrast, previous studies
194 have used a “top-down” spatial framework based on meso-scale grids (roughly 100 km²) into
195 which weather and current crop yield data obtained from databases at much coarser scale are
196 “interpolated” into this smaller grid size. Likewise, these previous studies do not provide
197 estimates of potential yield as distinguished by different rice cropping systems. In these top-
198 down studies, yield potential is estimated by either the 90th percentile of current farm yields²⁰, or
199 by a generic crop model not specific for rice and therefore not validated for ability to estimate
200 rice yield potential across the wide variation of rice-growing environments in China²¹.

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

219 Crop price supports and other types of subsidies to promote self-sufficiency in food
220 production are not considered sound agricultural policy due to high costs, market distortions, and
221 reduced incentives for innovation and efficiencies²². In contrast, Clapp²³ argues that populous
222 countries like China may benefit from maintaining self-sufficiency or near self-sufficiency, in
223 production of their primary staple food crops. Hence, for a country like China, reliance on

224 imports for even a small portion of total rice demand represents such a large fraction of global
225 rice trade that pressure from Chinese rice purchases can influence global rice prices in ways that
226 might lead to higher food prices and reduced access, not only for China but also for other
227 countries that import rice. Such pressures are of particular concern in years when global rice
228 supply falls short due to major drought or flooding in rice exporting countries. The good news is
229 that the scenarios evaluated in this study indicate that China has substantial flexibility to
230 maintain self-sufficiency in rice without increasing cropland area devoted to rice production.
231 Indeed, by strategic targeting of investments in research and development it may be possible to
232 maintain self-sufficiency with a net reduction in rice cropland area, especially if the rate of yield
233 gain can be accelerated in double-rice systems.

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287 **Author contributions** N.D., K.G.C., P.G., H.Y., J.H., and S.P. conceived the study and wrote
288 the paper. N.D., H.Y., and P.G. performed the statistical analysis. All authors contributed to
289 editing the paper.

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291 **Competing interests** The authors declare no competing interests.

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293 **Materials and Methods**

294 **Protocols for yield gap assessment and spatial upscaling.** For irrigated crops such as rice in
295 China, the yield gap represents the difference between current farm yields and the yield potential
296 when the crop is grown without limitations from nutrient deficiencies, insect pests, or diseases⁷.
297 To estimate yield gaps we followed protocols developed by the Global Yield Gap Atlas, which
298 utilizes primary, location-specific data to the extent possible⁹ and a robust upscaling framework
299 to estimate yield gap at larger levels of spatial aggregation such as climate zones (CZ), regions,
300 and national scales¹⁰. These protocols have been rigorously evaluated for their ability to estimate
301 yield gaps using Australian rainfed wheat as a test case²⁴. All underpinning data are available on
302 the Global Yield Gap Atlas (GYGA) website (<http://www.yieldgap.org/>). The GYGA protocols
303 are based on a climate zonation scheme developed by van Wart et al.²⁵ that is delineated by three
304 variables: (i) growing degree days, which determine the potential length of the crop growing
305 season, (ii) annual aridity index, which provides an estimate of water supply as the ratio between
306 rainfall and potential evapotranspiration, and (iii) temperature seasonality, which distinguishes
307 between temperate and tropical climates. One hundred and twenty-seven CZ are delineated in
308 China using this climate zonation scheme.

309 Briefly, a digital map of rice crop area distribution (SPAM map, with 10 x 10 km grid-cell
310 resolution)²⁶ was superimposed on the CZ map to identify weather stations located in areas with
311 greatest density of rice production area (Extended Data Fig. 1). Buffer zones of 100-km radius
312 surrounding each weather station, were clipped following van Bussel et al.¹⁰, so that their borders
313 fall within the same CZ. Weather stations were selected in sequence starting with the station and
314 associated buffer zone with largest rice area and continuing until ca. 50% of national rice area
315 was covered by the selected weather station buffer zones. Earlier work has shown that inclusion

316 of additional weather stations to achieve greater coverage of rice area does not improve national
317 estimates of yield gap²⁷. Selected weather stations are hereafter referred to as reference weather
318 stations (RWS). Following this approach, 50 RWS were selected containing 48% of national
319 harvested rice area within their associated buffer zones. The 50 RWS are located in 16 CZ, which
320 together contain 85% of national rice area (Extended Data Fig. 1). Details about selected RWS
321 locations and the dominant rice cropping system within each RWS buffer zone are provided in
322 Extended Data Table 1.

323 **Simulating rice potential yield.** The ORYZA model has been widely used to simulate yields of
324 different rice cultivars across a wide range of climatic conditions in Asia, Africa and USA^{14,28,29}.
325 We used the most recent version of this model, ORYZA v3³⁰. Because potential yield is a
326 location-specific property, ORYZA v3 requires input data for each RWS, including long-term
327 daily weather records and crop management practices. Rice cultivar specification and associated
328 cultivar-specific parameters are also required to run the simulation model to adequately represent
329 crop phenology, biomass production and dry matter partitioning amongst different plant organs
330 (roots, leaves, stems, panicles, and seeds).

331 (i) Weather data

332 Simulation of annual potential yield and temporal variability in potential yield due to year-
333 to-year variation in weather using the ORYZA v3 model requires daily weather records for
334 maximum and minimum temperature, wind speed, relative humidity, precipitation, and solar
335 radiation. For irrigated cropping systems, 10 years of weather data are sufficient for robust
336 estimation of weather-related temporal variation in potential yield⁷. We obtained daily weather
337 data for 11 years (2004-2014) for all weather variables (except solar radiation) from the National
338 Meteorological Information Center of the China Meteorological Administration. We obtained

339 solar radiation data from the NASA-POWER database (<http://power.larc.nasa.gov/>). Previous
340 studies have shown that crop yield simulations based on NASA-POWER solar radiation are in
341 close agreement with simulations based on ground-measured radiation across a wide range of
342 environments and regions³¹.

343 (ii) Crop management data

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

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

357 Cultivar-specific parameters were derived following standard procedures for the ORYZA v3
358 model³⁰, and related information is provided in Extended Data Table 2. Parameterization of crop
359 characteristics was obtained by two utility programs in ORYZA v3 model called *drate(v2).exe*
360 and *param(v2).exe*. The *drate(v2).exe* was used to determine the phenology development rate by
361 using the phenological stages and growth duration of local dominant cultivars. The

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

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

371 Since ORYZA v3 was developed for tropical areas, the model was calibrated in the present
372 study to account for the climate conditions and dominant cultivars grown in China. For cultivars
373 used in southern China, for example, the maximum temperature at which phenological
374 development rate falls to zero was increased from 42 °C as the default value in ORYZA v3 to
375 42.6 °C and the optimal temperature for growth and development from 30 °C to 31.2 °C; for
376 cultivars used in northern China, cold tolerant days was extended from 5 days to 10 days within
377 the optimal rice growth range³⁴.

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

$$381 \quad r^2 = \left(\frac{n(\sum xy) - (\sum x)(\sum y)}{[n \sum x^2 - (\sum x)^2][n \sum y^2 - (\sum y)^2]} \right)^2 \quad (1)$$

$$382 \quad RMSE = [(\sum(x - y)^2 / n)]^{0.5} \quad (2)$$

$$383 \quad RMSE_n = [(\sum(x - y)^2 / n)]^{0.5} / M_{mean} \times 100\% \quad (3)$$

384 where x and y represent the simulated and observed values, and n represents the number of

385 paired values. r^2 close to 1 and $RMSE$ and $RMSE_n$ close to 0 indicate a good agreement between
386 simulated and observed values.

387 The validation indicated that the calibrated ORYZA v3 model adequately reproduced
388 measured rice yields across a wide range of production environments in China (Extended Data
389 Fig. 3). Measured grain yields across experiments ranged from 7.7 to 14.5 t ha⁻¹ and were in
390 close agreement with simulated values after model calibration as indicated by relatively low
391 $RMSE$ of 0.84 t ha⁻¹, which is less than 10% of the mean measured yield (Extended Data Fig. 3).
392 Likewise, aboveground dry matter and growth duration (from emergence to physiological
393 maturity) were in close agreement as indicated by the low $RMSE$ of 0.61 t ha⁻¹ for shoot biomass
394 and 8 d for growth duration. High r^2 (0.90) between measured and simulated yields, indicates
395 little bias in simulated yields over the entire range of measured values, which gives confidence
396 that the calibrated ORYZA v3 model is robust at reproducing potential yield across the wide
397 range of climates and rice cropping systems in China.

398 **Current farm yield and yield gaps.** Current farm yields for the most recent 2-5 years were
399 retrieved from official statistical records and online statistics in national and provincial bureaus
400 for each of the counties in which the selected RWS is located. However, county-level farm yield
401 data are not accurate for a number of reasons, and the magnitude of inaccuracy varies across
402 counties and is difficult to predict^{35,36}. In contrast, provincial level farm yield data are more
403 reliable and accurate because a combination of different methods are used, including remote
404 sensing and ground trothing³⁷. Hence, using county-level data without adjustment to be
405 consistent with the provincial-level yield data gives inaccurate yield gap estimates when results
406 are aggregated to larger spatial scales. To adjust county-level yield data in a province, we
407 increased or decreased farm yields by an equivalent percentage so that the weighted average

408 farm yields across all RWS within that province equaled the provincial official average yield.
409 However, we did not adjust farm yield of counties in provinces for which there was little
410 difference (within $\pm 5\%$) between the official provincial farm yield and the upscaled provincial
411 farm yields following GYGA protocols.

412 The dominant cropping system (single- or double-rice) was identified for each RWS buffer
413 zone and used as the basis for simulating potential yields and for estimating yield gaps. In some
414 parts of central China and in northern provinces, only a single-rice crop is grown each year
415 because the growing season is too short for double-rice. Hence, the yield gap for each RWS
416 where a single-rice crop is grown was calculated as the difference between the single-rice
417 potential yield and the current farm yield. In south and some parts of central China, farmers
418 practice a double-rice cropping system. However, county level data provide only the average
419 yield for the two crops. But the area of early- and late-season rice crops is almost identical at
420 19% and 20% of total rice area, respectively, based on the estimates from¹. We therefore
421 simulated yields of early and late-rice crops separately, and used the average potential yield of
422 the two crops to calculate yield gaps for each RWS where double-rice systems dominate.

423 To upscale potential yield, current farm yield, and yield gap estimates from RWS to larger
424 spatial scales, weighted averages for each variable were calculated by the proportional
425 contribution of rice area within each spatial unit contributing to the spatially aggregated value at
426 the CZ or national scale¹⁰.

427 **Estimating rice production potential.** Current farm yields tend to stagnate when they reach 75-
428 80% of potential yield (called the attainable yield ceiling) due to diminishing returns from
429 investment in additional production inputs and effort as yields approach the potential yield
430 ceiling^{12,14,27}. Hence, prospects for increasing rice production at any spatial scale are best

431 indicated by the “exploitable” portion of the yield gap, which is the difference between current
432 farm yields and 75% or 80% of potential yields estimated at the CZ and national scales. All else
433 equal, achieving yields that are 80% of potential yield requires greater input of nutrients and
434 more aggressive pest control measures than production at 75% of potential yield. Given concerns
435 about the substantial environmental pollution associated with current intensive crop production
436 practices¹⁹, scenarios with either an 80% or 75% attainable yield ceiling were evaluated.
437 Additional exploitable production potential of single- versus double-rice systems were estimated
438 by the difference between 75% or 80% of potential yield and current farm yields for each rice
439 cropping system over the total national production area.

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

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

444 (ii) The amount of cropland devoted to rice production remains unchanged at the level of
445 2011-2014 average. This assumption is consistent with current trajectories based on the fitted
446 trends of observed harvested area (Extended Data Fig. 4). We plotted harvested area and yield
447 against year (1985-2014) for different rice cropping systems by linear function or by a linear-
448 segment piecewise function using SigmaPlot 10.0 (Systat. Software, Inc., San Jose California
449 USA), as shown in Extended Data Fig. 4.

450 Linear function:

$$451 \quad y = at + b \quad (4)$$

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

453 Two-linear-segments piecewise function:

454 $t_1 = \min (t)$, which is the year 1985 (5)

455 $t_2 = \max (t)$, which is the year 2014 (6)

456
$$y = \begin{cases} \frac{a(T_1-t)+b(t-t_1)}{T_1-t_1}, & t_1 \leq t \leq T_1 \\ \frac{b(t_2-t)+c(t-T_1)}{t_2-T_1}, & T_1 \leq t \leq t_2 \end{cases} \quad (7)$$

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

461 The linear regression for single-rice yield:

462 $y = 0.0488 t - 90.788$ (8)

463 The linear regression for double-rice yield:

464 $y = 0.0263 t - 47.255$ (9)

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

471 (iv) Total rice demand in 2030 is 217 MMT, which represents the average of three recent
 472 studies¹⁶⁻¹⁸ compared with current rice production of 206 MMT (average of 2013-2015)¹.

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

474 **Comparison of yield differences by GAEZ and GYGA methods.** Global Agro-Ecological
 475 Zones Model version 3.0 (GAEZ v3.0)²¹ was used for comparison of yield gap analyses. We
 476 selected GAEZ for comparison because the potential crop production data layer is being used to

477 evaluate future scenarios of agricultural production in several studies (e.g.^{38,39}). Compared to the
478 GYGA up-scaling method, a down-scaling method is used in GAEZ v3.0 such that both weather
479 and agricultural crop production data (e.g. current yields and crop production area) from much
480 coarser spatial scales are “interpolated” into 5 arc-minute grid cells (roughly 100 km²). National
481 estimates are then estimated by aggregation of data from all grids in which there is rice
482 production area. In contrast to our GYGA approach, which utilized provincial-level data on
483 proportion of rice area under either single- or double-rice systems to estimate area of each
484 system within RWS station buffer zones, GAEZ assigned one rice cropping system to each 5 arc-
485 minute grid cell by matching growth cycle and temperature requirements of rice with time
486 available for crop growth²¹.

487 In GAEZ the “Agro-climatic attainable yields with high input level” data layer is defined as
488 potential climatic yield with optimal management practices (Y_{p_GAEZ}), which is the proxy for
489 potential yield as estimated using GYGA methodology (Y_{p_GYGA}). The map of Agro-climatic
490 attainable yields with high input level for irrigated rice (map) was downloaded on May 26th,
491 2018 from GAEZ website: <http://gaez.fao.org/>.

492 We calculated Y_{p_GAEZ} at CZ, province and country levels and compared them with Y_{p_GYGA}
493 at those same levels of spatial upscaling using the following approach. First, each GAEZ grid
494 cell (5 arc-min) in Y_{p_GYGA} map was superimposed with the irrigated rice harvested area from the
495 SPAM map²⁶ to assign a harvested rice area to each grid cell. Second, each grid cell was assigned
496 to a GYGA CZ based on the CZ map. The two processes were performed in ArcGIS 10.2.
497 Weighted Y_p values based on harvested area were then estimated at the CZ, province and at the
498 country level. Potential yield in GAEZ was calculated:

$$499 \quad Y_p = \frac{\sum_{i=1}^n Y_{pi} \times ha_i}{\sum_{i=1}^n ha_i} \quad (10)$$

500 where Y_p is potential yield, and h_a is harvested area. For Y_p at CZ level, i is a grid cell and n is
501 the number of grid cells within a CZ. For Y_p at province level, i is a grid cell and n is the number
502 of grid cells within a province. For single-rice Y_p , i is a CZ and n is the number of CZ within
503 single-rice system. For double-rice Y_p , i is a CZ and n is the number of CZ within double-rice
504 system. For Y_p at country level, i is a cropping system and n is the number of cropping systems
505 within a country. Y_g in GAEZ (Y_a as a percent of Y_p) was calculated:

$$506 \quad Y_{g_GAEZ} (\%) = \frac{Y_{a_GYGA}}{Y_{p_GAEZ}} \times 100\% \quad (11)$$

507 where Y_a in GYGA was used to calculate Y_g for GAEZ because the Y_a in GAEZ is outdated
508 (from year 2000).

509

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

511

512

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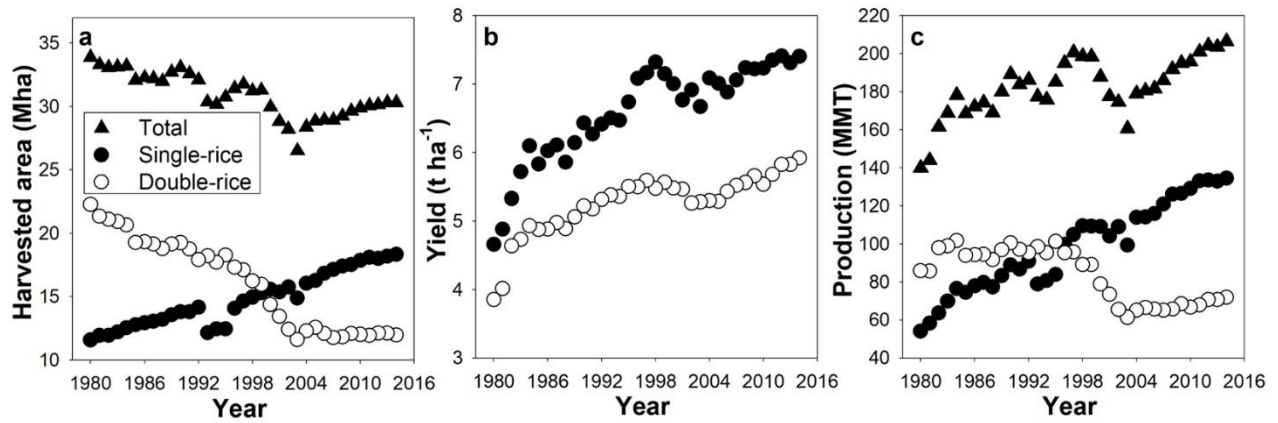
591

592 **Table 1 | Yields and production of single- and double-rice systems in China, and total**
 593 **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		

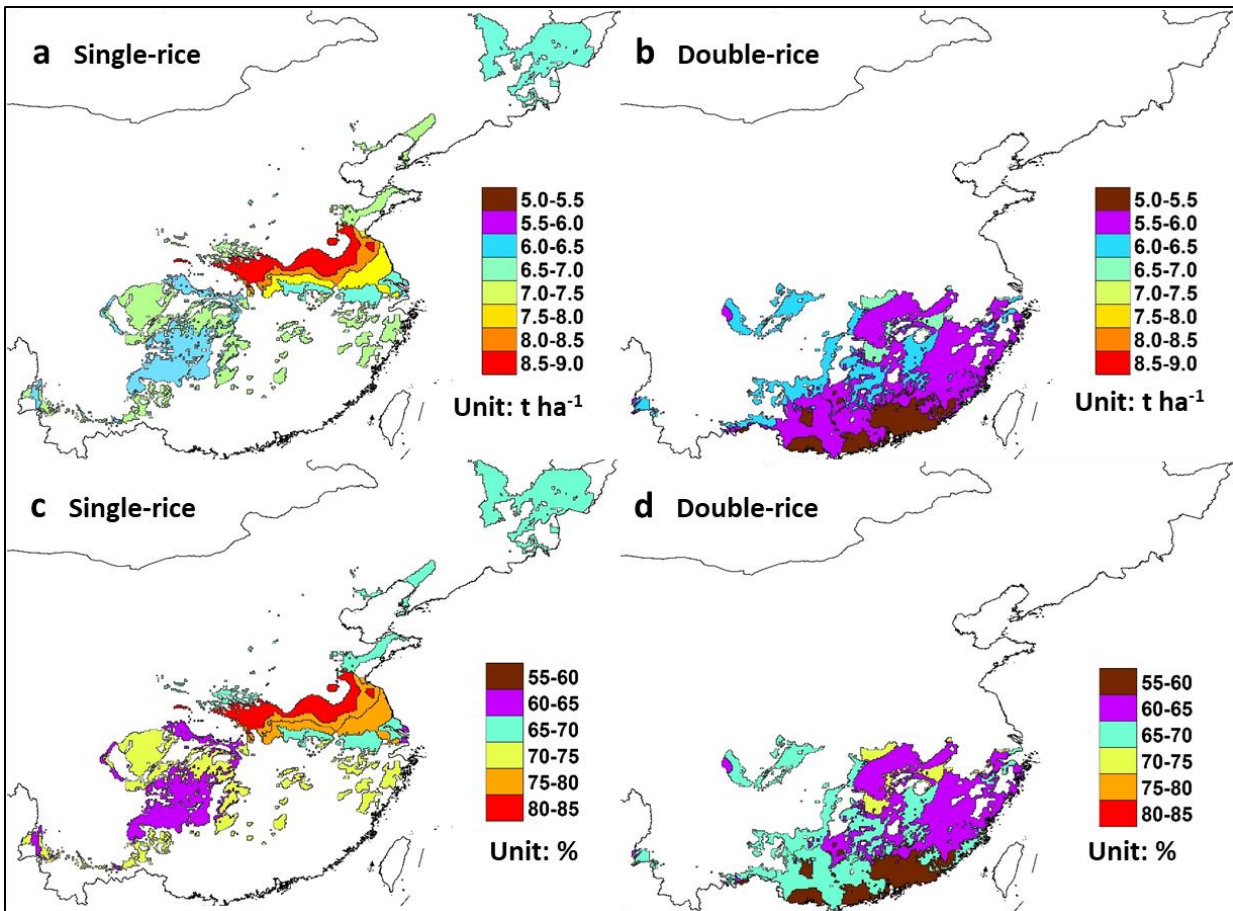
594 * S1: Farm yields stagnate at current levels to 2030. S2 and S3: Rates of yield gain follow
 595 current trajectories based on regression of national rice yields versus year since 1985 to present
 596 for single- and double-rice to 2030 (Extended Data Fig. 4) and an attainable yield ceiling that is
 597 80% (S2) or 75% (S3) of potential yield (Yp). S4: Rates of yield gain in double-rice systems
 598 increase to the current yield growth rate of single-rice (an increase from 0.03 t ha⁻¹ year⁻¹ to 0.05
 599 t ha⁻¹ year⁻¹) and an attainable yield ceiling that is 75% of Yp. In all four scenarios there is no
 600 change in rice production area for each rice system, which is consistent with recent land use
 601 trends as explained in the text.

602



603 **Fig. 1 | Rice production trends in China.** Trends in harvested rice area (a), rice yield (b) and
 604 total production (c) for single- and double-rice cropping systems during the past 35 years (1980-
 605 2014) in China. Note that the yield for double-rice is on a per-harvested area basis so that total
 606 annual yield is twice the values shown. Data were obtained from¹.

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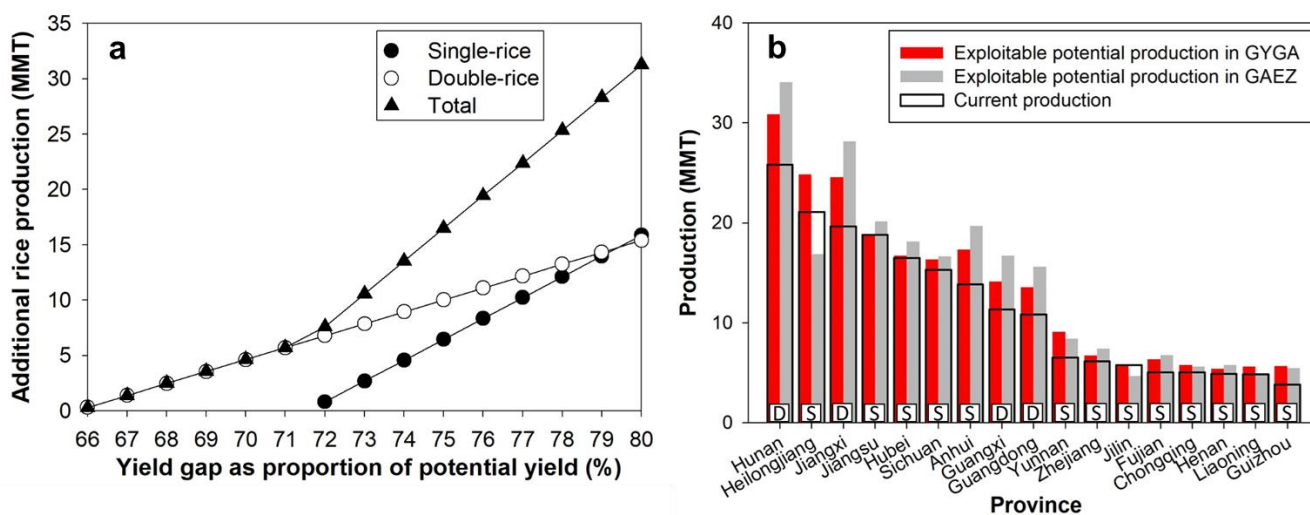


608

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

613

614



615

616 **Fig. 3 | Rice production in different cropping systems and provinces. a,** additional rice

617 production resulting from yield gap closure (expressed as % of potential yield) in single- and

618 double-rice systems assuming no change in harvested area for each system and a maximum

619 attainable yield ceiling that is 80% of potential yield. **b,** current annual rice production and

620 exploitable potential production for each major rice growing province as estimated using

621 protocols developed by the Global Yield Gap Atlas (GYGA) or by the Global Agro-Ecological

622 Zones Model version 3.0 (GAEZ v3.0). Capital letters at bottom of each province production bar

623 designate provinces in which double- (D) or single-rice (S) dominate. Exploitable potential

624 production for each province is calculated as the product of provincial average rice planting area

625 of 2013-2015 and the attainable yield whereby all rice farmers achieve yields that are 80% of

626 yield potential. The current production for each province is based on 2013-2015 average.

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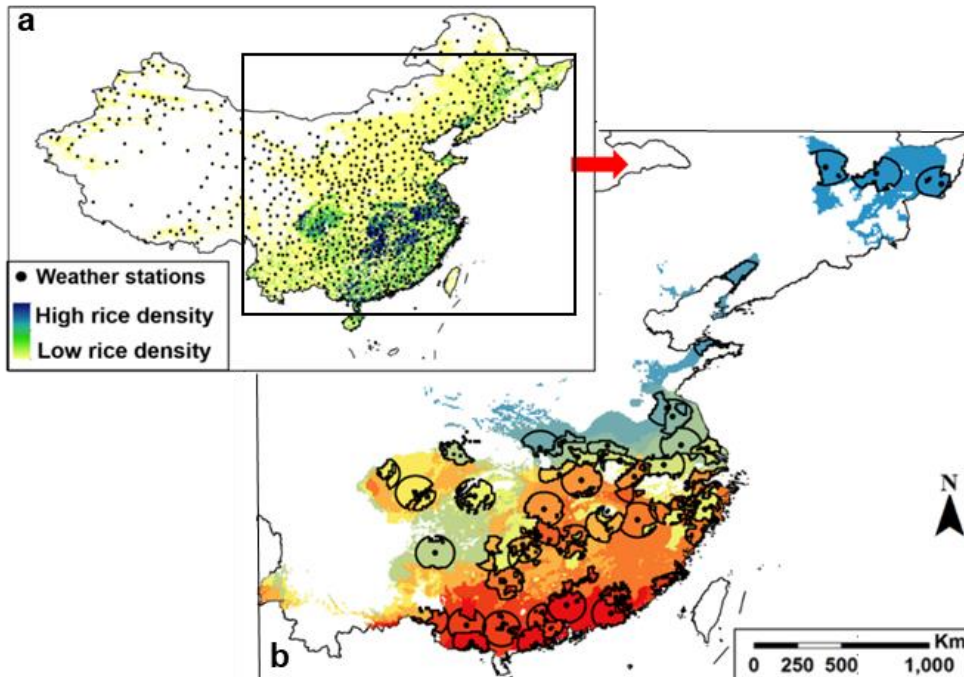
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Supplementary Information

631



632 **Extended Data Fig. 1 | Selected reference weather stations (RWS) and climate zones (CZ).**

633 **a**, Locations of 875 weather stations (dots) from the China Meteorological Administration

634 weather database (National Meteorological Information Center, <http://data.cma.cn>), and rice

635 harvested area density (SPAM map)²⁶. **b**, Selected RWS (black dots), borders of RWS buffers

636 (black lines), and CZ (different colors) in China. In total, 50 RWS were selected in northeast,

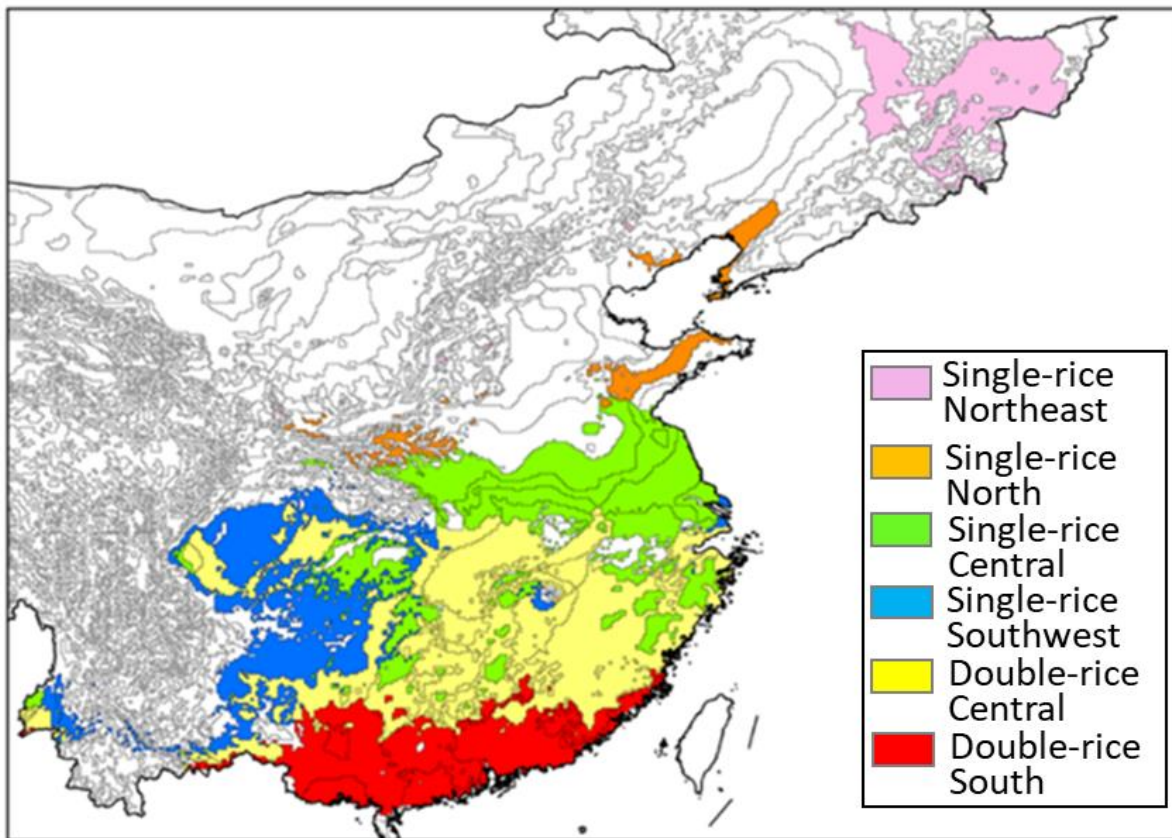
637 north, central, and south China, accounting for 48% of national rice harvested area within RWS

638 buffer zones. The 50 selected RWS are located in 16 CZ, which, in turn, account for 85% of

639 national rice harvested area.

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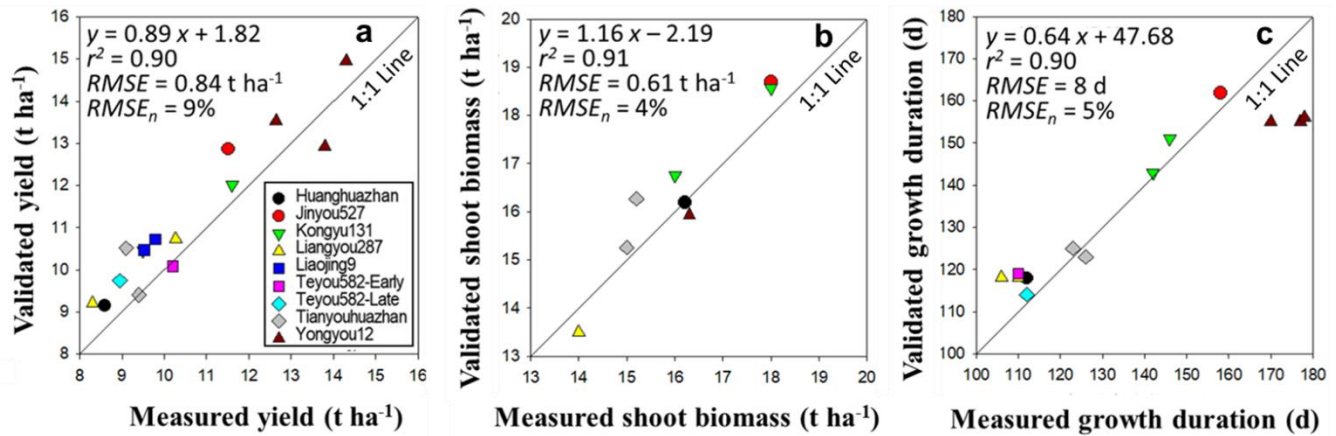


642

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

647

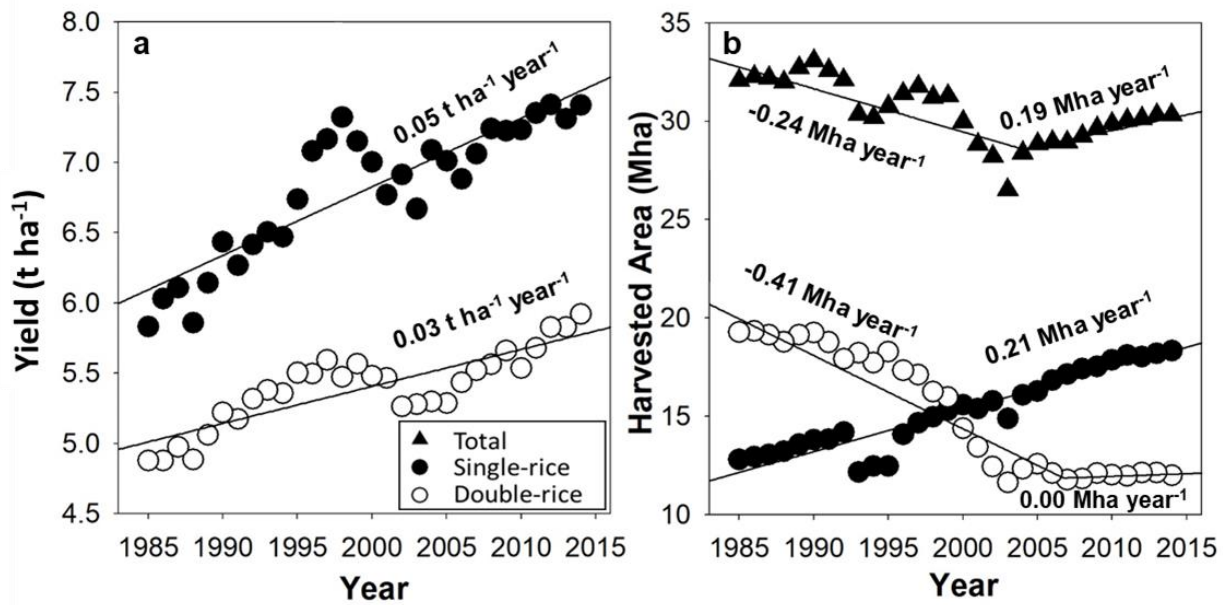
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650 **Extended Data Fig. 3 | ORYZA v3 model validation.** Comparison of validated versus
 651 measured grain yield (a), shoot biomass (b) and growth duration (c) by using calibrated ORYZA
 652 v3 model. Growth duration corresponding to the time period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

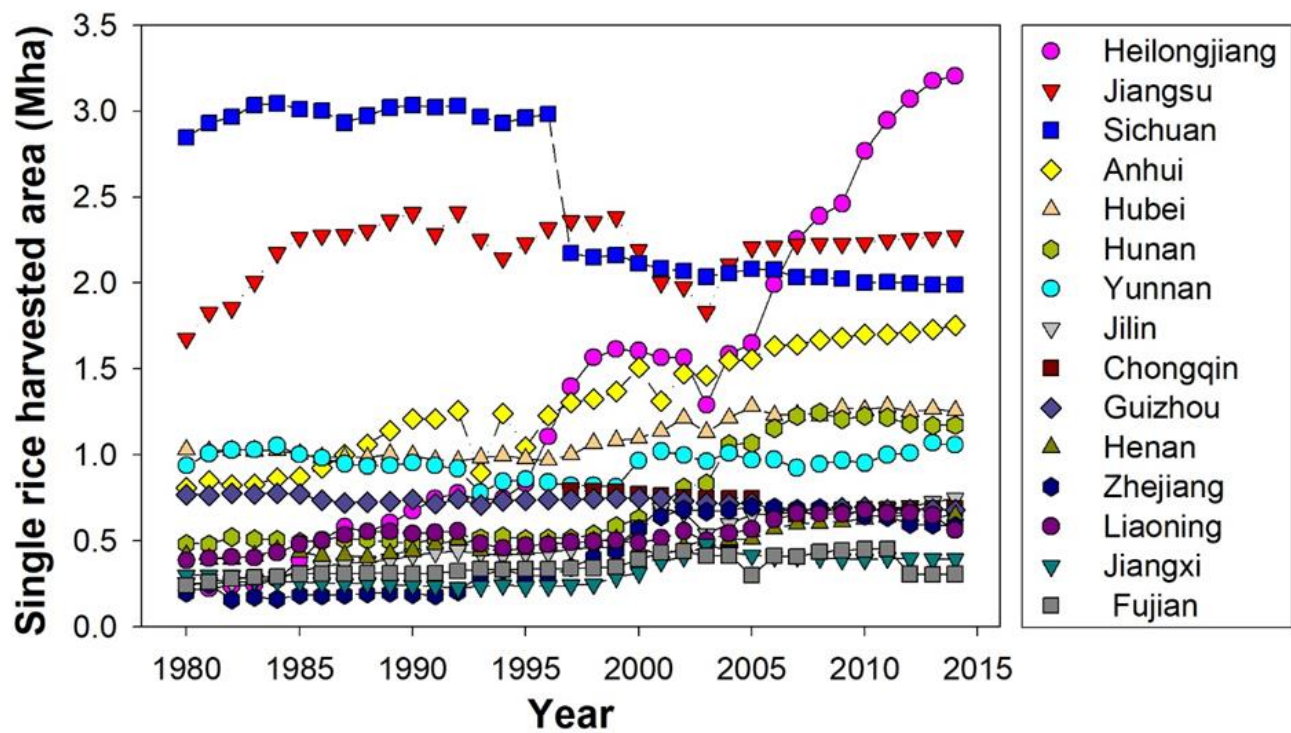
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656 **Extended Data Fig. 4 | Trends in national average rice yield (a) and harvested area (b) in**
 657 **China.** The data were disaggregated by total- (single and double), single- and double-rice crop
 658 production systems. Note that yields for double-rice are the average for the two rice crops grown
 659 each year in the same field so that total rice output per hectare is twice the values shown. Data
 660 were obtained from¹.

661



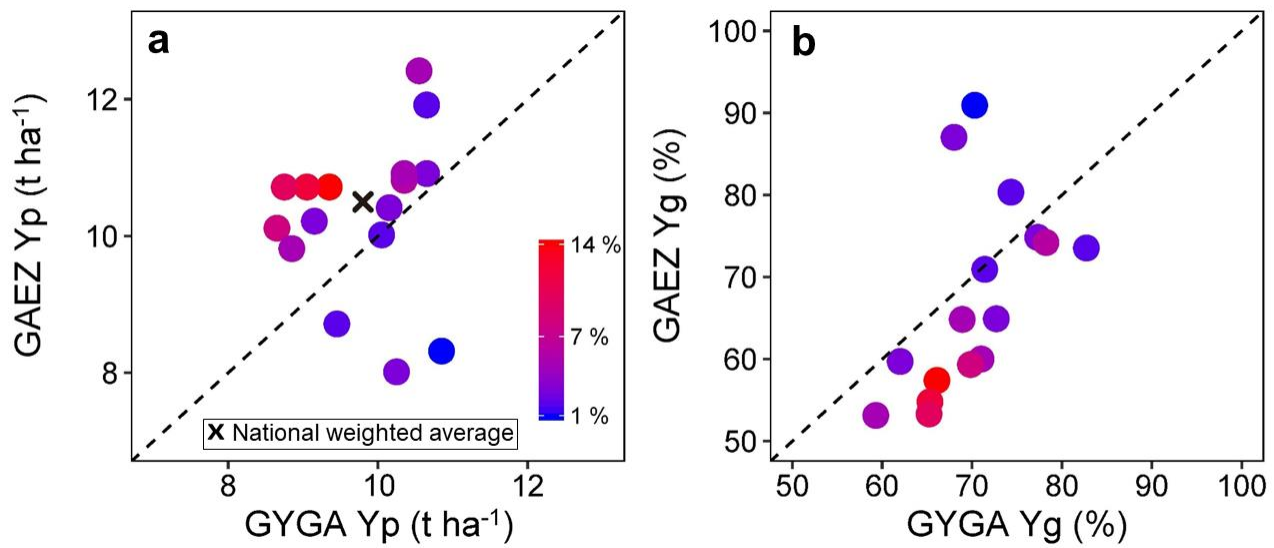
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663 **Extended Data Fig. 5 | Trends in rice harvested area of single-rice by province since 1980.**

664 Data were obtained from¹.

665

666



667

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

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

Station ID	RWS location (County, Province)	Longitude (°)	Latitude (°)	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	Qin Zhou, Guangxi	108.6	22.0	6	Double-rice
50	Yangjiang, Guangdong	112.0	21.9	22	Double-rice

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

679 **Extended Data Table 2 | Crop management information for each of the six rice-production**
680 **regions and the source of this information, and modifications to key parameters based on**
681 **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 (42.6/31.2°C)	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 (42.6/31.2°C)	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 °C)	55-56

682 * Growth duration: days from emergence to physiological maturity.

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685 **Extended Data Table 3 | Estimated potential total production in 2030 if all rice farmers**
 686 **achieved yields that were 80% of potential attainable production as estimated by protocols**
 687 **developed by the Global Yield Gap Atlas (GYGA) or by the Global Agro-Ecological Zones**
 688 **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

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