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1 **Building soil to reduce climate change impacts on global crop yield**

2

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20 **Abstract**

21 Improving soil health and resilience is fundamental for sustainable food production,
22 however the role of soil in maintaining or boosting crop productivity under climate
23 change is still unclear. Here, we examined the role of soil in yield response to climate
24 warming for four major crops (i.e., maize, wheat, rice and soybean), using global-scale
25 datasets and machine learning techniques. We found that each °C of warming have
26 reduced global yields of maize by 3.4%, wheat by 2.4%, rice by 0.3% and soybean by
27 5.0%, which are high spatial heterogeneous with positive impacts in certain regions.
28 Soil organic carbon (SOC) would dominantly regulate negative yield responses.
29 Improving SOC could build yield resilience to warming, avoiding an average of 3-
30 5% °C⁻¹ of warming-induced yield loss over 60% of global planting area. The avoided
31 loss of production in future could supply additional food for up to ~560 million people
32 in 2050. Our findings highlight the critical role of soil in reducing warming impacts on
33 food security, especially for developing regions, given that sustainable actions could be
34 taken broadly.

35 **Main**

36 The number of people suffering from food insecurity continues to increase, with over
37 700 million people in total in 2020¹. With a growing population and climate change,
38 the global food demand in 2050 is expected to increase by 30% to 62% relative to 2010².
39 How to feed this future population and achieve the Sustainable Development Goals (i.e.,
40 zero hunger) is a major global challenge³. Maize, wheat and rice account for 89% of
41 global cereal production, and soybean supplies 28% of the world's vegetable oil¹.
42 Climate change is threatening global crop production. Rising temperature has been
43 proved to be a major cause for global yield losses⁴⁻⁶, especially in less-developed and
44 warm areas such as sub-Saharan Africa and Latin America⁷. Recent modeling studies
45 have also shown that, without effective adaptation, warming may also reduce yields in
46 cooler regions^{4,8}.

47 Strengthening adaptations of agricultural systems is imperative to reduce exposure
48 and vulnerability to climate change⁹. Global assessments have mainly focused on

49 cultivar shifts and agronomic management practices to enhance adaptation¹⁰⁻¹². A
50 combination of cultivars (e.g., higher heat tolerance) and management (e.g., soil organic
51 matter management) adaptations could reduce yield losses due to warming by ~5% in
52 the mid-21st century¹³. In terms of common adaptation strategies, cultivar switch and
53 irrigation contribute significantly to crop yield gains¹⁰. However, the negative effects
54 of climate change on crop production cannot be fully offset by implementing adaptation,
55 especially in lower latitudes^{9,13}.

56 Resilient and productive soils are necessary to sustainably intensify agriculture, to
57 increase yields while minimizing environmental harm^{14,15}. High-quality soils can buffer
58 climate variability in cropping systems and sustain yield stability^{16,17}. Soil organic
59 carbon (SOC), in particular, has been suggested as an integrated and representative
60 indicator of soil quality, which relates to soil biological and physical properties such as
61 disease suppressiveness, heat capacity^{18,19} and soil heath, with important functions such
62 as water retention and nutrient supply^{20,21}. Improving SOC can help build climate
63 resilience to reduce risks to food insecurity^{22,23}, and decrease reliance on irrigation and
64 fertilizer application²⁴. A recent study has revealed that increasing SOC can reduce the
65 yield gaps of maize and wheat¹⁴. However, the role of soil in building crop yield
66 resilience to climate change is still missing from the crop-soil-environment system, it
67 remains difficult to quantify the complex interactions between soil, climate and
68 yield^{25,26}.

69 This study provides a soil-focused perspective to address escalating climate
70 challenges on global agriculture, and to look for opportunities in soils for future food
71 security. Here, we firstly determined the response of maize, wheat, rice and soybean
72 yields to warming temperature at grid scale, i.e., temperature response index
73 (TRI, % °C⁻¹). Then, we identified the role of soil properties (including SOC) in
74 explaining spatially heterogeneous responses of crop yield to warming, by using a
75 machine learning approach. With outcomes from these processes, we finally proposed
76 soil related strategies for securing food production under future climate change
77 scenarios, and further explored the potential impacts on food security.

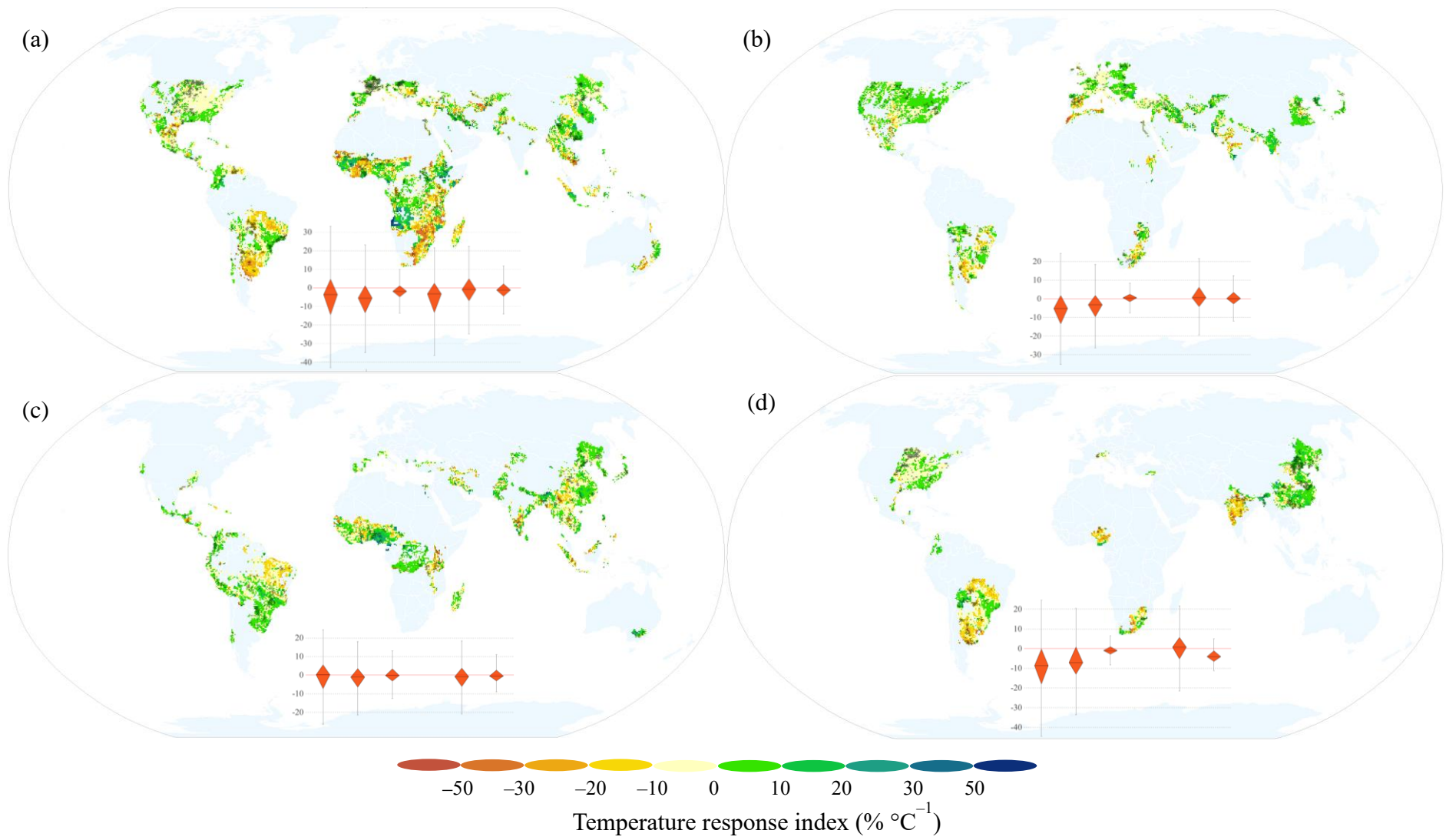
78 **Results**

79 **Climate change impacts on global crop yield**

80 We defined the temperature response index (TRI) as partial yield percentage changes
81 for each degree Celsius ($^{\circ}\text{C}^{-1}$) increase. By isolating effects of temperature, it can show
82 crop yield response to climate warming, and indicate yield resilience to future warming
83 by crop and location. TRI was computed for maize, wheat, rice and soybean at the grid
84 level ($0.5^{\circ} \times 0.5^{\circ}$), using global time series datasets. In general, warming has caused
85 global-scale yield loss, with crop-specific and spatially heterogeneous responses at finer
86 scales (Fig. 1). Globally, the estimates for all four crops show negative TRIs, suggesting
87 an average yield loss of $-3.4\% \text{ }^{\circ}\text{C}^{-1}$ (-32.0 to $-19.1\% \text{ }^{\circ}\text{C}^{-1}$, 95% distribution interval),
88 $-2.4\% \text{ }^{\circ}\text{C}^{-1}$ (-21.2 to $-15.0\% \text{ }^{\circ}\text{C}^{-1}$), $-0.3\% \text{ }^{\circ}\text{C}^{-1}$ (-22.8 to $-17.4\% \text{ }^{\circ}\text{C}^{-1}$), and $-5.0\% \text{ }^{\circ}\text{C}^{-1}$
89 1 (-25.2 to $-14.3\% \text{ }^{\circ}\text{C}^{-1}$) for maize, wheat, rice, and soybean, respectively. However,
90 crop- and location-specific TRIs vary significantly.

91 In particular, the TRIs for maize are consistently negative across five continents,
92 ranking from high to low: Africa ($-6.6\% \text{ }^{\circ}\text{C}^{-1}$), South America ($-6.3\% \text{ }^{\circ}\text{C}^{-1}$), North
93 America ($-3.4\% \text{ }^{\circ}\text{C}^{-1}$), Oceania ($-2.8\% \text{ }^{\circ}\text{C}^{-1}$) and Europe ($-2.2\% \text{ }^{\circ}\text{C}^{-1}$). While on
94 average, maize in Asia is less negatively affected by warming, yield loss is still observed
95 in regions including Southeast Asia, Central Asia and Northwest China (Fig. 1a). For
96 wheat, Africa is the most vulnerable continent, with a TRI of $-15.5\% \text{ }^{\circ}\text{C}^{-1}$, followed by
97 South America ($-7.3\% \text{ }^{\circ}\text{C}^{-1}$) and Asia ($-1.1\% \text{ }^{\circ}\text{C}^{-1}$) (Fig. 1b). Rice is least affected by
98 rising temperatures in many regions, with continental scale TRIs closing to zero (Fig.
99 1c). The highest yield loss for soybean occurred in South America ($-9.8\% \text{ }^{\circ}\text{C}^{-1}$), the
100 largest soybean producer, followed by Africa ($-8.7\% \text{ }^{\circ}\text{C}^{-1}$). The lowest yield loss ($-$
101 $1.4\% \text{ }^{\circ}\text{C}^{-1}$) appeared in North America (Fig. 1d). In general, crop production in Africa
102 and South America is more susceptible to warming.

103

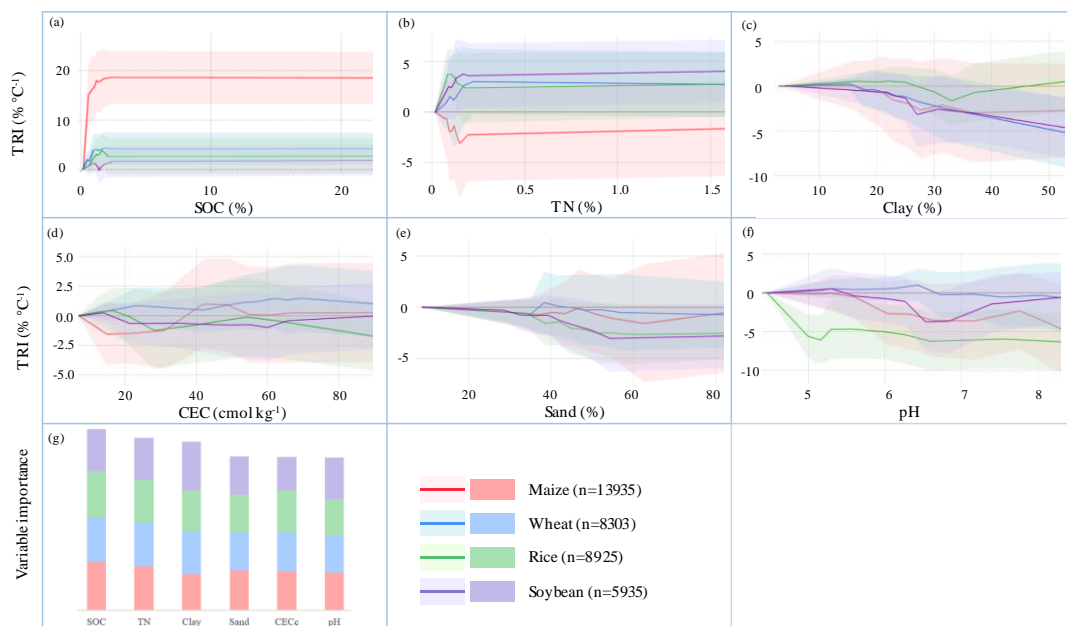


105 **Fig. 1. Global temperature response indices (TRIs, % °C⁻¹) of four crops.** (a) Maize
106 (n=14134), (b) wheat (n=8406), (c) rice (n=9048) and (d) soybean (n=5996). TRI values show
107 yield changes per °C of temperature increase, with positive and negative values indicating yield
108 gain and loss, respectively. The black marks in the grids represent the significant influence of
109 warming. The box chart reflects the interquartile range and the middle line in the box represents
110 the median. The boxes from left to right represent Africa, South America, North America,
111 Oceania, Asia and Europe, and the blank indicates insufficient data in Oceania (b-d).

112 **The role of soil in reducing climate impacts on yield**

113 The spatially heterogeneous response of crop yield to warming can largely be explained
114 by soil heterogeneity in terms of soil properties, including SOC, total nitrogen (TN),
115 clay and sand content, pH and cation exchange capacity (CEC). A random forest
116 technique, based on the concept of bagging sampling and regression decision trees²⁷,
117 was used to detect soil and spatial TRI relationship (Methods). After training and testing,
118 the random forest model can replicate the crop-specific yields to soil with the coefficient
119 of determination (R^2) of 0.46 to 0.66 (Supplementary Fig. 1), and the relationships can
120 be visualized by centered individual conditional expectation (c-ICE) plot (Fig. 2). c-
121 ICE plot can highlight the average change (colored curves) and variation range
122 (corresponding shadows) of TRI along with soil properties (Fig. 2a–f), and also identify
123 where, and to what extent, heterogeneities might exist²⁸. Among six soil properties that
124 potentially affect crop growth, SOC is identified as the most important predictor to TRI,
125 followed by TN, considering the variable importance metric (Fig. 2g). Other soil
126 properties do not affect TRI consistently across the whole range (Fig. 2c–g). This
127 implies that, with increased SOC or TN (except maize) in locations where their current
128 levels are relatively low, TRI could be improved, suggesting increased yield resilience
129 to warming (e.g., Fig. 2a–b). In particular, with increasing SOC, the TRI of four crops
130 would increase until reaching a “plateau” (Fig. 2a). When the SOC is lower than about
131 2.0%, increasing SOC can considerably reduce TRI, indicating improved yield
132 resilience to warming. Considering current low levels of SOC (Supplementary Fig. 2),
133 global soils have great potential to increase carbon content before reaching the TRI

134 “plateau” level. Current soil TN content, however, has already reached the “plateau”
 135 level in most of the planting regions (Supplementary Fig. 3), leaving limited room for
 136 improving TRI via TN change. Therefore, in this study, we further quantify spatial TRIs
 137 after soil improvement, specifically SOC increase, with associated TN change to
 138 maintain soil C:N (Methods).
 139



140
 141 **Fig. 2. The temperature response indices (TRIs) vary with soil properties. a–f,**
 142 centered individual conditional expectation (c-ICE) plot of TRI by six soil properties.
 143 Red, blue, green and purple lines represent the averaged TRI changes of maize, wheat,
 144 rice and soybean, respectively, with shadow indicating the distribution of all individual
 145 instances, relative to the starting point fixed at zero. **g,** the importance of soil properties,
 146 sorted from high to low according to the model outputs.

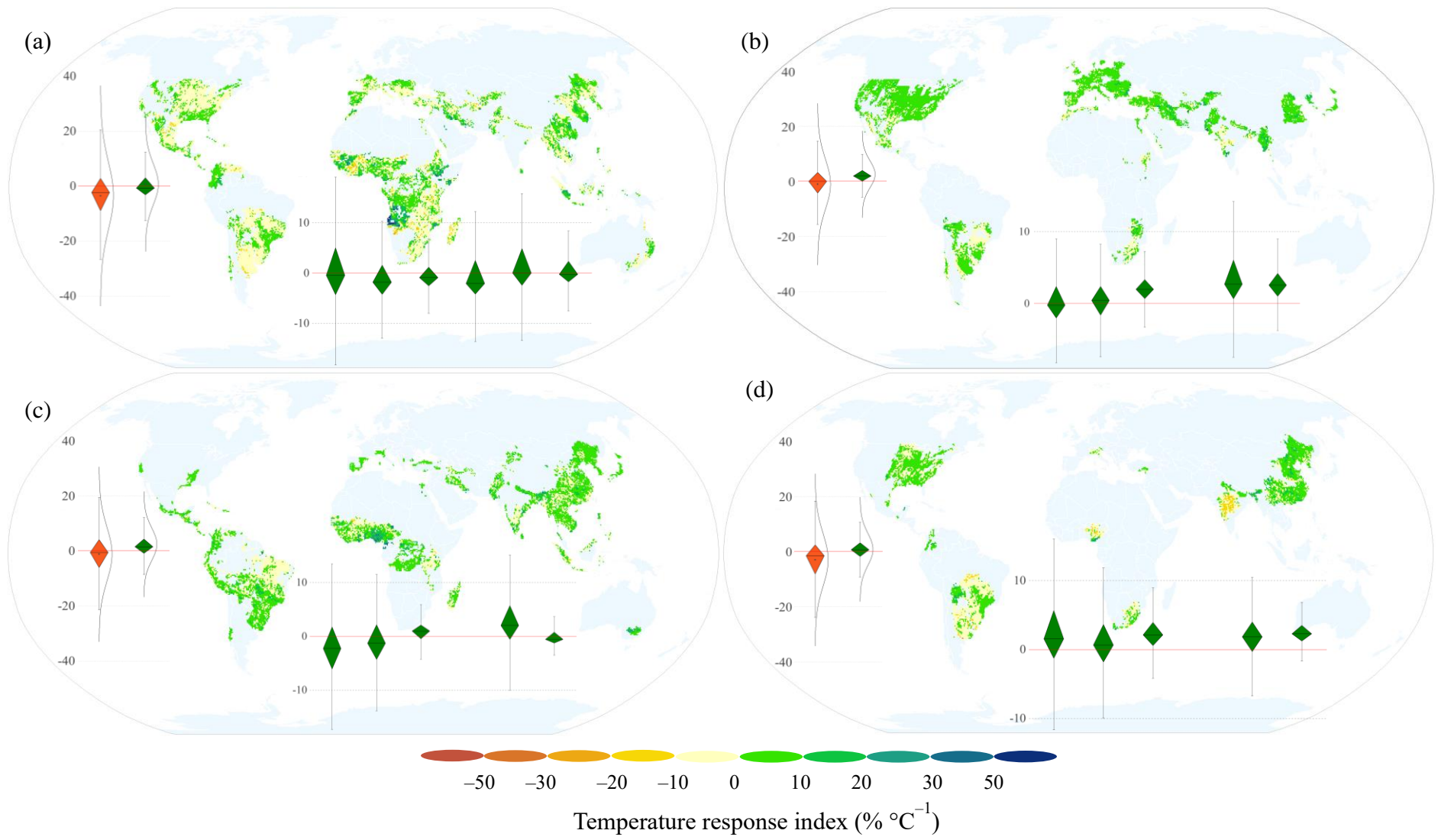
147
 148 Our analysis shows that improving soil can generally lead to less negative or more
 149 positive TRIs (Fig. 3), relative to those with existing soil conditions (Fig. 1). SOC can
 150 be sequestered in croplands, depending on biomass and manure inputs, and other
 151 management practices, but with an upper limit^{29,30}. By considering a “medium”
 152 sequestration scenario that SOC increase rate would achieve 26% of the “4p1000”
 153 target^{31,32}, the SOC level can be increased by an average of 1.3% in the study areas

154 (Supplementary Fig. 2). The considerable SOC increase would mostly occur in Europe
155 (2.6%), North America (2.4%) and Asia (1.6%), where soil carbon loss hotspots are
156 located³³. With the increase of SOC, the warming-induced yield losses could be
157 significantly reduced (Fig. 3). From a global perspective, the TRIs for maize, wheat,
158 rice and soybean would be 0.1% °C⁻¹ (-10.4 to 18.8% °C⁻¹), 2.7% °C⁻¹ (-4.5 to
159 15.0% °C⁻¹), 3.4% °C⁻¹ (-6.7 to 17.4% °C⁻¹) and -0.6% °C⁻¹ (-11.2 to 14.2% °C⁻¹),
160 respectively. With improved yield resilience owing to soil improvement, about 3.3%-
161 5.1% °C⁻¹ of yield loss can be avoided relative to the scenarios without soil
162 improvement.

163 For maize, in the United States, the largest maize producer, the average TRI would
164 change from -3.7% °C⁻¹ to -1.5% °C⁻¹, about 60% of warming-induced yield loss could
165 be avoided (Fig. 3a). In West Africa and East Africa, where yield has reduced by more
166 than 30% °C⁻¹ in some areas (Fig. 1a), most of the loss decreased to less than -10% °C⁻¹
167 after improving SOC (Fig. 3a). As for wheat, in both China and India, two of the
168 largest producers, the yield has suffered from different degree of loss due to warming,
169 about -0.1% °C⁻¹ and -7.0% °C⁻¹, respectively. With improved soil, the TRIs turns
170 positive in both countries (3.9% °C⁻¹ in China, and 1.1% °C⁻¹ in India), suggesting
171 potential yield benefit with warming regardless of possible effects from other factors.
172 It is not unexpected that rice is less affected by warming as an irrigated crop, it also
173 benefits from SOC improvement. In particular, for China and India, the top two rice
174 producers, the average TRIs would increase from 1.0% °C⁻¹ and 0.3% °C⁻¹ to 3.5% °C⁻¹
175 and 4.7% °C⁻¹, respectively, showing even stronger yield resilience to warming. For
176 soybean, its high vulnerability to warming would also be significantly reduced,
177 especially in the main producing countries, Brazil, Argentina and India (Fig. 3d). The
178 SOC strategy would reduce soybean yield loss by 6.4% °C⁻¹ in South America (Fig. 3d).

179 Globally, 53.2%, 67.8%, 51.8% and 71.6% of planting area for maize, wheat, rice
180 and soybean, respectively, could benefit from improved crop resilience due to increased
181 SOC, covering 60.0% of global total planting area (Fig. 1, 3 and Supplementary Fig. 4).
182 Among these area, 77.1%, 95.9%, 90.2% and 88.3% of maize, wheat, rice and soybean,
183 respectively, have experienced yield loss due to warming (i.e., TRI<0). For most of the

184 cropland that have already benefited from warming, i.e., with original $TRI > 0$, SOC
185 improvement has only minimum effect on yield resilience, especially for wheat and rice.



187 **Fig. 3. The estimated global TRIs (% °C⁻¹) of four crops with SOC improvement.** (a) maize,
 188 (b) wheat, (c) rice and (d) soybean. The box plots and the curve on the left show the frequency
 189 distribution of TRI at global scale. Orange and green boxes represent the overall results without
 190 and with SOC improvement, respectively. Green boxes at the bottom show the frequency
 191 distribution of TRI of six continents, Africa, South America, North America, Oceania, Asia and
 192 Europe, and the blank indicates insufficient data in Oceania (b-d).

193

194 **Building SOC to secure future food production**

195 Under future climate change, temperature will continue to increase and crop yields are
 196 expected to decrease. Over the growing seasons, the average temperature can increase
 197 by 0.18-0.21°C, and 1.18-1.44°C in 2050 under RCP 2.6 and RCP 8.5, respectively
 198 (Table 1 and Supplementary Fig. 5). Without any improvement to the SOC level, a total
 199 of about 15.0 million tonnes of the four crops would be lost in 2050 under RCP 2.6 due
 200 to warming (Table 1), leaving 60.0 million people suffering from food insecurity. The
 201 loss of production would mainly occur in South America (4.7 million tonnes) and Africa
 202 (4.8 million tonnes). The total production loss and the food insecure population would
 203 be tripled under RCP 8.5. The largest loss of production can be seen for maize, mainly
 204 due to yield loss and relatively large production area (Table 1).

205

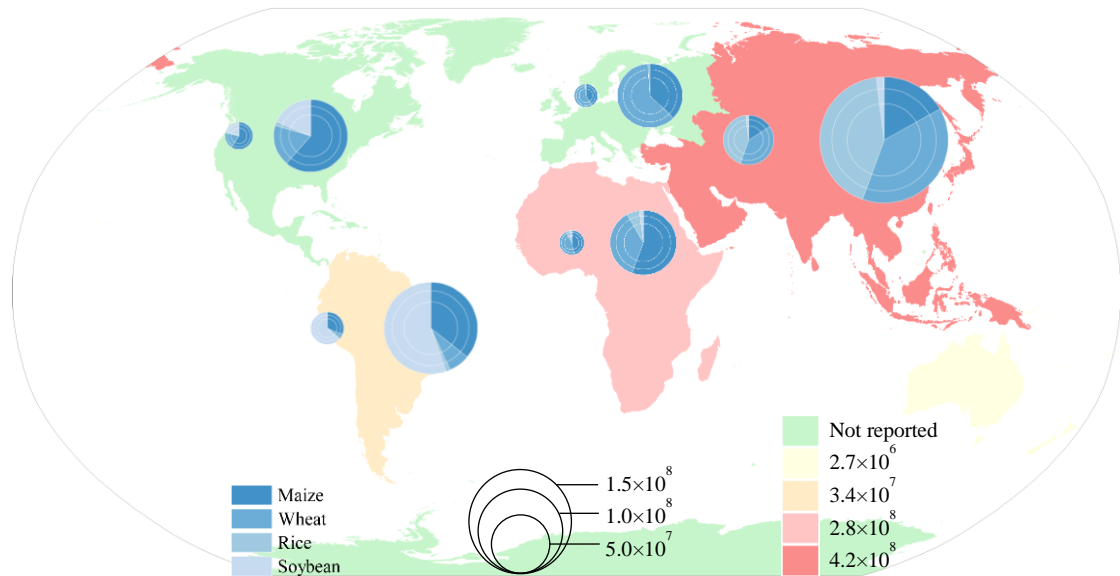
206 Table 1. Changes in temperature (°C) and warming-induced crop production (million
 207 tonnes) in 2050 relative to 2020 level under two climate scenarios.

Crops	Temperature increase		Production change without SOC improvement		Production change with SOC improvement	
	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5
Maize	0.19 (±0.12)	1.42 (±0.31)	-7.5 (±4.6)	-45.7 (±10.1)	-1.4 (±0.9)	1.3 (±0.3)
Wheat	0.21 (±0.06)	1.44 (±0.17)	-3.5 (±1.1)	-13.9(±1.6)	3.2 (±1.0)	31.7(±3.7)
Rice	0.18 (±0.04)	1.18 (±0.24)	-0.2 (±0.0)	-2.9 (±0.6)	5.0 (±1.0)	30.3 (±6.2)
Soybean	0.20 (±0.12)	1.39 (±0.27)	-3.8 (±2.3)	-26.7 (±5.1)	-0.5 (±0.3)	-2.9 (±0.6)
Total	0.20 (±0.06)	1.36 (±0.20)	-15.0 (±4.8)	-89.3 (±13.2)	6.4 (±2.0)	60.4 (±8.9)

208

209 However, our analysis showed that with improved yield resilience due to SOC
210 improvement, the warming-induced yield loss can be largely minimized or even
211 reversed. Compared with current SOC levels, improving soil could increase total
212 production of maize, wheat, rice and soybean by 0.6%-1.0% under RCP 2.6, and 4.3%-
213 6.7% under RCP 8.5 in 2050, which would significantly reduce yield loss for maize and
214 soybean, and lead to a global net yield gain for wheat and rice, relative to the reference
215 scenario without SOC improvement. The global production of these four crops would
216 increase by 6.4-60.4 million tonnes, depending on the climate scenario (Table 1). With
217 global efforts to enrich soil carbon, food systems are predicted to provide additional
218 49.9, 99.7 and 149.6 million tonnes of food that would otherwise lost due to warming,
219 which would be enough to feed an additional 187.9, 375.8, and 563.7 million people in
220 2030, 2040 and 2050 under RCP 8.5, respectively (Fig. 4). Asia would benefit the most
221 from SOC improvement. An additional 78.5, 157.0 and 235.5 million people could be
222 fed in 2030, 2040 and 2050 under RCP8.5, respectively (Fig. 4). Among the four crops
223 in Asia, wheat and rice contribute more than 90% to the increase of food production. In
224 Africa, an additional 21.2, 42.4 and 63.6 million people are expected to avoid hunger
225 in 2030, 2040 and 2050 under RCP8.5, respectively, mainly due to the contribution of
226 maize (Fig. 4). Other areas would also benefit from improved yield resilience owing to
227 increased soil carbon content (Fig. 4).

228



229

230 **Fig. 4. Increased food secure population (people) with improved soil.** The results
 231 are aggregated by continents. A pair of pies in each continent correspond to RCP 8.5
 232 (left) and RCP 2.6 (right) climate scenarios. Pies from the inside out indicate the results
 233 in 2030, 2040 and 2050, and the area of the pie represents the predicted size of increased
 234 food secure population. The background map shows the number of people
 235 undernourished in 2020¹. The undernourished people consume calories below the
 236 minimum energy requirement for an active and healthy life, and food secure population
 237 indicates that an individual's dietary calorie requirements are fully met.

238

239 Discussion

240 This study specifically investigated partial crop yield response to warming by
 241 excluding other factors (e.g., precipitation, crop variety, management), showing
 242 relatively comparable findings with other relevant studies. Globally, rising temperature
 243 caused maize, wheat and soybean yield losses on average, but with spatial divergence
 244 (Fig. 1). For instance, crop in high-latitude regions would benefit from climate warming
 245 due to the relief of chilling³⁴. Rice yield was less affected by rising temperature
 246 compared with the other three major crops, consisted with previous meta-analyses and
 247 statistical modeling^{5,13}. More irrigated area of rice in the main producing country may
 248 bridge the water deficit associated with warming³⁵. Note that the yield loss per °C of

249 global average warming for maize and wheat was smaller than that found in previous
250 studies^{5,6}. A major reason is that we further isolated the effects of nitrogen and
251 phosphate fertilizer application. Fertilizer additions can meet higher nutrient
252 requirements of crops under climate change^{36,37}. With SOC improvement, the yield
253 losses due to warming are predicted to be reduced or even reversed, and therefore the
254 food demands of tens to hundreds of millions of people worldwide would be met.

255 While there have been studies investigating the relationships between crop yield and
256 climate factors, there has been a lack of field evidence to isolate the role of soil in
257 building yield resilience to climate warming¹⁶. However, some existing understanding
258 and evidence can still imply the importance of soil system. A recent report from on-
259 farm trials in China suggests that high-quality soils can reduce the sensitivity of crop
260 yield to climate variability and stabilize crop yield¹⁶. Compared with soils of low quality,
261 high-quality soils are proven to improve yield under climate change by an average of
262 1.7%¹⁶. This study provides field evidence to our findings at the global scale that soil
263 improvement can increase resilience of the soil-crop system to climate change (i.e., soil
264 resilience, crop resilience and resilience of the integrated system) and help secure future
265 crop production. Globally, the benefits of increased SOC are particularly pronounced
266 in wheat cropping systems (Table 1), and this negative-to-positive effects of improved
267 soil on yield also appeared in regional cases¹⁶. More importantly, our study indicates
268 that for regions that are more susceptible to warming, increasing SOC would lead to
269 greater yield resilience. For instance, in Africa that has the highest prevalence of
270 undernourishment (19% in 2018-2020)¹, the TRI of maize and soybean can be increased
271 by $\sim 7\% \text{ } ^\circ\text{C}^{-1}$ with SOC improvement, doubling the global average. In these warmer and
272 less irrigated areas, increasing SOC would prominently alleviate the heat stress on crops
273 (Supplementary Fig. 4, 6). However, SOC above 2% would not result in additional
274 benefits to crop yields (Fig. 2). The threshold effects of SOC was also detected in field
275 experiments²⁴. Currently, SOC content is below 1.5% in two-thirds of planting grids
276 (Supplementary Fig. 2), which leaves great potential to stabilize crop yield under
277 warming by improving SOC.

278 Notably, the mechanisms by which improved soil reduces the climate impact on

279 crops are not fully known. Soil health management by increasing SOC can increase
280 crop resilience under extreme climate stress^{22,26,38}, which is likely to ensure food
281 security under climate change at regional and global scales. Specifically, SOC
282 underpins soil structure, soil formation, water cycling and nutrient cycling²⁰. Poor soil
283 structure (e.g., soil compaction) lowers root biomass. Increasing SOC concentration
284 could therefore increase the porosity across different soil textures³⁹, which promotes
285 root growth, and nutrient and water uptake of crops under climate change⁴⁰. Increased
286 organic matter can increase soil water holding capacity, thereby alleviating the damage
287 of heat and drought and increasing resilience of maize⁴¹. The crop is less sensitive to
288 heat in medium- and fine- textured and carbon rich soils, partially due to restricted water
289 loss through evapotranspiration⁴². In this study, compared with wheat and soybean,
290 maize and rice would benefit less from improving SOC, probably because maize as C4
291 plant has smaller stomatal conductance to concentrate CO₂^{43,44}, and rice are often
292 irrigated and less water-stressed. Field experiment showed that rice could benefit from
293 a higher temperature when soil nutrients keep up with the demand³⁶. Given that higher
294 crop biomass returns more C into soil⁴⁵, the interaction between yield and SOC increase
295 presents a positive feedback²⁴. SOC and TN losses, which were pre-simulated by the
296 process-based model under a 3°C warming, would reduce wheat yield by 13% and
297 maize yield by 19%⁴⁶. However, few studies have achieved timely feedback on the
298 interaction between crop yield resilience and soil properties, primarily because multiple
299 factors and complex processes are involved, and the role of soil cannot easily be isolated
300 in the overall yield resilience observation. It is expected that the relationship between
301 TRI and soil might be revealed if paired warming experiments could include diverse
302 crop-soil-environment conditions.

303 It should also be noted that the ability of building SOC to improve yield resilience
304 may be limited in certain regions (Supplementary Fig. 4), and management practices
305 should be well examined. Due to the increase of soil water retention, the negative effects
306 of increasing SOC on maize, wheat and soybean may occur in wet regions with poorer
307 drainage⁴². The increase of SOC significantly increases the specific heat capacity of the
308 soil⁴⁷, which causes soil to warm slowly during the wheat rejuvenation period⁴². The

309 areas with greater benefits after improving SOC could be given higher priority in
310 regional or national planning (Fig. 1, 3 and Supplementary Fig. 4). For areas with higher
311 poverty and undernourishment, smallholders may not be able to afford costly
312 measures⁴⁸, so effective economic and policy incentives would need to be in place^{25,49}.
313 Food security and other benefits, including ecosystem service and negative
314 emissions^{50,51}, can further justify government investment. Fast and effective action is
315 required globally^{52,53}.

316 Soil management should also well reflect the level of confidence in both science and
317 practice. The potential SOC in our study considered the management scenario with
318 cover cropping, manure application and conservation tillage, it would be higher than
319 the potential based on the meta-analysis with applicable constraints⁵⁴. Compared with
320 “4p1000” initiative, potential SOC was simulated with a relatively conservative
321 sequestration rate, reaching only 26% of the “4p1000” target³¹. SOC losses due to
322 warming was not specifically considered in this estimation. Regarding the regional
323 sequestration potential, long-standing cropping regions in Europe, North America and
324 Asia show higher rate (Supplementary Fig. 2), which is associated with large carbon
325 losses due to intensive land use, leaving more room for carbon accumulation^{33,55}. From
326 a technical perspective, increasing organic inputs (e.g., crop residue, cover crop and
327 manure) is considered as the most effective measure to accumulate SOC in cropland^{56,57}.
328 Crop residue return is a feasible and efficient way to increase SOC density by 0.69 Mg
329 C ha⁻¹ yr⁻¹ under a high retention rate⁴⁵. Irrigation of arid and semiarid regions may
330 increase SOC through increase biomass production⁵⁸. Optimal agricultural management
331 in China is estimated to sequester 2.4 Pg C into cropland before 2050, with higher
332 potential for paddy soil (26.1 Mg C ha⁻¹)^{29,59}. Notably, soil N₂O and CH₄ emissions
333 may change as a result of management improvement, which should be further studied
334 and well balanced in estimating crop yield and climate benefits^{60,61}.

335 Future work is urgently required to further improve yield resilience and future yield
336 estimation, and investigate potential unintended consequences. Modeling uncertainties
337 may arise from data limitation, choice of GHG emission scenarios, climate model
338 projections and understanding of mechanisms. For instance, although precipitation

339 change was included in our modeling analysis, no significant trends were detected. The
340 lack of irrigation in the model, due to data limitation, may have partially missed the
341 water impacts. If crop-specific irrigation data with high spatio-temporal resolution
342 become available, the cooling and water supply effects of irrigation could be better
343 modeled^{62,63}. Spatially referenced and crop-specific data on fertilization, if become
344 available, could also help improve model simulations. Additionally, since TRI is a
345 simplification of the actual response of crop to temperature change, future studies could
346 further include biophysical processes to better understand crop-soil-environment
347 interactions²⁰. Furthermore, socioeconomic drivers of food supply and demand besides
348 domestic production of crops, e.g. trade⁶⁴, are important to assess the hunger and food
349 secure population. Finally, acting on soil may lead to other unintended negative
350 environmental (e.g., water, nutrients input), social (e.g., competitive use of resources)
351 and even economic outcomes (e.g., shift of investment), and these should be avoided to
352 the greatest extent possible⁶⁵⁻⁶⁷. Given the multiple benefits of building SOC, the
353 priority should be given to take efficient management steps considering the integrated
354 crop-soil-environment system to close the yield gap and ensure the security of food
355 supply.

356 **Methods**

357 **Yield response to temperature.** On the basis of historical data reflecting crop yields,
358 climate and management, the yield models (Eq. 1) were developed for individual crops
359 (i.e., maize, wheat, rice, and soybean), and then used to identify yield's partial response
360 to temperature (i.e., TRIs or temperature response indices, Eq. 2). Historical yields
361 (1981–2010) of main crops, maize (major), wheat (winter), rice (major) and soybean
362 with the spatial resolution of 0.5°, were derived from GDHY v1.3, a global dataset of
363 historical yields of major crops with a data combination of agricultural census, satellite
364 and model⁶⁸. Historical daily weather data were sourced from the AgMERRA, a
365 post-processing dataset of the NASA Modern-Era Retrospective Analysis for Research
366 and Applications (MERRA) for agricultural modeling⁶⁹. Average temperature (T), total
367 precipitation (P) and solar radiation (R) of crop growing season were extracted
368 according to phenology of each crop⁷⁰. Both linear and quadratic forms of temperature
369 and precipitation were characterized in the model to account for the non-linear response
370 of crop yields to climate (Eq. 1). The model has been widely applied in the studies of
371 yield-climate relationship^{5,71,72}, and fully verified^{73,74}. Nitrogen ($Nfer$) and phosphorus
372 ($Pfer$) fertilizers⁷⁵ were further included to better estimate the impacts of management
373 on crop yields. The input datasets with higher resolution were integrated to 0.5°, to be
374 consistent with the resolution of yields (Supplementary Table 1). The model structure
375 is shown as:

$$\begin{aligned} 376 \quad \ln(Y_{i,t}) = & \beta_{0,i} + \beta_{1,i}t + \beta_{2,i}T_{i,t} + \beta_{3,i}T_{i,t}^2 + \beta_{4,i}P_{i,t} + \beta_{5,i}P_{i,t}^2 + \beta_{6,i}R_{i,t} + \\ 377 \quad & \beta_{7,i}Nfer_{i,t} + \beta_{8,i}Pfer_{i,t} + \varepsilon_{i,t} \end{aligned} \quad (1)$$

378 where $\ln(Y_{i,t})$ represents the logarithm of crop yields. Models of four crops were
379 developed for grid cell i ($0.5^\circ \times 0.5^\circ$). The time term (t) was used to simulate the
380 possible impact of other factors on crop yields (Supplementary Fig. 7), e.g. cultivar
381 shifts. As showed in this study (Supplementary Fig. 8) and elsewhere^{5,76}, including the
382 quadratic form (e.g., T^2) can better simulate the nonlinear responses of the crop to
383 warming. The response of crop yield to temperature was measured by the partial

384 derivative of equation (1)⁷⁶:

$$385 \quad \partial \ln(Y_i) / \partial T_i = \partial Y_i / (Y_i \times \partial T_i) = \beta_{2,i} + 2\beta_{3,i} T_i \quad (2)$$

386 where $\partial Y_i / Y_i$ represents the proportion of yield change in grid cell i . Temperature
387 response index (TRI_i) was defined as the yield change (%) per °C of temperature change,
388 which can be measured as⁷⁷:

$$389 \quad TRI_i \approx (\beta_{2,i} + 2\beta_{3,i} \bar{T}_i) \times 100\% \quad (3)$$

390 where \bar{T}_i is the average temperature of the crop growing season during 1981–2010.
391 The parameters $\beta_{2,i}$ and $\beta_{3,i}$ represent the location-specific response of yield to
392 temperature change. TRI varies spatially, with values determined by grid level
393 parameters and local climate. The TRI at the continental and global scales was
394 calculated on the basis of the area-weighted average, considering geographic
395 distribution of crop harvest area derived from a gridded dataset⁷⁸. Modeling and
396 analysis were batched in Python version 3.6.

397

398 **Estimation of the role of soils.** Soil plays a crucial role in providing nutrients,
399 maintaining relatively stable environment, and supporting crop growth as a whole^{24,26}.

400 We hypothesized that the spatial heterogeneity of TRI correlates to the differences of
401 soil properties across space. The machine learning approach, random forest²⁷, was
402 employed to estimate the correlation between TRI and soil properties due to its efficient
403 modeling performance. WISE30sec dataset⁷⁹ was selected for its comprehensive soil
404 properties and data sources. Six key soil properties (0–30 cm), SOC (%), total nitrogen
405 (TN, %), cation exchange capacity (CEC, cmol kg⁻¹), clay content (%), sand content
406 (%), and pH were extracted by depth-weighted method and resampled to 0.5° resolution.
407 Random forest models were built for individual crops, maize (n=13935), wheat
408 (n=8303), rice (n=8925) and soybean (n=5935). Model training and testing were
409 implemented with the Scikit-learn Library in the Python. Three key parameters needed
410 to be adjusted for training the models, the number of trees in the forest ($n_estimators$),
411 the maximum depth of the tree (max_depth) and the number of soil variables in the

412 random subset at each node (*max_features*), for the trade-off between over-fitting and
413 high bias of the model. When training, all decision trees in the forest were formed by
414 the method of bagging sampling with replacement. In each training set, about one third
415 of samples were left out as out-of-bag data, which were then used to estimate the
416 generalization error.

417 The key soil properties were determined by the importance and the interaction
418 between *TRI* and each soil variable. The former was measured by calculating the
419 increase of prediction error after randomly permuting the target soil variables in the
420 random forest model. The greater the increase in error, the more important the variable
421 is. The latter was visualized by centered individual conditional expectation (c-ICE)
422 plot²⁸. The curve in the plot showed how the *TRI* changes when a soil variable changed
423 after considering the average effects of other variables. All individual samples were
424 centered at a certain point in the plot, which was helpful in examining the cumulative
425 effect of the selected feature. Besides, the c-ICE plot visualized the condition of each
426 individual sample (shaded areas on both sides of the curve, Fig. 2).

427 Through these analysis, SOC content was determined to be the most important soil
428 factor affecting crop response to temperature change, followed by TN. For global soil,
429 a linear relationship was observed between SOC and TN ($R^2=0.91$), and this was further
430 built into the equation to estimate future TRI with improved SOC. In other words, the
431 improved yield resilience would be realized by feeding in SOC potential and associated
432 TN change. Specifically, SOC potential was based on the field-supported assumption
433 that best management could help soil carbon accumulation and reach a relatively high
434 and stable SOC level⁵⁴. In this analysis, SOC data from Zomer, et al.³¹ was used for its
435 global-scale availability and accuracy. The medium scenario was considered here with
436 the sequestration rate of $0.56 \text{ t C ha}^{-1} \text{ yr}^{-1}$ (0.9 Pg C yr^{-1} globally) lasting at least 20
437 years³¹, by implementing practices including cover cropping, manure application, and
438 reduced tillage. The unit (%) and resolution (0.5°) of SOC data were converted and
439 integrated to match the random forest model. The average TN content modeled through
440 the linear model was 0.19% (0.07-0.49%, 95% percentile).

441

442 **Crop yields under future climate.** With the changing temperature in the future, crop
 443 yield would respond differently among crops following individual TRI pattern. The
 444 highest and lowest additional radiative forcing scenarios (RCP2.6 and RCP8.5), 2.6 and
 445 8.5 W m⁻², respectively, were considered for future climate scenarios^{80,81}. The monthly
 446 temperatures of two scenarios were obtained from the outputs of Global climate models
 447 (GCMs) in CMIP6. According to the latest comparison of the equilibrium climate
 448 sensitivity (ECS)⁸², we chose three GCMs with lowest ECS from different institutes,
 449 including INM-CM5-0, CAMS-CSM1-0 and NorESM2-MM. In order to be spatially
 450 consistent with other data, we aggregated the temperature data of above GCMs to a 0.5°
 451 resolution. We averaged all model outputs for a relatively stable and accurate
 452 temperature projection. According to the phenology data of maize, wheat, rice and
 453 soybean, we extracted growing season temperature between planting and harvest date.
 454 Warming trends of crops in growing season were detected by linearly fitting the
 455 temperature from 2015 to 2100 in each grid. Then, we calculated the warming level in
 456 2030, 2040 and 2050 relative to 2020 by using the above parameter of trends. The future
 457 crop yield changes as a result of yield response and future warming.

458

459 **Estimation of increased feed.** Future production under changing climate varies with
 460 SOC strategies (i.e., with vs. without SOC improvement), which would lead to different
 461 estimates of food secure population (FSP) that could be met with full dietary calorie
 462 requirements. The production was determined by yield depending on crop-specific TRI,
 463 and harvest area simulated under future climate⁸³. The *FSP* was calculated as follows:

$$464 \quad FSP_{c,j,t} = TRI_{c,j} \times \Delta T_{c,j,t} \times Y_{c,j} \times H_{c,j} \times CC_j / PC_{c,t} \quad (4)$$

465 where $TRI_{c,j,t}$ indicates the temperature response index of continent c , crop j and year t .
 466 $\Delta T_{c,j,t}$ is the temperature change of the crop growing season under two climate
 467 scenarios compared to current level. $Y_{c,j}$ and $H_{c,j}$ represent the yield and harvest area⁸³,
 468 which were assumed to be constant. Using four variables described above, we
 469 calculated the production change due to future warming. CC_j is the calorie content per
 470 unit of crop j ⁸⁴. $PC_{c,t}$ is the calorie need per capita per year⁸³, which was simulated
 471 under two scenarios, business-as-usual (BAU) and towards sustainability (TSS)

472 scenarios, corresponding to RCP8.5 and RCP2.6, respectively, to be consistent with
473 future climate scenarios. $PC_{c,t}$ of two scenarios was estimated based on the different
474 forward-looking assumptions, e.g., economic growth and policy⁸³. The $FSP_{c,j,t}$ with and
475 without SOC strategy was estimated with their corresponding $TRI_{i,j,t}$. The FSP , and
476 increased food secure population (ΔFSP , difference between FSP with and without
477 SOC strategy) were estimated for year t (i.e., 2030, 2040 and 2050).

478

479 **Data availability**

480 All the source data of this study are freely available online and referenced within the
481 paper. The summary of the dataset is included in the Supplementary Information.

482

483 **Code availability**

484 The code used to perform analyses in this study is generated in Python36 and is
485 available upon reasonable request.

486

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675

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681

682 **Author contributions**

683 Z. Q. and Y. H. conceived and designed the research. X. D. and Z. Q. developed data-
684 model simulations and analyzed results, with key inputs from Y. H., W. Y. and W. Z. on
685 model improvement. P. C., W. D. and P. S. helped with interpretation of the results and
686 discussion. X. D., Y. H. and Z. Q. wrote the manuscript with contributions from all
687 authors.

688

689 **Competing interests**

690 The authors declare no competing interests.