

Securing food under adverse climate and socioeconomic scenarios in Jiangsu Province, China

Critical role of human adaptation under change

Lyu, Haoyang; Dong, Zengchuan; Pande, Saket

DOI

[10.1016/j.jhydrol.2021.126344](https://doi.org/10.1016/j.jhydrol.2021.126344)

Publication date

2021

Document Version

Accepted author manuscript

Published in

Journal of Hydrology

Citation (APA)

Lyu, H., Dong, Z., & Pande, S. (2021). Securing food under adverse climate and socioeconomic scenarios in Jiangsu Province, China: Critical role of human adaptation under change. *Journal of Hydrology*, 598, 1-15. Article 126344. <https://doi.org/10.1016/j.jhydrol.2021.126344>

Important note

To cite this publication, please use the final published version (if applicable). Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights. We will remove access to the work immediately and investigate your claim.

1 **Securing food under adverse climate and socioeconomic scenarios in**
2 **Jiangsu Province, China: Critical role of human adaptation under**
3 **change**

4

5 Haoyang Lyu^{1,2}, Zengchuan Dong^{1*}, Saket Pande²

6

7 ¹College of Hydrology and Water Resources, Hohai University, Nanjing, China

8 ²Department of Water Management, Delft University of Technology, Delft, Netherlands

9

10 *Corresponding author: Zengchuan Dong (zcdong@hhu.edu.cn)

11

12 **Highlights:**

13● Food security in Jiangsu can be ensured by improving crop water and nutrient use
14 efficiency.

15● Water and nutrient use efficiency can be improved by adapting human agency.

16● Conditions with more water and land, and less population, labor more important than
17 machinery.

18● Under unfavorable conditions, machinery more important for higher crop production.

19

20

21

22 **Abstract:**

23

24 Food security is important for human well-being worldwide. However, changing
25 climate, population growth and shrinking land resources are threatening food security
26 in many regions of the world. Jiangsu Province, China, is one such region. It is a major
27 food-producing region of the country but is witnessing rapid population growth and
28 urbanization that is putting pressure on agricultural water and land resources and
29 threatening food security of the region.

30

31 This paper interprets the nexus between regional water availability and food security in
32 Jiangsu Province under different climate change and socio-economic scenarios of
33 population growth and land resource availability. Climate change scenarios are
34 generated based on historical data and Global Climate Model (GCM) products. Socio-
35 economic scenarios are generated based on population growth and crop planted area
36 projections.

37

38 The uptake of water and nutrients are considered as two dominant biophysical processes
39 of crop growth and food production. Complementing it is human agency, including
40 human labor, irrigation and land-preparation machinery, which are the factors behind
41 water and nutrient use efficiencies of crops grown. Two dominant crops are considered,
42 rice and wheat, that contribute to 61.4% of total crops produced in the province.

43

44 Results show that adaptation by human agency is necessary to ensure that food supply
45 meets at least the demand of the province under all climate change and socio-economic
46 scenarios. Under relatively favorable scenarios, labor could replace land-preparing

47 machinery since the level of food production can be easily maintained with abundant
48 water and land availability. Mechanization in agricultural production significantly
49 increases food production under unfavorable conditions, since it improves water and
50 nutrient use efficiencies and leads to higher crop yields. This demonstrates that human
51 agency plays an important role in securing food under stressful scenarios of drier
52 climate, population growth, and contraction of agricultural lands.

53

54 **Key words:** climate change; food security; scenario analysis; water and nutrient use
55 efficiencies; trade-off between human labor and machinery in agriculture

56

57

58 **1. Introduction**

59 Maintaining sufficient food supply is key to a healthy population and social stability
60 (Springmann et al., 2016 ; Kaiser, 2011). This can either be realized through trade or
61 through high and stable level of food produced locally. The latter is especially important
62 under changing climate and evolving socio-economic conditions (Turrall et al., 2011),
63 such as rapid population growth (McCarthy et al., 2018), and shrinking agricultural
64 lands (Hou et al., 2019; Qiu et al., 2020). This is because trade will likely be disrupted
65 more often, offering less reliable means of securing food for local population (Cardwell,
66 2014).

67
68 Under changing climate, local food production is expected to be affected by changing
69 water availability and impact food security and agricultural employment (Hertel &
70 Rosch, 2010; Rosemberg, 2010; Siwar et al., 2013). Food security, i.e. when food
71 supply of a region is at least able to meet its own demand, is affected directly by such
72 changing agro-ecological conditions and crop yields, as well as indirectly by
73 inequitable distribution of incomes (Schmidhuber and Tubiello, 2007). Changing socio-
74 economic conditions (Garibaldi and Pérez-Méndez, 2019), such as shrinking
75 agricultural land resources for food crops, are also expected to reduce overall food
76 production (van Vliet et al., 2017; Wang, 2019). This exasperates food insecurity with
77 rising demand for food due to population growth (Avery et al., 2019; Mondal and
78 Sanaul, 2019).

79
80 Jiangsu Province, China, is one such region that exemplifies the pressures on food
81 security. As one of the major regions of crop production in China (Gu and Guo, 2011),
82 the province produces 37 million tons of food crops (BSC, 2019) and supports the

83 enormous food demand of the country. It is also one of the regions which is under water
84 stress (Li, J. & Li, L., 2012, Xu et al., 2011), and witnessing land and population growth
85 pressures (Zhang et al., 2004; Qian et al., 2008; Zhu and Ou, 2020). With agricultural
86 land shrinking in the process of urbanization, people are shifting from rural agriculture
87 to modern industries, leading to rural to urban migration (Lyu et al., 2019). The province
88 is likely to face food insecurity in the future and adaptation strategies are urgently
89 needed (Xu and Ding, 2015).

90

91 Often not enough adaptation to bio-physical impacts, high-cost of measures, short-term
92 merit but long-term negative adaptations, and lack of feasible adaptive strategies hinder
93 adequate response to climate and socioeconomic changes (Warner and Geest, 2013).

94 This highlights the need to unravel possible means to adapt under diverse future
95 scenarios and secure sufficient food (Challinor et al., 2010), which move away from
96 more expensive hard interventions such as supply oriented measures to soft
97 interventions. Examples of the latter include how water and land resources are governed
98 and used in crop production (Medeiros and Sivapalan, 2020; Li and Sivapalan, 2020;
99 Kakinuma et al., 2014).

100

101 This paper uniquely views humans as agents of change that improve water and nutrient
102 use efficiencies, and inquires to what extent food security can be ensured for Jiangsu
103 Province. Since most food crops are farmed, labor is an indispensable part of such
104 human agency (Achille et al., 2015). The agency also includes machineries, for
105 irrigation and land-preparation, which improves the efficiency of water and nutrients
106 uptakes for food crop production (Febrina et al., 2013; Ma et al., 2020; Huang et al.,
107 2018).

108

109 The human agency can adapt crop production to changing conditions and secure food
110 (Crane et al., 2011; Olesen et al, 2011; Leisnham et al., 2013; Preston et al., 2015;
111 Gomez-Zavaglia et al., 2020). However, no studies yet exist that have modelled human
112 agency in context of crop production and assessed the effects of its adaptation to
113 changing environment on food security. The aim of the paper is to assess the extent to
114 which food security can be ensured by adapting human agency under changing
115 conditions of water and land availability in Jiangsu Province.

116

117 The paper is organized into five sections. Section 2 describes the methodology used for
118 generating climate change and socio-economic scenarios, modeling crop production,
119 evaluating food security and maximizing it by adapting human agency, together with
120 the main data sources used. Section 3 presents the results of “optimized” food security
121 under different climate and socio-economic scenarios. Section 4 first discusses the
122 improvements in crop water and nutrient use efficiencies that are brought about by
123 adapting human agency. It then discusses the trade-offs between labor and machinery
124 employed to optimize food security under different climate change and socio-economic
125 scenarios. Section 5 then summarizes the main conclusions.

126

127 **2. Methods and Materials**

128 Figure 1 illustrates the overall methodology. A crop model which combines bio-
129 physical mechanisms with human agency (Lyu et al., 2020) is applied. Climate change
130 brought about by greenhouse gas emissions is assumed to effect crop yields due to
131 changes in precipitation. The human agency, including labor, irrigation machinery
132 power and land-preparing machinery power per unit area, determines the water and
133 nutrient use efficiencies during crop growth.

134

135 The socio-economic conditions are assumed to be dominated by population growth and
136 food crop plant area and affect crop production and the ratio of food supply to food
137 demand, i.e. food self-sufficiency rate – a key indicator of food security.

138

139 The human agency adapts to changing climate and socio-economic conditions by
140 improving the water and nutrient use efficiencies of food crops so that higher yields are
141 achieved. The food self-sufficiency rate within Jiangsu Province is then determined as
142 the ratio of food supply and food demanded for given population and planted area
143 scenarios. Here food supply is the product of yield and planted area and food demand
144 is determined by the dietary demand of the population of the province.

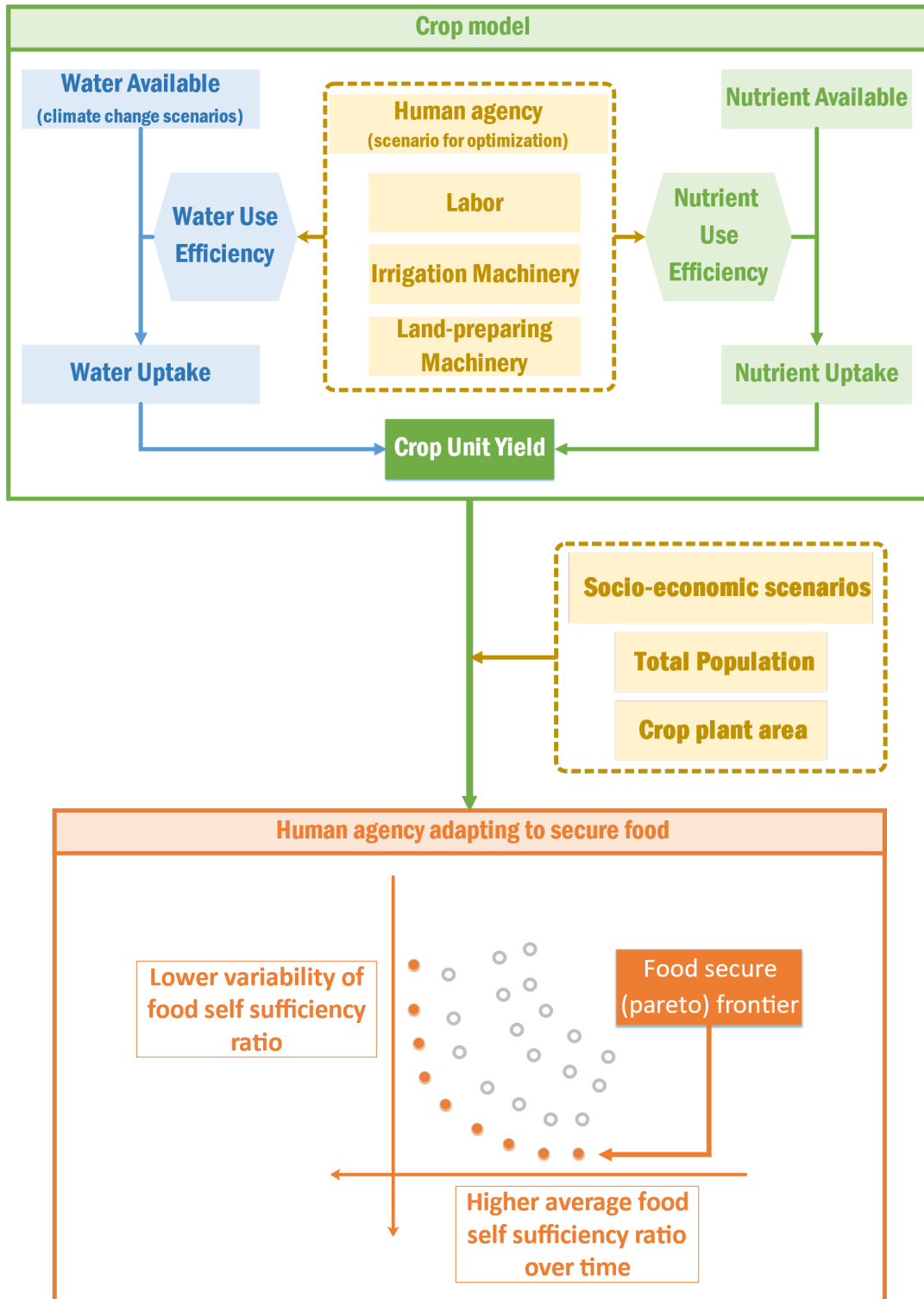
145

146 Finally, it is assumed that the objective of adaptation by human agency is to jointly
147 maximize the magnitude and stability (i.e. lower variance) of food self-sufficiency rate
148 (FSR) for a given climate change and socioeconomic scenario over the next 30 years
149 till 2050. The human agency adapts in order to identify non-dominated sets of higher
150 and stabler (lower variance) FSRs. Here by non-dominated sets it is meant that there
151 are no other sets that dominate this set in terms of either having higher or stabler FSR.

152

153

154



155

156

157

158

Figure 1 Illustration of the overall methodology. FSR stands for Food Sufficiency Ratio, which is the ratio of food demand and food supply.

159

160 2.1 Study area

161 As shown in Figure 2, Jiangsu Province is located in the southeastern coast of China.

162 The province is in a transition zone between subtropical and warm temperate climate,

163 with annual precipitation around 1000mm/year. Three of the main rivers of China run

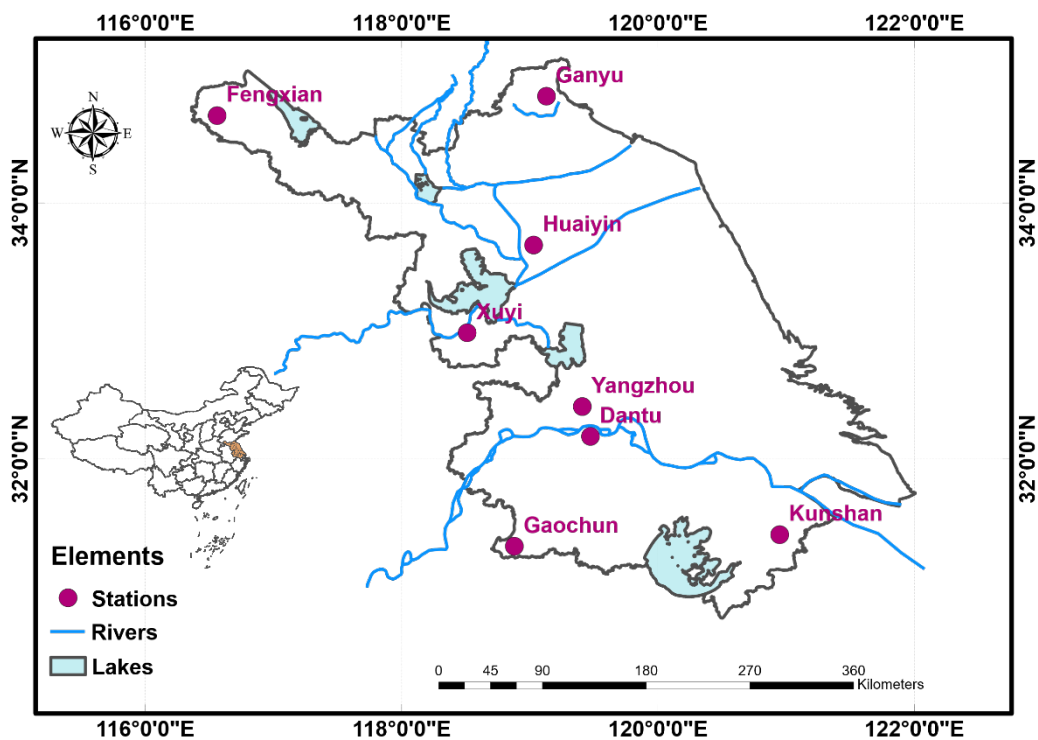
164 through it: Yi-Shu-Si, Huaihe and Yangzi (including the Taihu Lake river network).

165 Benefiting from its abundant river systems and water resources, Jiangsu is one of the

166 main exporters of food crops to other provinces in China (Li et al., 2009). It is able to

167 supply food not only for its own residents, but also to other provinces across the country.

168



169

170 Figure 2 Jiangsu Province, China. Also shown are the stations that are used in the
171 study.
172

173 There are eight crop-monitoring stations providing crop locations and related

174 information of the growing seasons. Six stations for wheat: Fengxian, Ganyu, Xuyi,

175 Huaiyin, Yangzhou, Kunshan and three stations for rice: Ganyu, Dantu, Gaochun, are

176 considered.

177

178

179 *2.2 Stochastic climate scenario generation*

180 Representative Concentration Pathways (RCPs) (IPCC, 2019) have been applied as
181 emission scenarios for climate backgrounds to generate regional precipitation and
182 temperature time series with uncertainty (Lobell et al., 2006). Regional precipitation
183 time series have been produced with a multi-model climate generator called Simgen
184 (Greene et al, 2012a; Greene et al, 2012b; Greene et al, 2015). The Simgen climate
185 generator incorporates nonlinear climate change trends, inferred using an ensemble of
186 global climate models from the Coupled Model Intercomparison Project (CMIP5)
187 (Taylor et al., 2012; Meehl & Hibbard, 2007; Hibbard et al., 2007; Hurrell et al., 2011).

188

189 Under a given RCP condition, Simgen first uses a selected number of Global Climate
190 Models (GCMs) to simulate historical precipitation data at the stations within the study
191 area (as shown in Figure 2) and evaluates the performance of each GCM based on its
192 correlation with the historical precipitation time series (Greene et al, 2012a; Eyring,
193 2013; Aloysius et al., 2016). GCMs with correlation coefficients higher than 0.50 are
194 selected for generating climate scenario time series for future time steps. The frequency
195 distributions of temperature change (°C) and fractional change of precipitation with
196 per °C change of temperature, together with the cumulative frequency distribution
197 function (CDF) of the selected GCMs for RCPs 8.5 and 2.6 are shown in Figure 3a, b,
198 for the study area.

199

200 A combination of a selected GCM (corresponding to a percentile on the frequency

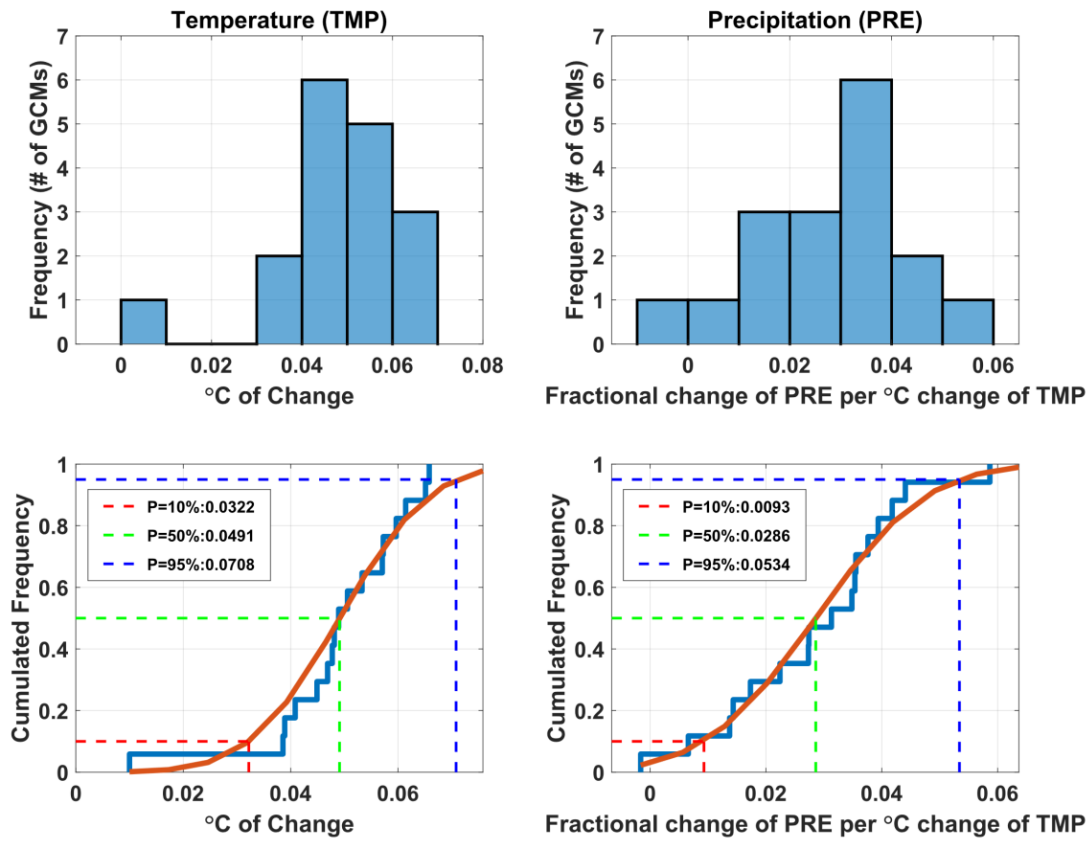
201 distribution) with a RCP used by Simgen then produces corresponding precipitation and
202 temperature time series with stochastic effects. Here, 100 runs each of 2×3
203 combinations of two RCPs (2.6, 8.5) and three GCM percentiles (10%, 50%, 95%) are
204 used to generate climate change scenarios. For more details on Simgen, readers are
205 referred to Greene et al. (2012b).

206

207 RCP2.6 represents a pathway where the radiation forcing reaches to about 3 W/m^2
208 before 2100 and then declines. The corresponding greenhouse gas emission
209 concentration path (Emission Concentration Pathway, ECP) assumes constant
210 emissions after 2100. RCP8.5 represents a pathway in which the radiation forcing
211 reaches greater than 8.5 W/m^2 and continues to rise after 2100. The corresponding ECP
212 assumes constant greenhouse gas emission after 2100 and constant greenhouse gas
213 concentration after year 2250.

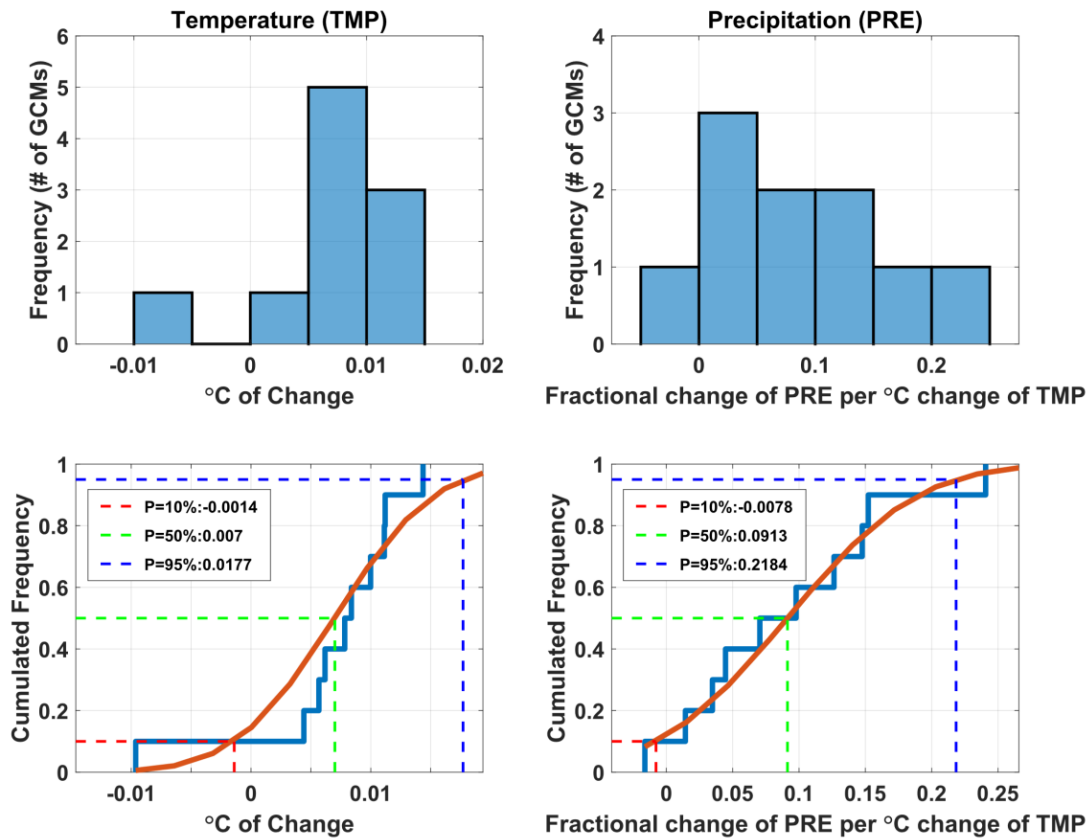
214

215 Precipitation time series have been generated for the six wheat crop stations and three
216 rice crop stations (see Figure 2). For each combination of RCP and GCM percentile,
217 the generated climate scenarios have four dimensions: $P(t)_{i,j,k}$, where t is the time
218 step (50 years from 2001 to 2050 in total, with climate scenarios applied since 2018),
219 i denotes crop type (1 for wheat and 2 for rice), j represents crop-monitoring station
220 ($j \in [1,6]$ for wheat, $j \in [1,3]$ for rice), k indexes a stochastic run of Simgen with
221 given RCP and GCM percentile (100 runs in total)



222
 223
 224

Figure 3a Frequency distribution representing GCM related uncertainty and selection of percentile models under RCP 8.5



225
 226 Figure 3b Frequency distribution representing GCM related uncertainty and selection
 227 of models at 10, 50 and 90 percentiles under RCP 2.6
 228

229
 230 *2.3 Generation of options for adaptation by human agency*

231 Labor (capita), irrigation machinery (power) and land-preparing machinery (power) per
 232 unit area are treated as human agency. It improves the efficiencies of water and nutrient
 233 uptake, thereby improving crop yields.

234

235 In order to generate realistic options for adaptation by human agency, appropriate data
 236 generating processes that describe temporal evolution of human agency are first
 237 identified. These are based on growth rate time series from 2002 to 2017 of labor force,
 238 g_L , irrigation machinery power, g_{MI} and land-preparing machinery power, g_{ML} .

239

240 Autoregressive Integrated Moving Average model (Kotu and Deshpande, 2018),

241 ARIMA(1,0,0) is applied to the time series of g_L , g_{MI} and g_{ML} , as it is found to be
242 most appropriate model of the past time series. Being ARIMA(1,0,0), the lag
243 coefficients of the models, i.e., τ_L , τ_{MI} , and τ_{ML} , for respective time series are
244 sufficient to describe the time series.

245

246 In order to stochastically simulate the time series, 2000 tuples of ARIMA coefficients
247 τ_L , τ_{MI} , and τ_{ML} within the range of $[-0.9999, 0.9999]$ are randomly sampled for a
248 given climate scenario. The generated coefficient tuples are then expressed as $[\tau_{L,r},$
249 $\tau_{MI,r}, \tau_{ML,r}]$, $r \in [1, 2000]$. With 2000 samples of coefficient tuples, time series of g_L ,
250 g_{MI} and g_{ML} are stochastically generated and 2000 human agency time series of
251 human labor force, irrigation machinery power and land-preparing machinery power
252 per area are thus obtained.

253

254

255 *2.4 Crop production simulation*

256 As shown in Figure 1, a crop production model is used that combines both bio-physical
257 factors and human agency in simulating crop yields. Lyu et al., (2020) have
258 demonstrated its utility in simulating wheat and rice production in Jiangsu Province,
259 China.

260

261 The crop production model treats Normalized Difference Vegetation Index (NDVI) as
262 resulting from the joint effect of water and nutrient uptakes on plant greenness.
263 Therefore, the effect of water uptake (represented by transpiration T) on NDVI is first
264 filtered out and the remaining variance of NDVI is then assumed to approximate the
265 effect of uptake of nutrients N . The yield-uptake relationship is then defined in the

266 form of a production function $Y = \lambda x_W^\alpha x_N^\beta$, where Y is crop yield, x_W is water
 267 uptake given by $\eta_W P$, x_N is nutrient uptake given by $\eta_N F$, α and β are
 268 corresponding elasticities and λ is a scaling factor. This production function represents
 269 the biophysical responses of crop yields to water and nutrient uptakes (Lyu et al., 2020).
 270 The parameters (λ, α, β) therefore do not assess economic or technological aspects of
 271 human agency. The human agency determines the water and nutrient use efficiencies,
 272 η_W and η_N respectively, that translate available water P and applied nutrients F to
 273 water and nutrient uptakes x_W and x_N respectively. The relationship between water
 274 or nutrient use efficiency and human agency is estimated based on the following
 275 equations:

$$\eta_W^j = \Lambda H^j + \delta^j + \epsilon_W$$

$$\eta_N^j = \Theta H^j + \theta^j + \epsilon_N$$

(1a, b)

279 Here, j refers to a crop-monitoring station, H^j represent station-specific human
 280 activities but its effect on efficiencies, (Λ, Θ) , are general across all the stations. Fixed
 281 station-specific effects are quantified by (δ^i, θ^i) , and (ϵ_W, ϵ_N) represent the
 282 residuals accounting for the variances of efficiencies not explained by H .

283
 284 Human agency such as labor used in crop production L_C , irrigation machinery power
 285 M_I and land-preparing machinery power M_L per unit area are considered in the set of
 286 independent variables H . All combinations of joint and individual effects (such as
 287 $L_C M_I M_L$, $L_C M_I$, $M_I M_L$, $L_C M_I$, L_C , M_I and M_L) are first regressed and only those
 288 effects that were statistically significant are selected in the final model. In the
 289 calibration of Eq. 1, station specific observed values of η_W and η_N were calculated

290 as $\eta_W = \frac{T}{P}$ and $\eta_N = \frac{N}{F}$, where T and P are transpiration and precipitation fluxes
291 respectively integrated over the crop growing seasons, N is the nutrient proxy, and F
292 is fertilizer use per area, which is the nutrient resource for croplands. See supplementary
293 materials for the estimated parameters of the equations.

294

295 Climate change scenarios impose its effects on crop growth via precipitation P
296 (Kawuma Menya, 2011; Kukul & Irmak, 2018; Makowski et al., 2020). The simulated
297 crop yields (i.e., crop production per unit planted area) under each climate scenario (i.e.,
298 a combination of a RCP and a GCM percentile) q for either wheat or rice is
299 represented by variable $Y(t)_{j,p,q,r}$, where t is time step (50 years from 2001 to 2050,
300 with climate scenarios applied since 2018), j represents a crop-monitoring station ($j \in$
301 $[1,6]$ for wheat, $j \in [1,3]$ for rice), r denotes human agency scenario ($r \in$
302 $[1,2000]$), and p represents a stochastic run of Simgen under each climate scenario,
303 $p \in [1,100]$.

304

305

306 *2.5 Socio-economic scenarios*

307 For a given level of crop yield as determined by the human agency factors under a
308 climate change scenario, socio-economic conditions linked to population and plant area
309 finally determine the level of food self-sufficiency within the study area.

310

311 As shown in Figure 4, three scenarios of population (Low, Mid, High) have been
312 simulated based on provincial population prediction datasets (Bureau of Statistics of
313 Jiangsu, 2002; Bureau of Statistics of Jiangsu, 2012) and the observed time series of
314 population within the province (Bureau of Statistics of Jiangsu, 2019).

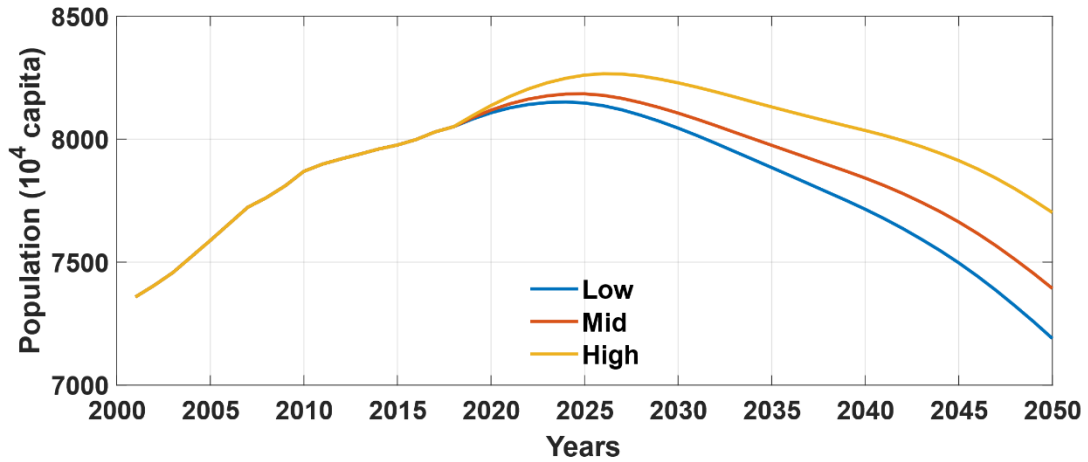


Figure 4 Socio-economic scenario I: Population

315
316
317

318 The crop plant area scenarios are based on the planted area dataset in the Statistical
 319 Yearbook of Jiangsu (Bureau of Statistics of Jiangsu, 2018) and the cost per unit area
 320 dataset in the China Rural Statistical Yearbook (National Bureau of Statistics,
 321 2002~2018). Future crop planted area time series have been simulated based on
 322 relationships between two food crops (wheat, rice) and six cash crops (used as
 323 benchmark) since these crops compete over finite land area available and the decisions
 324 to grow which crops are affected by the costs of growing those crops (Chen et al., 2016;
 325 Zhao and Yan, 2019). It is assumed that farmers are cost minimizers. The farmers decide
 326 on how much area is allocated to food crops relative to cash crops based on minimizing
 327 costs (Chen, 2019; Mo et al., 2020). Corresponding efficiency conditions imply linear
 328 relationships between areas under food crops relative to cash crops and costs of cash
 329 crops relative to food crops. Following steps outline the steps taken to unravel the linear
 330 relationships.

331

332 First the time series of the total planted areas of the eight selected crops are observed to
 333 vary linearly in time. A linear forecasting model ($R = 0.95$, $p\text{-value} < 10^{-3}$, as shown in
 334 Figure 5a) is used to estimate past trend based on historical data from 2011 to 2018 and

335 to generate trend-based scenarios of total planted area for the future.

336

337 The ratios of food crop planted areas with the six cash crops (C) planted areas are then
338 estimated based on linear regressions, with the ratios of cash crop average cost per unit
339 area with the food crops cost per unit area as the independent variables:

$$340 \quad \frac{A_V}{A_C} = f_1 \left(\frac{Y_C}{Y_V} \right)$$

$$341 \quad \frac{A_R}{A_C} = f_2 \left(\frac{Y_C}{Y_R} \right)$$

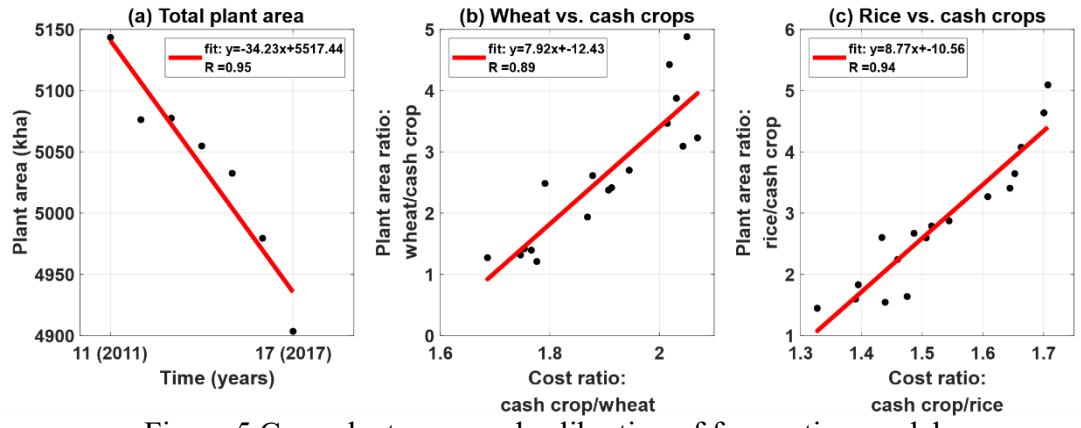
342 (2a, b)

343 where A_V and A_R are the planted areas of wheat (V) and rice (R) respectively, Y_V ,
344 Y_R and Y_C are the costs per unit areas of wheat, rice and cash crops respectively, and
345 f_1 and f_2 are linear functions. Figure 5b and 5c show the regression results for wheat
346 ($R = 0.84$, p-value $< 10^{-4}$) and for rice ($R = 0.92$, p-value $< 10^{-7}$). It shows that the cash
347 crops within the province have been gradually replaced by food crops because the cost
348 per unit area of cash crops have been increasing relative to that of food crops. Finally,
349 the slope of the trend line for total planted area, estimated based on historical data above,
350 is used to generate scenarios for future areas planted under food crops.

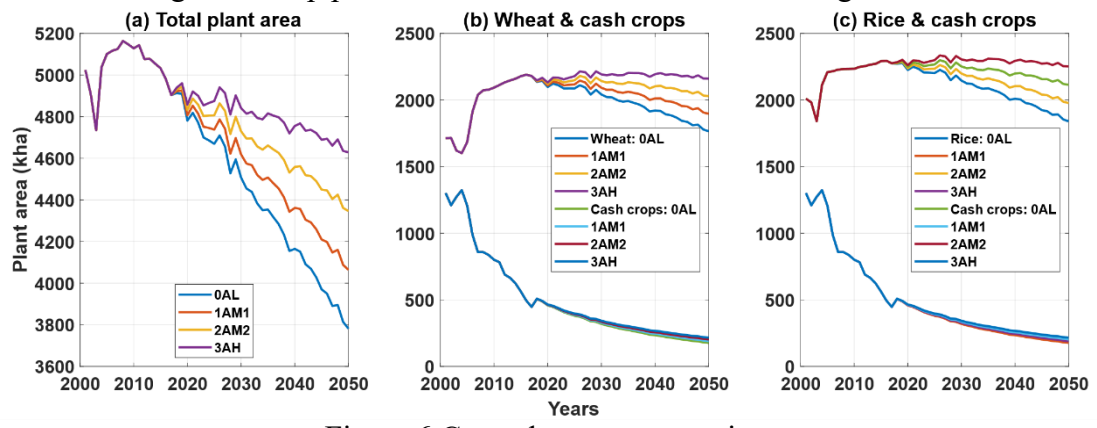
351

352 According to the Statistical Yearbook of Jiangsu, in 2018 the area planted under wheat
353 and rice in Jiangsu was 4618.68 kha (10^3 hectares), whereas the area under the six cash
354 crops was 274.93 kha (i.e., ~5% of area under food crops). This means that food crops
355 have already dominated the cash crops in the province and may not significantly
356 increase in the future. Therefore, the future scenarios of area under food crops only
357 considered stable or declining trends, i.e., constant or negative slopes of the linear
358 forecasting models for wheat and rice, for it to be realistic. Random errors were added

359 based on the residuals between observed and linear model of the historic data.
 360
 361 Four scenarios from low to high slopes are created as shown in Figure 6. The lowest
 362 slope scenario is based on the slope displayed in Figure 5a, the other three use scaled
 363 slopes which are 75%, 50%, and 25% of the slope in the lowest slope scenario. As
 364 shown in Figure 6, the four crop plant area scenarios, from low to high, were named as
 365 '0AL', '1AM1', '2AM2' and '3AH'. 'A' means 'Area', 'L', means 'Low', 'M' means
 366 'Medium', and 'H' means 'High'.



368 Figure 5 Crop plant areas and calibration of forecasting models



370 Figure 6 Crop plant area scenarios.

371
 372
 373
 374 *2.6 Food security indicator: self-sufficiency ratio*

375 Food self-sufficiency rate, Ψ , is defined as the ratio of food crop production to food

376 crop demand of the province.

377

378 The food crop production per capita is calculated as follows:

$$379 \quad \tilde{Y}(t)_{m,n,p,q,r} = \frac{\frac{A_V(t)_n}{6} \sum_{j=1}^6 Y_V(t)_{j,p,q,r} * + \frac{A_R(t)_n}{3} \sum_{j=1}^3 Y_R(t)_{j,p,q,r}}{\phi(t)_m} \quad (3)$$

380

381 where,

382 $\tilde{Y}(t)_{m,n,p,q,r}$ is the food crop production per capita at time step t , for human agency
383 scenario r with precipitation time series p , (for each climate scenario q there are
384 $k \in [1,100]$ precipitation time series with stochastic effects of climate), under plant
385 area scenario n and population scenario m .

386 $A_V(t)_n$ and $A_R(t)_n$ are the plant areas of wheat (V) and rice (R) at time t , under plant
387 area scenario n .

388 $\phi(t)_m$ is the population at time step t , under population scenario m .

389 j represent the agricultural meteorological monitoring stations, for wheat $j \in [1,6]$,
390 for rice $j \in [1,3]$. Note that the numerator of equation (3) is the sum of wheat and rice
391 production levels averaged over the six and three corresponding stations respectively.

392

393 The calculation of self-sufficiency ratio $\Psi(t)_{m,n,p,q,r}$ is defined as.

$$394 \quad \Psi(t)_{m,n,p,q,r} = \frac{\tilde{Y}(t)_{m,n,p,q,r}}{\tilde{D}} \quad (4)$$

395

396 Where,

397 $\tilde{Y}(t)_{m,n,p,q,r}$ is the food crop production per capita.

398 \tilde{D} is the demand per capita for wheat and rice. The total food crop demand was assumed

399 as 400 kg/capita (Wang et al., 2013). No shift in diet is considered that may lead to
400 changes either in the total demand for food crops per capita or in the demand for wheat
401 relative to rice. Considering that the total production of wheat and rice in 2018
402 accounted for about 88.7% of all food crops (BSJ, 2019), a factor of 0.90 is used to
403 estimate total \tilde{D} for wheat and rice as 360 kg/capita.

404

405

406 *2.7 Food security*

407 Under each of the six climate change scenarios (two RCPs and three GCM percentiles),
408 100 precipitation time series are stochastically generated. For each such generation,
409 2000 human agency options are applied that are randomly sampled according to the
410 ARIMA model to obtain corresponding crop yields for rice and wheat. Then 12 socio-
411 economic scenarios, i.e., three population scenarios and four crop planted area scenarios,
412 are used to estimate the food sufficiency ratio within Jiangsu Province, China.

413

414 For a given climate scenario q , population scenario m , and crop planted area scenario
415 n , a collection of food self-sufficiency rates $\Psi(t)_{m,n,p,q,r}$, are obtained. Note here that
416 $r \in [1,2000]$ denotes the human agency options, i.e., combination of labor, irrigation
417 and land-preparing machinery power per unit area of cropland and $p \in [1,100]$
418 denotes the 100 precipitation time series with stochastic effects under the given climate
419 scenario q .

420

421 Simplifying $\Psi(t)_{m,n,p,q,r}$ to $\Psi(t)_{p,r}$, a two-dimensional food security indicator is
422 estimated that considers the magnitude and variance of food sufficiency ratio over time.

423

424 In order to estimate the average magnitude of food sufficiency, average of food
 425 sufficiency ratio is first estimated over the 100 stochastic precipitation time series.

$$426 \quad \bar{\Psi}(t)_r = \frac{1}{100} \sum_{p=1}^{100} \Psi(t)_{p,r}$$

427 (5)

428 The magnitude and variance of food self-sufficiency rate are then obtained by the
 429 equations below respectively,

$$430 \quad \bar{\bar{\Psi}}_r = \frac{1}{50} \sum_{t=1}^{50} \bar{\Psi}(t)_r$$

431 (6a)

$$432 \quad \sigma_{\bar{\Psi}_r} = \sqrt{\frac{1}{50-1} \sum_{t=1}^{50} \left| \bar{\Psi}(t)_r - \frac{1}{50} \sum_{t=1}^{50} \bar{\Psi}(t)_r \right|^2}$$

433 (6b)

434 These two quantities provide the two dimensions of food security, which are how large
 435 and how stable food sufficiency is over time. The two quantities can also be thought of
 436 as two objectives to be optimized by adapting human agency under different climate
 437 and socioeconomic scenarios, e.g., in the form

$$438 \quad \min(-\bar{\bar{\Psi}}_r, \sigma_{\bar{\Psi}_r})$$

439 (7a, b)

440 Given the nature of the objective function being multi-objective, non-dominated sets of
 441 $(-\bar{\bar{\Psi}}_r, \sigma_{\bar{\Psi}_r})$ are sought. The human agency parameter tuples $[\tau_{L,r}, \tau_{MI,r}, \tau_{ML,r}]$
 442 corresponding to non-dominated sets are identified as the adaptation by human agency
 443 to secure food. Non-dominated sets are such that there are no other ways human agency
 444 can adapt that will result in both larger magnitude of food self-sufficiency ratio as well

445 as stabler (i.e., with lower variance) ratio. These therefore describe how the time series
446 of human agency should evolve over time in order to optimize food security for the
447 region.

448

449

450 *2.8 Data sources*

451 The data sources of all the datasets are shown below in Table 2.

452 Table 2. Description of data used.

<i>Data categories</i>	<i>Variables (symbol)</i>	<i>Unit</i>	<i>Period</i>	<i>Spatial Resolution</i>	<i>Temporal Resolution</i>	<i>Data source</i>
Hydro-climatic	Temperature (T)	° C	2000-2017	0.5*0.5 °	Daily time series distributed using monthly data	CRU (CRU, 1901-2017; Harris et al., 2014)
	Precipitation (P) For crop model calibration.	mm	2000-2017	0.5*0.5 °	Derived from monthly data. Growing-season-accumulated value for each year.	CRU (CRU, 1901-2017; Harris et al., 2014)
	Precipitation (P) For climate scenarios.		1969-2013	0.25*0.25 °	Derived from daily data.	GLDAS Catchment Land Surface Model L4 daily 0.25*0.25 ° V2.0 (Li et al., 2018; Rodell et al., 2004)
	Transpiration (Tr)	W/m ² (converted to mm)	2000-2017	0.25*0.25 °	Derived from monthly data. Growing-season-accumulated value for each year.	GLDAS Noah Land Surface Model L4 monthly 0.25*0.25 ° V2.1 (Rodell et al., 2004)
Crop Information	NDVI (g)	-	2000-2017	30 m	Derived from 8-day data. Growing-season-maximum value for each year.	Landsat 7 NDVI (imported from Google Earth Engine: 'LANDSAT/LE07/C01/T1_8 DAY_NDVI', Gorelick et al., 2017)
	Crop type & Growing season		1991-2010	Station-level	Yearly	National Meteorological Information Center of China (2006)
	Provincial crop yield (Y)	kg/ha	2001-2017	Provincial	Yearly	Statistical Yearbook of Jiangsu (BSJ, 2018)
	Crop plant area (A)	1000ha (kha)	2001-2018	Provincial	Yearly	Statistical Yearbook of Jiangsu (BSJ, 2019)
	Crop cost per area (Y)	CNY/mu (1 mu = 1/15ha)	2001-2018	Provincial	Yearly	China Rural Statistical Yearbook (NBS, 2019)
Human Agency	Total Population	10 ⁴ Capita	2001-2019	Provincial	Yearly	Statistical Yearbook of Jiangsu (BSJ, 2019)
	Population Prediction Data 2011-2030	10 ⁴ Capita	2011-2030			Compilation of population prediction data in Jiangsu Province 2011-2030 (BSJ, 2012)
	Population Prediction Data 2001-2050	10 ⁴ Capita	2001-2050			Compilation of population prediction data in Jiangsu Province 2001-2050 (BSJ, 2002)
	Labor force in crop cultivation (L_C)	Capita/kha	2001-2017			Statistical Yearbook of Jiangsu (BSJ, 2018)
	Irrigation machinery (M_I)	Kw/kha				
	Land-preparing machinery (M_L)					
	Fertilizer use (F)	Ton/kha				

454 **3. Results**

455

456 *3.1 Food secure non-dominated sets*

457

458 Figure 7a and 7b show the non-dominated sets (pareto frontier) of $(-\bar{\Psi}_r, \sigma_{\bar{\Psi}_r})$ for two
459 climate scenarios, which correspond to food secure options identified from amongst the
460 simulated adaptation options by human agency (i.e., from 2000 random samples of
461 tuples $[\tau_{L,r}, \tau_{MI,r}, \tau_{ML,r}]$).

462

463 The impact of crop plant area contraction scenarios on food security is most significant.

464 Figure 7a and 7b display the food security scenarios, including non-dominated sets, for
465 the least optimistic climate scenario ‘(RCP8.5, P10%)’ and the most optimistic climate
466 scenario, ‘(RCP2.6, P95%)’. RCP 8.5 is generally taken as the basis for worst case
467 climate change scenario, since it assumes that the emission of green-house gases will
468 continue to rise throughout the 21st century. On the other hand, RCP 2.6 assumes the
469 most stringent limitations on future green-house gas emissions. The temperature rise
470 under RCP 8.5 is generally higher than that under RCP 2.6 as shown in Figure 3a, b and
471 leads to less precipitation.

472

473 In each of the figures, the three rows correspond to the three population scenarios
474 named as ‘1PopL’, ‘2PopM’, ‘3PopH’. The definitions of these population scenarios
475 are listed in Table 3.

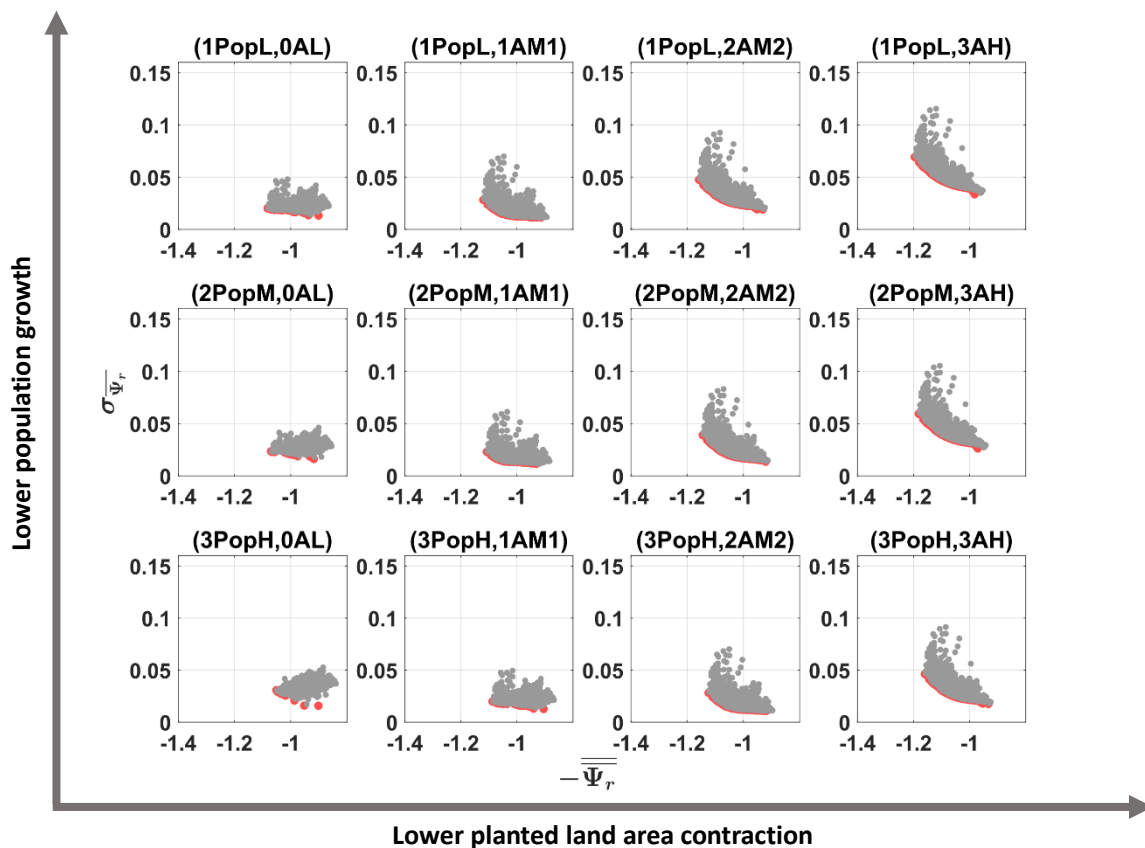
476

477 Table 3 Population scenarios and its definitions in terms of fertility rate and time to
478 peak (BSJ 2002, 2012, 2019)

Year	Fertility rate (%)			Peak population (10^4)		
	Low (1PopL)	Mid (2PopM)	High (3PopH)	Low (1PopL)	Mid (2PopM)	High (3PopH)
2001~2019	Historical population data					
2020~2050	1.65	1.75	1.85	8139.8 (2024)	8167.5 (2025)	8241.1 (2026)

479

480 The four columns of Figure 7a and 7b correspond to the four crop planted area (A)
 481 scenarios, namely '0AL', '1AM1', '2AM2', and '3AH' (see Figure 6). Here 'L' means
 482 low, standing for the most negative growth rate (i.e., contraction rates) of -33.93
 483 kha/year after 2018 of planted area; M1 and M2 correspond to relatively mild planted
 484 area contraction rates after 2018, i.e. 75% and 50% of low scenario rates respectively.
 485 H means High, with a relatively stable growth rate of planted area after 2018, which is
 486 25% of the value in the low scenario.



487

488

489

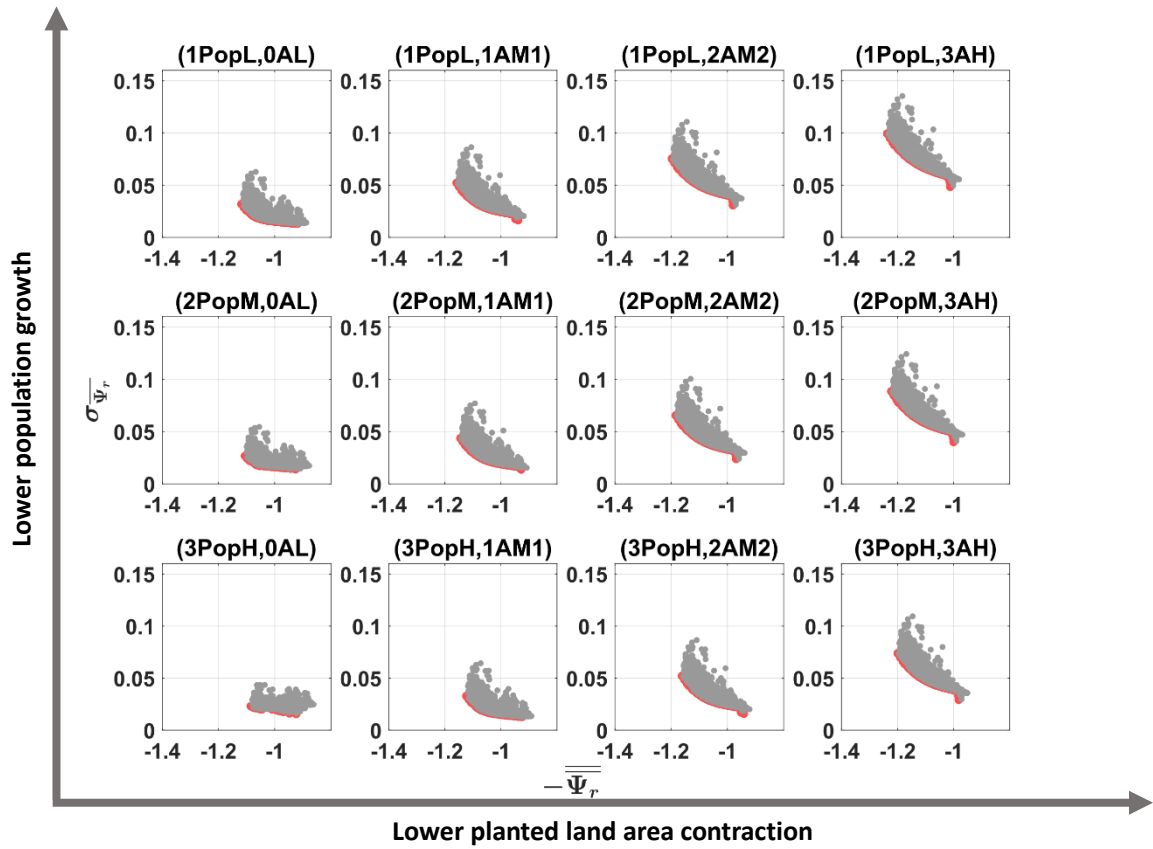
490 Figure 7a Food secure pareto frontiers under least optimistic climate scenario

491 (RCP8.5, P10%). The

492 x-axis shows the objective of minimizing the negative of average food self-sufficiency

493 ratio ($-\bar{\Psi}_r$), y-axis shows the objective of minimizing the standard deviation of self-
 494 sufficiency ratio over time, i.e., $\sigma_{\bar{\Psi}_r}$.

495 Red markers represent the non-dominated sets of $(-\bar{\Psi}_r, \sigma_{\bar{\Psi}_r})$, i.e., the food secure
 496 pareto frontier, while the grey markers represent the dominated set.



497
 498
 499

500 Figure 7b Food secure Pareto frontiers under most optimistic climate scenario
 501 (RCP2.6, P95%)

502 Red markers represent the non-dominated sets of $(-\bar{\Psi}_r, \sigma_{\bar{\Psi}_r})$, i.e., the food secure
 503 pareto frontier, while the grey markers represent the dominated set.
 504

505 Both the figures confirm that the food secure (pareto) frontier moves towards higher
 506 level of average food sufficiency ratios when population growth rate is lower or planted
 507 area contracts slower. This is intuitive because faster population growth puts food
 508 security under stress, while more available land for crops leads to more production of
 509 food, thereby increasing food self-sufficiency.

510

511 Moreover, the pareto frontier rotates clockwise as higher levels of food self-
 512 sufficiency, $\bar{\Psi}$, are achieved. This means that food self-sufficiency is more variable

513 over time at higher levels of average food self-sufficiency, indicating that the tradeoff
514 between the two objectives, i.e., $\min -\bar{\Psi}_r$ and $\min \sigma_{\bar{\Psi}_r}$, increases with higher levels
515 of average food self-sufficiency rate.

516

517 The pattern of the effects of climate scenarios on food self-sufficiency rate is similar to
518 those of socio-economic scenarios. The food secure pareto frontier moves towards
519 higher level of food sufficiency in the most optimistic scenario (RCP2.6, P95%), but
520 with higher variability, than in the case of (RCP8.5, P10%).

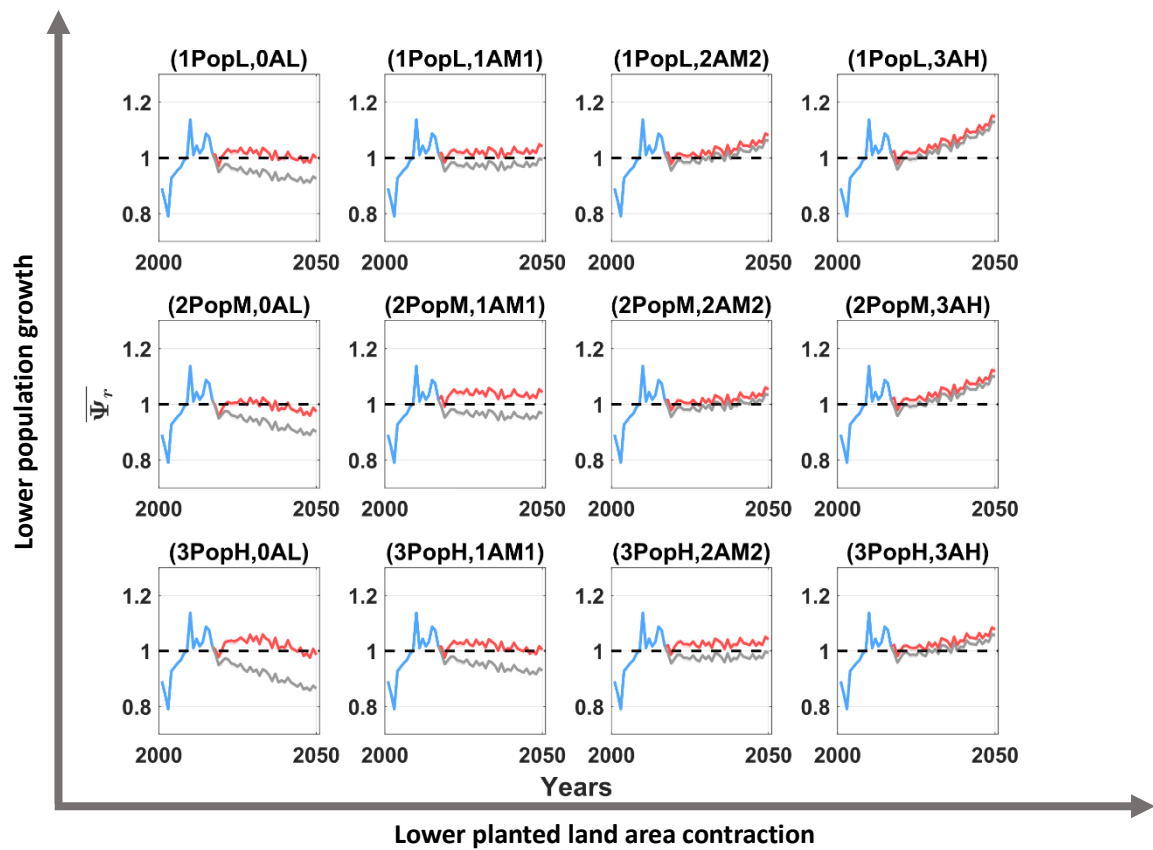
521

522 *3.2 Pareto optimal food self-sufficiency time series*

523

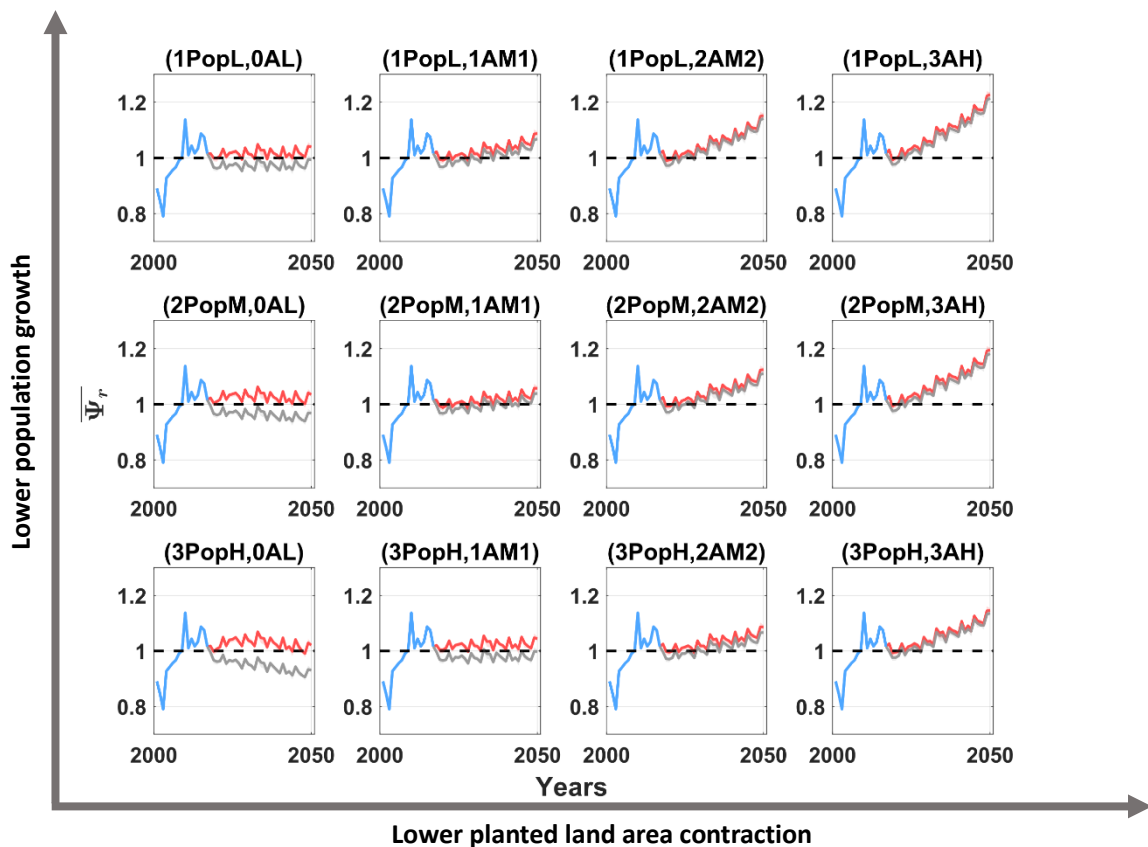
524 Figure 8a and 8b show the median values of average food self-sufficiency ratios for
525 non-dominated human agency sets and for dominated sets (in gray) sets for the two
526 scenarios (RCP8.5, P10%) and (RCP2.6, P95%). The time series are from 2018 to 2050,
527 which are shown along with the historical values available from 2001 to 2017.

528



529
 530
 531
 532
 533
 534
 535
 536

Figure 8a Median food self-sufficiency ratios time series $\bar{\Psi}(t)_r$ for dominated and non-dominated sets under climate scenario (RCP8.5 P10%). Blue line: historical time series; Red line: time series corresponding to non-dominated human agency sets; Grey line: time series corresponding to dominated sets. The province is self-sufficient if it remains above the dashed line (i.e., $\bar{\Psi}(t)_r > 1$).



537
 538
 539
 540
 541
 542
 543
 544
 545
 546

Figure 8b Food self-sufficiency rate time series $\bar{\Psi}(t)_r$ for dominated and non-dominates sets for climate scenario (RCP2.6 P95%). Blue line: historical time series; Red line: optimized (non-dominated) time series; Grey line: dominated time series. The province is self-sufficient if it remains above the dashed line.

547 The (3PopH, 0AL) scenario is the worst socioeconomic scenario for food security for
 548 both the climate scenarios. The worst scenario is the least optimistic climate scenario
 549 with highest population growth rate and rapidly declining crop planted area. Under the
 550 scenario of rapidly declining crop planted area, the average food self-sufficiency rate
 551 drops below 1.0 when human agency doesn't adapt, indicating heightened risk of food
 552 insecurity. However, with adaptation by human agency, the food self-sufficiency rate is
 553 maintained above 1.0. This means that human agency has the ability to ensure food
 554 security even under least optimistic scenarios of the future.

555

556 Under the most optimistic socioeconomic scenario of (1PopL, 3AH) shown in Figure
557 8b, the average food self-sufficiency rate keeps rising and finally reaches a value above
558 1.2. The most optimistic scenario is the most optimistic climate scenario with slowest
559 growth in population and no contraction of available cropland. With food self-
560 sufficiency rate higher than 1.0, the crop production within the province can satisfy the
561 food demand of the province and outside. Also note that the difference between the
562 dominated and non-dominated solutions is not as high as in the least optimistic scenario,
563 meaning that adaptation by human agency plays a critical role when dealing with less
564 optimistic future scenarios.

565

566 For the scenarios in between, average food self-sufficiency can be maintained between
567 1.0 and 1.2 when human agency adapts to changing conditions. Adaptation by human
568 agency is important even under more optimistic scenarios since without it food self-
569 sufficiency can fall below 1.0 (corresponding to the dominated food sufficiency time
570 series). The median levels of food self-sufficiency for non-dominated solutions (red
571 lines in Figure 8a and 8b) are always higher than that of dominated solutions (gray line).
572 Again, the gap between the non-dominated and the dominated time series is more
573 significant under less optimistic scenarios, i.e., with higher temperature, less
574 precipitation, less crop plant area, and more stress from population growth.

575

576 The subplot '3PopH, 0PAL' in Figure 8a shows that the gap of food self-sufficiency
577 between non-dominated and dominated solutions can exceed by 10% under the least
578 optimistic climate and socioeconomic scenario. Under the scenarios of, e.g., lower
579 pressure on cropland area and from population growth (from 0AL to 3AH), the gap
580 between non-dominated and dominated solutions narrows and is between 5 to 10%.

581 This indicates the importance of adaptation by human agency under more stressful
582 climate and socioeconomic conditions, e.g., of drought, or fast-pace urbanization.
583 Human agency, which is a combination of labor, irrigation and land-preparation
584 machinery, can effectively ensure food security within Jiangsu Province under possible
585 future water or land resources stresses.

586

587

588 **4. Discussion**

589

590 *4.1 Improving water and nutrient use efficiencies by adapting human agency*

591

592 Modern technologies in agriculture such as irrigation and land preparation machineries
593 can bring significant improvements in the water and nutrient use efficiencies of crops.

594 Water-saving irrigation technology has been applied to 2637.47-2767.23 kha from 2017
595 to 2018 (Bureau of Statistics of Jiangsu, 2019), which is about 34.9%-36.8% of total

596 agricultural cropland within the province. Across China, latest technologies such as

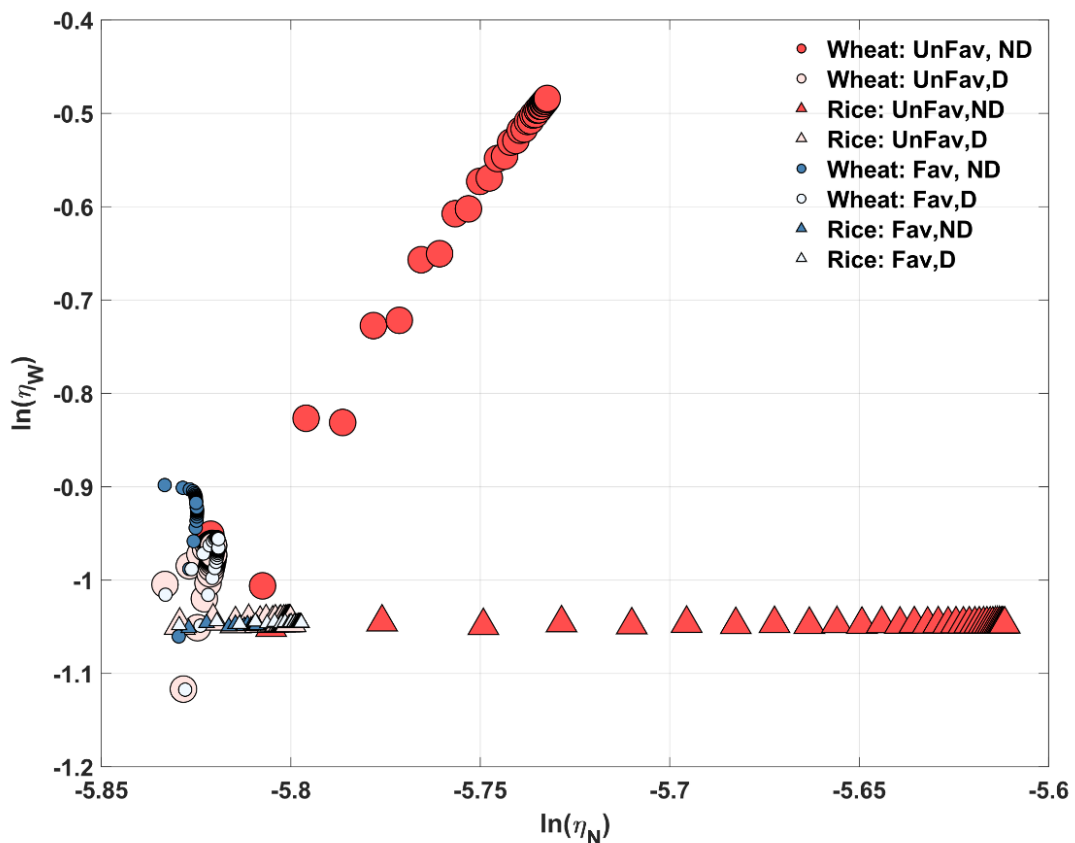
597 water-fertilizer integrated irrigation system based on Internet of Things (IoT) has also

598 been designed and proposed (Shi et al., 2017; Hao et al., 2020). Also, land-preparing

599 machinery are better in preparing croplands for higher nutrient use efficiency of food

600 crops than human labor.

601



602
 603
 604
 605
 606
 607
 608
 609
 610

Figure 9 Water and nutrient use efficiencies in log-space with optimized (non-dominated, ND) and dominated (D) solutions of human agency under unfavorable (UnFav) and favorable (Fav) scenarios.

Unfavorable: least optimistic climate (RCP8.5, P10%), and most stressed socioeconomic scenario ('3PopH, 0AL')

Favorable: most optimistic climate scenario (RCP2.6, P95%) and least stressed socioeconomic scenario ('1PopL, 3AH')

611 Figure 9 shows the average level of water and nutrient use efficiencies in log-space
 612 under two extreme scenarios: most optimistic and least optimistic climate and
 613 socioeconomic scenarios.

614

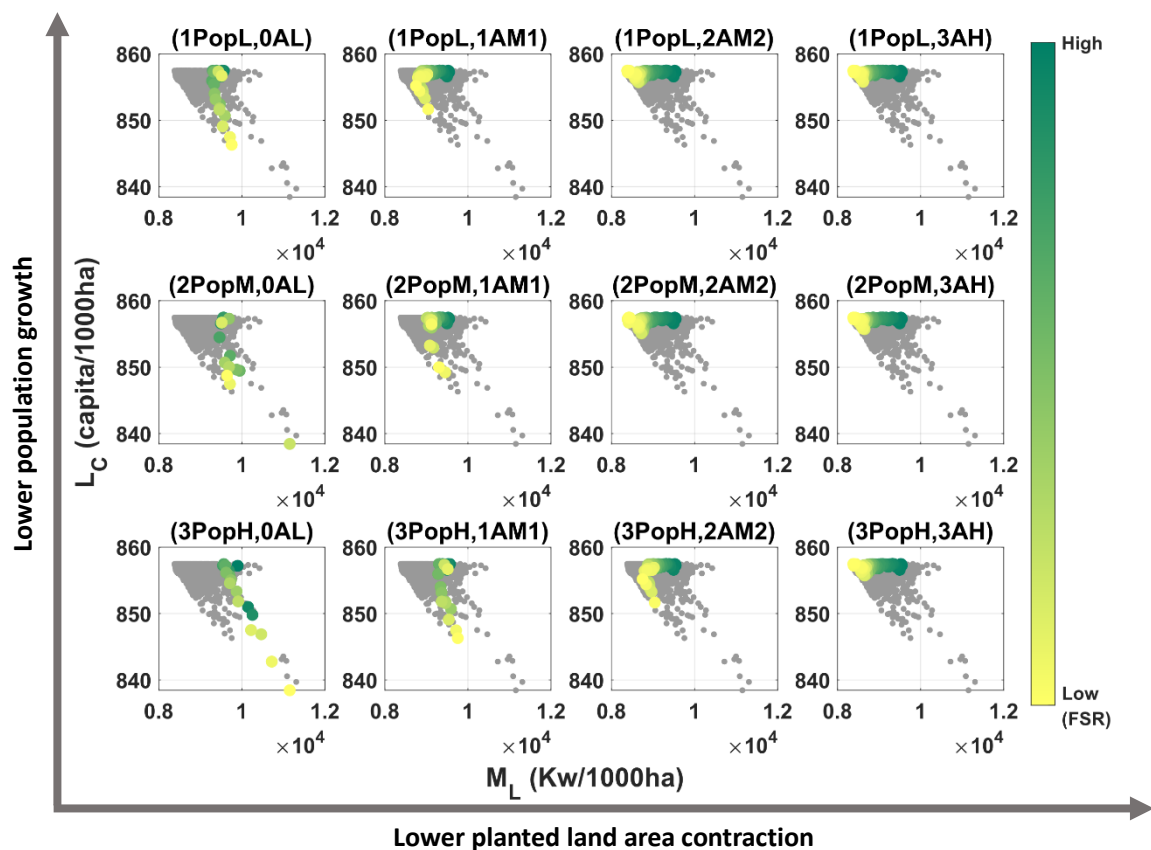
615 The non-dominated efficiencies are higher in general under unfavorable conditions.
 616 More trade-off between the two in wheat production compared to rice is due to how
 617 sensitive crop specific efficiencies are related to human agency. The water use
 618 efficiency of wheat is sensitive to the human agency under non-dominated cases, while

619 that of rice is not. However, the nutrient use efficiency of both wheat and rice can be
 620 significantly improved with adapting human agency, i.e. corresponding to non-
 621 dominated cases. The difference between non-dominated and dominated efficiencies
 622 under favorable conditions is insignificant, which again emphasizes that human agency
 623 matters when conditions are unfavorable. There is more scope for improving
 624 efficiencies when conditions are unfavorable due to poor water and land supply and
 625 high food demand.

626

627

628 *4.2 Trade-offs between labor and machinery used*



629

630

631

632 Figure 10a Trade-off between crop labor force, L_C , and land-preparing machinery
 633 power, M_L , used under least optimistic climate scenario (RCP8.5, P10%).

634

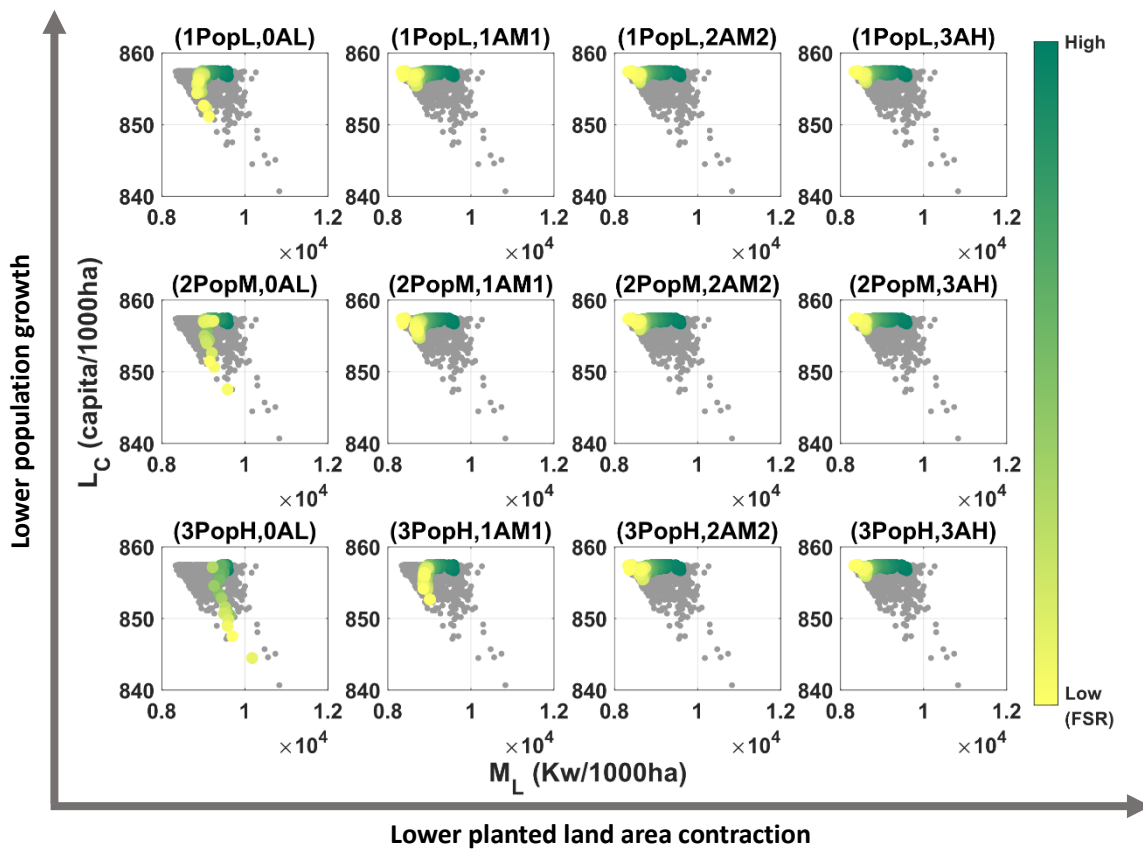
Points with color correspond to food secure pareto frontier

635

Green color means higher average food self-sufficiency $\bar{\Psi}_r$, yellow color means

636

lower $\bar{\Psi}_r$.



638

639

640

641 Figure 10b Trade-off between crop labor force L_C and land-preparing machinery

642

power M_L under most optimistic climate scenario (RCP2.6, P95%)

643

Points with color correspond to food secure pareto frontier

644

Green color means higher food self-sufficiency rate $\bar{\Psi}_r$, yellow color means lower

645

$\bar{\Psi}_r$.

646

647

648 Figure 10a and 10b plot labor (L_C) against land-preparing machinery power (M_L) for

649

two climate scenarios: (RCP 8.5, P10%) and (RCP 2.6, P95%). The rows of each figure

650

denote population growth rates (three levels from low to high), whereas the columns

651

represent crop plant area contraction rates (four levels from low to high).

652

653

Modern machinery appears to be the main agency that delivers higher food self-

654

sufficiency under all circumstances. Under unfavorable socioeconomic conditions, i.e.,

655

with higher population growth and sharper contraction of available land resources for

656 crop cultivation, agricultural land-preparing machinery plays more important role to
657 ensure nutrient and water use efficiency in order to increase the production of food crop,
658 ensuring a higher and stabler supply of food. The effect of labor on food sufficiency is
659 relatively low. This indicates that agricultural mechanization would ensure food
660 security in Jiangsu Province under the unfavorable scenario of rapid urbanization.
661 Agricultural lands will shrink in the process of urbanization. This will shift people from
662 rural agriculture to modern industries, leading to rural to urban migration (Lyu et al.,
663 2019). Agricultural mechanization can however replace the demand of shrinking human
664 labor while ensuring same or higher levels of food production, thereby ensuring food
665 security in the region.

666

667 Under the scenarios of less stressed socioeconomic conditions, i.e., lower population
668 growth or lower contraction of crop planted area, the need for agricultural machinery,
669 which can rapidly improve crop unit yields and thus result in higher food self-
670 sufficiency rate, would not be that urgent compared to the unfavorable case. More labor
671 can be hired to relieve under-employment in rural agriculture areas.

672

673 Similarly, in context of climate scenarios, agricultural labor demand would slightly rise
674 in more optimistic climate scenarios since the urgency to use agricultural machinery is
675 eased to a certain extent. When the climate is less optimistic, e.g. (RCP8.5, P10%),
676 agricultural machinery is important agency that should be adapted to improve food crop
677 production capacity and ensure high and stable food self-sufficiency.

678

679 **5. Conclusion**

680 This study investigated how food security can be ensured within Jiangsu Province,
681 China under different climate and socioeconomic scenarios by adapting human agency.
682 The human agency comprises of crop production labor, irrigation machinery power and
683 land-preparing machinery. Climate scenarios included six combinations of two RCPs
684 (RCP 2.6, and RCP 8.5) and three percentiles (10%, 50%, 95%) of a distribution of
685 GCMs most representative of the past climate conditions of the province. The
686 socioeconomic scenarios considered combinations of three population growth rates and
687 four rates of crop plant area growth into the future. Two crops, rice and wheat, were
688 considered. The predicted time series of food self-sufficiency rate were evaluated, and
689 trade-offs between human power and land-preparing machinery power were analyzed
690 to reveal the critical role played by human agency in adapting to different climate and
691 socio-economic conditions.

692

693 The results demonstrated that adapting human agency led to improved water and
694 nutrient use efficiencies of crop production, especially in least optimistic climate and
695 socioeconomic scenarios. The Jiangsu Province can be self-sufficient in food under all
696 considered climate and socioeconomic scenarios considered when options are available
697 for human agency to adapt. The gap between adaption and non-adaptation solutions
698 was found to be larger under more challenging scenarios of lesser precipitation, higher
699 population growth or stronger contraction of crop plant area. This suggests that human
700 adaptation can significantly improve food security within Jiangsu Province especially
701 when there are higher stresses of water or land resources insecurity.

702

703

704 Under lower water or land resources stress conditions, labor could replace land-
705 preparing machinery since the level of food production can be easily maintained with
706 abundant water and land availability. On the other hand, when climate change
707 negatively affects the precipitation, or when population rises more rapidly, machinery
708 such as water-saving irrigation or even water-fertilizer integrated irrigation systems
709 together with land-preparing machinery, instead of human labor, could lead to higher
710 levels of water and nutrient use efficiencies. These are much needed to secure food
711 under adverse conditions.

712

713 The applied crop model (Lyu et al., 2020) ignores seeds and pesticides inputs to crop
714 production. As reported in the literature, ignoring these inputs can lead to over-
715 estimation of production levels (Zida et al., 2011). Similarly, only precipitation and
716 temperature effects of climate change were considered and not those of CO₂
717 fertilization. This may lead to under-estimation of production levels under adverse
718 climate change scenarios (Rashid et al., 2019). We used historical 18 years agro-
719 meteorological stations data. Here crop yields were not limited by availability of seeds
720 and fertilizers, therefore it would not be possible to assess the effects of these inputs on
721 crop yields and production. However, assessing the positive feedbacks between CO₂
722 concentration and crop yields is possible. We defer this improvement in crop model for
723 future research.

724

725

726

727 **References:**

728

729 Achille, Jean, Jaza, & Folefack. (2015). The rural exodus of young farmers and its
730 impact on the shortage of labor and food crop production in cameroon: a
731 computable general equilibrium model's analysis. *Journal of Human Ecology*.
732 Doi: <https://doi.org/10.1080/09709274.2015.11906838>

733

734 Aloysius, N. R. , Sheffield, J. , Saiers, J. E. , Li, H. , & Wood, E. F. . (2016). Evaluation
735 of historical and future simulations of precipitation and temperature in central
736 africa from cmip5 climate models. *Journal of Geophysical Research*
737 *Atmospheres*, 121(1), 130-152. Doi: 10.1002/2015JD023656

738

739 Avery, S. V., Singleton, I., Magan, N., & Goldman, G. H. (2019). The fungal threat to
740 global food security. *Fungal biology*, 123(8), 555-557. Doi:
741 <https://doi.org/10.1016/j.funbio.2019.03.006>

742

743 Bureau of Statistics of Jiangsu. (2018). Statistical Yearbook of Jiangsu: China Statistics
744 Press. Retrieved from <http://tj.jiangsu.gov.cn/col/col70123/index.html> (Chinese
745 version, access for free.)

746

747 Bureau of Statistics of Jiangsu. (2019). Statistical Yearbook of Jiangsu: China Statistics
748 Press. Retrieved from <http://tj.jiangsu.gov.cn/col/col70123/index.html> (Chinese
749 version, access for free.)

750

751 Bureau of Statistics of Jiangsu. (2002). Compilation of population prediction data in
752 Jiangsu Province 2001-2050.

753

754 Bureau of Statistics of Jiangsu. (2012). Compilation of population prediction data in
755 Jiangsu Province 2011-2030.

756

757 Cardwell, R. (2014). *Food Security and International Trade*. Springer Netherlands.

758

759 Challinor, A. J., Simelton, E. S., Fraser, E. D., Hemming, D., & Collins, M. (2010).
760 Increased crop failure due to climate change: assessing adaptation options using
761 models and socio-economic data for wheat in China. *Environmental Research*
762 *Letters*, 5(3), 034012. Doi: 10.1088/1748-9326/5/3/034012

763

764 Chen, Yashu. (2019). Path analysis of influencing factors of grain planting area from
765 the perspective of supply side reform. *Journal of Liaoning University of*
766 *Technology (Social Science Edition)*, 21(4), 36-39. Doi: 10.15916/j.issn1674-
767 327x.2019.04.010

768

769 Chen, Yuzhu, Zhou, Hong, & Yin, Ge. (2016). Comparative analysis between the
770 changes of corn planting area and the profitability in Northeast China from the
771 perspective of planting substitutions. *Research of Agricultural Modernization*,
772 37 (3), 489-495. Doi 0.13872/j.1000-0275.2016.0051

773

774 Crane, T. A., Roncoli, C., & Hoogenboom, G. (2011). Adaptation to climate change and
775 climate variability: The importance of understanding agriculture as
776 performance. *NJAS-Wageningen Journal of Life Sciences*, 57(3-4), 179-185.
777 Doi: <https://doi.org/10.1016/j.njas.2010.11.002>
778

779 Eyring, V. (2013). Performance metrics and observations in global climate model
780 evaluation. *ESA CMUG Integration-3 meeting*. DLR.
781

782 Febrina Torop Simangunsong, Sumono Sumono, Ainun Rohana, & Edi Susanto. (2013).
783 Drip irrigation efficiency analysis and crop water requirements of mustard
784 (brassica juncea) in the inceptisol soil. *Jurnal Rekayasa Pangan Dan Pertanian*.
785

786 Garibaldi, L. A., & Pérez-Méndez, N. (2019). Positive outcomes between crop diversity
787 and agricultural employment worldwide. *Ecological Economics*, 164, 106358.
788 Doi: <https://doi.org/10.1016/j.ecolecon.2019.106358>
789

790 Gomez-Zavaglia, A., Mejuto, J. C., & Simal-Gandara, J. (2020). Mitigation of emerging
791 implications of climate change on food production systems. *Food Research*
792 *International*, 109256. Doi: <https://doi.org/10.1016/j.foodres.2020.109256>
793

794 Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017).
795 Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote*
796 *Sensing of Environment*, 202, 18-27. Doi:
797 <https://doi.org/10.1016/j.rse.2017.06.031>
798

799 Greene, A. M., Hellmuth, M., & Lumsden, T. (2012a). Stochastic decadal climate
800 simulations for the Berg and Breede water management areas, western Cape
801 province, South Africa. *Water Resources Research*, 48(6). Doi:
802 <https://doi.org/10.1029/2011WR011152>
803

804 Greene, A. M. (2012b). The simgen software package: User guide and notes.
805 International Research Institute for Climate and Society.
806

807 Greene, A. M., Goddard, L., Gonzalez, P. L., Ines, A. V., & Chryssanthacopoulos, J.
808 (2015). A climate generator for agricultural planning in southeastern South
809 America. *Agricultural and forest meteorology*, 203, 217-228. Doi:
810 <https://doi.org/10.1016/j.agrformet.2015.01.008>
811

812 Gu, L., & Guo, Q. (2011). Evolution and Development of China's Major Grain
813 Producing Areas. *Issues in Agricultural Economy*, 2011(8), 4-9. Doi:
814 CNKI:SUN:NJWT.0.2011-08-001
815

816 Hao, Y., Hu, X., & Li, F. (2020). Water and fertilizer integrated irrigation system based
817 on Internet of Things technology. *Internet of Things technologies*, 9, 58-61. Doi:
818 [10.16667/j.issn.2095-1302.2020.09.017](https://doi.org/10.16667/j.issn.2095-1302.2020.09.017)
819

820 Harris, I. P. D. J., Jones, P. D., Osborn, T. J., & Lister, D. H. (2014). Updated high-
821 resolution grids of monthly climatic observations—the CRU TS3. 10 Dataset.
822 *International journal of climatology*, 34(3), 623-642. Doi:
823 <https://doi.org/10.1002/joc.3711>

824

825 Hertel, T. W., & Rosch, S. D. (2010). Climate change, agriculture and poverty. The
826 World Bank. Doi: <https://doi.org/10.1596/1813-9450-5468>

827

828 Hibbard, K. A., Meehl, G. A., Cox, P. M., & Friedlingstein, P. (2007). A strategy for
829 climate change stabilization experiments. *Eos, Transactions American*
830 *Geophysical Union*, 88(20), 217-221. Doi:
831 <https://doi.org/10.1029/2007EO200002>

832

833 Hou, H., Wang, R., & Murayama, Y. (2019). Scenario-based modelling for urban
834 sustainability focusing on changes in cropland under rapid urbanization: A case
835 study of Hangzhou from 1990 to 2035. *Science of the Total Environment*, 661,
836 422-431. Doi: <https://doi.org/10.1016/j.scitotenv.2019.01.208>

837

838 Huang, M., Wang, Z., Luo, L., Wang, S., Cao, H., He, G., & Diao, C. (2018). Effects of
839 ridge mulching, furrow seeding, and optimized fertilizer placement on NPK
840 uptake and utilization in dryland wheat. *Journal of Plant Nutrition and*
841 *Fertilizers*. 2018, 24(5): 1158–1168. Doi: 10.11674/zwyf.17463

842

843 Hurrell, J., Visbeck, M., & Pirani, P. (2011). WCRP Coupled Model Intercomparison
844 Project-Phase 5-CMIP5. *Clivar Exchanges*, 16(56).

845

846 Kaiser, M. L. (2011). Food security: an ecological–social analysis to promote social
847 development. *Journal of Community Practice*, 19(1), 62-79. Doi:
848 10.1080/10705422.2011.550261

849

850 Kakinuma, K. , Yoshikawa, S. , Endo, T. , & Kanae, S. . (2014). Water law as an
851 adaptation strategy for global water scarcity in the future. *Agu Fall Meeting*.
852 AGU Fall Meeting Abstracts. Retrieved from:
853 <https://ui.adsabs.harvard.edu/abs/2014AGUFM.H13A1039K/abstract>

854

855 Kawuma Menya, C. (2011). Rainfall variation due to climate change: an intertemporal
856 investigation into its impact on subsistence crop net revenue. URI:
857 <http://hdl.handle.net/11250/187225>

858

859 Kotu, V., & Deshpande, B. (2018). *Data science: concepts and practice*. Morgan
860 Kaufmann.

861

862 Kukal, M. S., & Irmak, S. (2018). Climate-driven crop yield and yield variability and
863 climate change impacts on the US Great Plains agricultural production.
864 *Scientific Reports*, 8(1), 1-18. Doi: [https://doi.org/10.1038/s41598-018-21848-](https://doi.org/10.1038/s41598-018-21848-2)
865 2

866

867 Leisnham, P. T., Montas, H., Shirmohammadi, A., Chanse, V., Lansing, D., Rockler,
868 A., ... & Lipton, D. (2013). Watershed diagnostics for improved adoption of
869 management practices: Integrating biophysical and social factors across urban
870 and agricultural landscapes. In *2013 Kansas City, Missouri, July 21-July 24,*
871 *2013* (p. 1). American Society of Agricultural and Biological Engineers. Doi:
872 <http://dx.doi.org/10.13031/aim.20131668614>

873

874 Li, Bailing, H. Beaudoin, and M. Rodell, NASA/GSFC/HSL (2018), GLDAS
875 Catchment Land Surface Model L4 daily 0.25 x 0.25 degree V2.0, Greenbelt,
876 Maryland, USA, Goddard Earth Sciences Data and Information Services Center
877 (GES DISC), Accessed: [1969.1.1 - 2013.12.31], 10.5067/LYHA9088MFWQ
878

879 Li, B., & Sivapalan, M. (2020). Long - term coevolution of an urban human - water
880 system under climate change: Critical role of human adaptive actions. *Water*
881 *Resources Research*, 55, e2020WR027931. Doi:
882 <https://doi.org/10.1029/2020WR027931>
883

884 Li, G., X, J., & Li, F. (2009). Analysis of the restriction factors and approaches to
885 increase grain production in Jiangsu Province. *Journal of Nanjing University of*
886 *Finance and Economics*, 2009 (3), 20-24.
887

888 Li, J., & Li, L. (2012). Water Resources Supporting Capacity to Regional Socio-
889 economic Development of China. *Acta Geographica Sinica*, 67 (3), 410-419.
890 Doi: 10.11821/xb201203012
891

892 Lobell, D. B., Field, C. B., Cahill, K. N., & Bonfils, C. (2006). Impacts of future climate
893 change on California perennial crop yields: Model projections with climate and
894 crop uncertainties. *Agricultural and Forest Meteorology*, 141(2-4), 208-218.
895 Doi: <https://doi.org/10.1016/j.agrformet.2006.10.006>
896

897 Lyu, H., Dong, Z., Roobavannan, M., Kandasamy, J., & Pande, S. (2019). Rural
898 unemployment pushes migrants to urban areas in Jiangsu Province, China.
899 Palgrave Communications, 5(1), 1-12. Doi: [https://doi.org/10.1057/s41599-](https://doi.org/10.1057/s41599-019-0302-1)
900 [019-0302-1](https://doi.org/10.1057/s41599-019-0302-1)
901

902 Lyu, H., Dong, Z., & Pande, S. (2020). Interlinkages between human agency, water use
903 efficiency and sustainable food production. *Journal of Hydrology*, 582, 124524.
904 Doi: <https://doi.org/10.1016/j.jhydrol.2019.124524>
905

906 Ma, X., Sanguinet, K. A., & Jacoby, P. W. (2020). Direct root-zone irrigation
907 outperforms surface drip irrigation for grape yield and crop water use efficiency
908 while restricting root growth. *Agricultural Water Management*, 231. 1-11. Doi:
909 <https://doi.org/10.1016/j.agwat.2019.105993>
910

911 Makowski, D., Marajo-Petitzon, E., Durand, J. L., & Ben-Ari, T. (2020). Quantitative
912 synthesis of temperature, CO2, rainfall, and adaptation effects on global crop
913 yields. *European Journal of Agronomy*, 115, 126041. Doi:
914 <https://doi.org/10.1016/j.eja.2020.126041>
915

916 McCarthy, U., Uysal, I., Badia-Melis, R., Mercier, S., O'Donnell, C., & Ktenioudaki, A.
917 (2018). Global food security—Issues, challenges and technological
918 solutions. *Trends in Food Science & Technology*, 77, 11-20. Doi:
919 <https://doi.org/10.1016/j.tifs.2018.05.002>
920

921 Meehl, G. A., & Hibbard, K. A. (2007). A strategy for climate change stabilization
922 experiments with AOGCMs and ESMs. WCRP Informal Rep, 3, 2007.
923

- 924 Mo, F., Wang, G., & Hu, M. (2020). Analysis of soybean production status in Northeast
925 China based on cost. *Soybean Science*, 39(6), 947-953. Doi:
926 10.11861/j.issn.1000-9841.2020.06.0947
927
- 928 Mondal, M., & Sanaul, H. (2019). The implications of population growth and climate
929 change on sustainable development in Bangladesh. *Jàmbá: Journal of Disaster
930 Risk Studies*, 11(1), 1-10. Doi: <http://dx.doi.org/10.4102/jamba.v11i1.535>
931
- 932 National Bureau of Statistics of China. (2016). *China Rural Statistical Yearbook: China
933 Statistics Press*. Retrieved from
934 http://www.stats.gov.cn/tjsj/tjcbw/202008/t20200826_1785896.html
935 [https://navi.cnki.net/KNav/YearbookDetail?pcode=CYFD&pykm=YMCTJ&
936 bh=](https://navi.cnki.net/KNav/YearbookDetail?pcode=CYFD&pykm=YMCTJ&bh=)
937
- 938 National Meteorological Information Center of China, Crop growth and development
939 and farmland soil moisture data set in China. 2006.
940
- 941 Olesen, J. E., Trnka, M., Kersebaum, K. C., Skjelvåg, A. O., Seguin, B., Peltonen-Sainio,
942 P., ... & Micale, F. (2011). Impacts and adaptation of European crop production
943 systems to climate change. *European Journal of Agronomy*, 34(2), 96-112. Doi:
944 <https://doi.org/10.1016/j.eja.2010.11.003>
945
- 946 Preston, B. L., King, A. W., Ernst, K. M., Absar, S. M., Nair, S. S., & Parish, E. S.
947 (2015). Scale and the representation of human agency in the modeling of
948 agroecosystems. *Current Opinion in Environmental Sustainability*, 14, 239-249.
949 Doi: <https://doi.org/10.1016/j.cosust.2015.05.010>
950
- 951 Qian, Xiaolong, Guan, Hua, & Yuan, Xiaoyan. (2008). Empirical Study on Utilization
952 Benefit of Cultivated Land in Jiangsu Province. *SYSTEM SCIENCES AND
953 COMPREHENSIVE STUDIES IN AGRICULTURE*, 24 (2), 163-166,171. Doi:
954 10.3969/j.issn.1001-0068.2008.02.008
955
- 956 Qiu, B., Li, H., Tang, Z., Chen, C., & Berry, J. (2020). How cropland losses shaped by
957 unbalanced urbanization process?. *Land Use Policy*, 96, 104715. Doi:
958 <https://doi.org/10.1016/j.landusepol.2020.104715>
959
- 960 Rashid, M. A. , Jabloun, M. , Andersen, M. N. , Zhang, X. , & Olesen, J. E. . (2019).
961 Climate change is expected to increase yield and water use efficiency of wheat
962 in the north china plain. *Agricultural Water Management*, 222, 193-203. Doi:
963 <https://doi.org/10.1016/j.agwat.2019.06.004>
964
- 965 Rodell, M., P.R. Houser, U. Jambor, J. Gottschalck, K. Mitchell, C. Meng, K. Arsenault,
966 B. Cosgrove, J. Radakovich, M. Bosilovich, J.K. Entin, J.P. Walker, D.
967 Lohmann, and D. Toll, 2004: The Global Land Data Assimilation System, *Bull.
968 Amer. Meteor. Soc.*, 85, 381-394. Doi: 10.1175/BAMS-85-3-381
969
- 970 Rosemberg, A. (2010). Building a just transition: The linkages between climate change
971 and employment. *International Journal of Labour Research*, 2(2), 125. Retrieved
972 from:

973 <https://search.proquest.com/docview/884976739/fulltext/8F5C77FD512543F9>
974 [PQ/1?accountid=27026](https://search.proquest.com/docview/884976739/fulltext/8F5C77FD512543F9)
975
976 Schmidhuber, J., & Tubiello, F. N. (2007). Global food security under climate
977 change. *Proceedings of the National Academy of Sciences*, 104(50), 19703-
978 19708. Doi: www.pnas.org/cgi/doi/10.1073/pnas.0701976104
979
980 Shi, Z., Liu, Q., Bai, M., Shi, Y., & Zhang S. (2017) Water and fertilization integrated
981 intelligent irrigation system design and benefit analysis based on the Internet of
982 Things. *Journal of Water Resources & Water Engineering*, 28(3), 221-227. Doi:
983 [10.11705/j.issn.1672-643X.2017.03.40](https://doi.org/10.11705/j.issn.1672-643X.2017.03.40)
984
985 Siwar, C., Ahmed, F., & Begum, R. A. (2013). Climate change, agriculture and food
986 security issues: Malaysian perspective. *Journal of Food, Agriculture and*
987 *Environment*, 11(2), 1118-1123.
988
989 Springmann, M., Mason-D'Croz, D., Robinson, S., Garnett, T., Godfray, H. C. J., Gollin,
990 D., ... & Scarborough, P. (2016). Global and regional health effects of future
991 food production under climate change: a modelling study. *The*
992 *Lancet*, 387(10031), 1937-1946. Doi: [https://doi.org/10.1016/S0140-](https://doi.org/10.1016/S0140-6736(15)01156-3)
993 [6736\(15\)01156-3](https://doi.org/10.1016/S0140-6736(15)01156-3)
994
995 Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the
996 experiment design. *Bulletin of the American Meteorological Society*, 93(4),
997 485-498. Doi: <https://doi.org/10.1175/BAMS-D-11-00094.1>
998
999 Turrall, H., Burke, J., & Faurès, J. M. (2011). Climate change, water and food security
1000 (No. 36). Food and Agriculture Organization of the United Nations (FAO).
1001 Retrieved from: <http://www.fao.org/3/i2096e/i2096e00.htm>
1002
1003 van Vliet, J., Eitelberg, D. A., & Verburg, P. H. (2017). A global analysis of land take
1004 in cropland areas and production displacement from urbanization. *Global*
1005 *environmental change*, 43, 107-115. Doi:
1006 <https://doi.org/10.1016/j.gloenvcha.2017.02.001>
1007
1008 Wang, H., Guo, F., & Li, X. (2013) China Grain Map: From "South-to-North Grain
1009 Transport" to "North-to-South Grain Transport", 2013(25). Retrieved from:
1010 <http://www.cweekly.cn/2013/0701/32114.shtml>
1011
1012 Wang, Y. S. (2019). The challenges and strategies of food security under rapid
1013 urbanization in China. *Sustainability*, 11(2), 542. Doi:
1014 <https://doi.org/10.3390/su11020542>
1015
1016 Warner, K., & Van der Geest, K. (2013). Loss and damage from climate change: local-
1017 level evidence from nine vulnerable countries. *International Journal of Global*
1018 *Warming*, 5(4), 367-386.
1019
1020 Xu, J., & Ding, Y. (2015). Research on early warning of food security using a system
1021 dynamics model: evidence from Jiangsu province in China. *Journal of food*
1022 *science*, 80(1), R1-R9. Doi: <https://doi.org/10.1111/1750-3841.12649>

1023

1024 Xu, L., Huang, Y. & Liu, A. (2011). Study on the carrying capacity of water resources
1025 in Jiangsu Province based on the principal component analysis. *Resources and*
1026 *Environment in the Yangtze Basin*, 2011,20(12):1468-1474.

1027

1028 Zhang, Yueping, Liu, youzhao, Mao, Liangxiang, & Zhang, bingning. (2004).
1029 EVALUATION OF THE SECURITY OF LAND RESOURCES BY LAND
1030 CARRYING CAPACITY——A CASE STUDY OF JIANGSU PROVINCE.
1031 *Resources and Environment in the Yangtze Basin*, 13 (4), 328-332. Doi:
1032 10.3969/j.issn.1004-8227.2004.04.006

1033

1034 Zhao, Yu & Yan, Wu. (2019). Can China's Grain Acreage Respond Correctly to Market
1035 Mechanism? An empirical Study Based on Panel Simultaneous Equations.
1036 *Journal of Agro-Forestry Economics and Management*, 18 (3), 313-324. Doi:
1037 10.16195/j.cnki.cn36-1328/f.2019.03.35

1038

1039 Zhu, Jie, & Ou, Xiangjun. (2020). Research on the Allometric Growth and Coordinated
1040 Development of Population Land Urbanization in Jiangsu. *TERRITORY &*
1041 *NATURAL RESOURCES STUDY*, 185 (2), 37-42. Doi:
1042 10.16202/j.cnki.tnrs.2020.02.010

1043

1044 Zida, E. P. , Lund, O. S. , & JB Néya. (2011). Seed treatment with a binary pesticide
1045 and aqueous extract of *eclipta alba* (L.) hassk. for improving sorghum yield in
1046 burkina faso. *Journal of Tropical Agriculture*, 50, 1-7.