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1 **Delayed use of bioenergy crops might threaten climate and food security**

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30 **Abstract**

31 **The potential of mitigation actions to limit global warming within 2 °C<sup>1</sup> might rely**  
32 **on the abundant supply of biomass for large-scale bioenergy with carbon capture**  
33 **and storage (BECCS) that is assumed to scale up significantly in the future<sup>2-5</sup>.**  
34 **However, the detrimental effects of climate change on crop yields may reduce the**  
35 **capacity of BECCS and threaten food security<sup>6-8</sup>, thus creating an unrecognized**  
36 **positive feedback loop on global warming. We quantified the strength of this**  
37 **feedback by implementing the responses of crop yields to increases in growing-**  
38 **season temperature, atmospheric CO<sub>2</sub> concentration and intensity of nitrogen (N)**  
39 **fertilization in a compact Earth system model<sup>9</sup>. Exceeding a threshold of climate**  
40 **change would cause transformative changes in social-ecological systems by**  
41 **jeopardizing climate stability and threatening food security. If global mitigation**  
42 **alongside large-scale BECCS is delayed to 2060 when global warming exceeds**  
43 **~2.5 °C, then the yields of agricultural residues for BECCS would be too low to**  
44 **meet the Paris goal of 2 °C by 2200. This risk of failure is amplified by the**  
45 **sustained demand for food, leading to an expansion of cropland or intensification**  
46 **of N fertilization to compensate for climate-induced yield losses. Our findings**  
47 **thereby reinforce the urgency of early mitigation, preferably by 2040, to avoid**  
48 **irreversible climate change and serious food crises unless other negative-emission**  
49 **technologies become available in the near future to compensate for the reduced**  
50 **capacity of BECCS.**

51 One hundred and ninety-one parties responsible for 97% of global anthropogenic  
52 greenhouse-gas (GHG) emissions have joined the Paris Agreement with the objective  
53 to limit global warming by this century to 2 °C, while pursuing efforts to stay within  
54 warming of 1.5 °C<sup>1</sup>. Global warming in 2021 is approaching 1.2 °C above the 1850–  
55 1900 average<sup>2</sup>. Achieving all pledges under the nationally determined contributions  
56 may limit warming just below 2 °C, which requires steep emission reductions in the  
57 current decade<sup>10</sup>. Many mitigation scenarios nonetheless assume that climate change  
58 could be mitigated by negative-emission technologies such as bioenergy with carbon  
59 capture and storage (BECCS), which would be deployed in the second half of this  
60 century to benefit from technological advances<sup>3-5</sup>. However, large-scale deployment of  
61 BECCS faces biophysical, technical and social challenges<sup>11,12</sup>. An overreliance on  
62 BECCS could delay other decarbonizing technologies and fail to meet the Paris goal  
63 under overshoot scenarios<sup>13</sup>. Early actions are important to avoid irreversible climate  
64 change and drastic shifts in land use<sup>14</sup>. The USA, the EU and China, the three largest  
65 emitters of carbon dioxide (CO<sub>2</sub>), aim to achieve carbon (C) neutrality by either 2050  
66 or 2060<sup>1</sup>. The effectiveness of these pledges depends largely on the remaining emissions  
67 in countries that have not yet made such pledges and on feedbacks in the carbon-climate  
68 systems<sup>15</sup> that have not been fully recognized by current integrated assessment models  
69 (IAMs)<sup>2</sup>.

70 Climate change is projected to be decelerated by dramatically abating CO<sub>2</sub> emissions  
71 from fossil fuels<sup>10</sup>, but large-scale negative-emission technologies at a global scale are  
72 required in most of the scenarios limiting global warming to 2 °C<sup>2</sup>. Retrofitting coal-  
73 fired power plants to BECCS, which substitutes fossil fuels by generating electricity  
74 with biomass from lignocellulosic energy crops or residues and removes CO<sub>2</sub> from the  
75 atmosphere, is assumed to be a cost-effective option in IAMs<sup>16,17</sup>. Capturing CO<sub>2</sub> from  
76 the combustion of agricultural residues from food crops (e.g. maize and rice) or  
77 dedicated energy crops and storing it in geological sites are proposed to achieve the 2  
78 or 1.5 °C target in the sixth assessments of the Intergovernmental Panel on Climate  
79 Change (IPCC)<sup>2</sup>. Using the biomass from agricultural residues as feedstocks to generate  
80 electricity is more economical than growing dedicated energy crops (e.g.  
81 *Miscanthus*)<sup>18,19</sup>. Since the population and food demand from developing countries are  
82 both increasing<sup>20</sup>, transferring residues of agricultural crops to BECCS would reduce  
83 the competition of new dedicated energy crops with food production for resources such  
84 as land, fertilizers and water<sup>21</sup>. Future crop yields, however, may decline due to the

85 detrimental effects of climate warming<sup>6-8</sup> if strong mitigation actions are delayed,  
86 thereby reducing the capacity of BECCS for mitigation (**Fig. 1**). These feedbacks have  
87 not been considered in current IAMs<sup>2-4</sup>, which rely on the availability of agricultural  
88 residues<sup>18</sup> or dedicated energy crops<sup>5</sup> for BECCS at a large scale. The impacts of  
89 BECCS on the food-climate-energy nexus have been assessed in the literature (**Table**  
90 **S1**), but the feedbacks of reduced BECCS capacity to climate warming are unclear.  
91 Additional measures such as irrigation<sup>22</sup>, adaptation of crop cultivars<sup>23</sup> and  
92 conservation agriculture<sup>8</sup> are helpful for increasing the productivity of cropland, but the  
93 widespread water scarcity due to the increasing frequency and intensity of droughts  
94 around the globe<sup>24</sup> may limit the potential of those adaptation measures for increasing  
95 crop yields. A quantification of the impact of reduced crop yields on climate change  
96 mitigation is needed for estimating the interactions between biological and techno-  
97 economic components<sup>25</sup> of the Earth system, recognizing the tipping points in social-  
98 ecological systems<sup>26</sup> and assessing the effectiveness of emission pledges to meet the  
99 2 °C goal in the Paris Agreement<sup>1</sup>.

100

### 101 **Scenarios of climate mitigation with BECCS**

102 We examined how the benefits of ambitious mitigation with large-scale BECCS aimed  
103 at meeting climate and food targets could be offset due to reduction in crop yields under  
104 climate change (**Fig. 1**). We quantified the impact of climate change on crop yields in a  
105 set of scenarios, where global large-scale mitigation is initiated at the start of each  
106 decade from 2030 to 2100. When ambitious mitigation starts, we assumed that policy  
107 reduces fossil emissions from the baseline scenario of the Shared Socioeconomic  
108 Pathway (SSP) 5-8.5 to the lower-emission scenario of SSP2-4.5<sup>2</sup>, while BECCS is  
109 deployed using agricultural residues globally (**Fig. S1** and **Methods**). There are other  
110 decarbonizing technologies taking place from 2030 to meet emission pledges in the  
111 SSP2-4.5 scenario, but they imply a lack of negative emissions to be compliant with  
112 net-zero emissions<sup>2</sup> by 2100. SSP5-8.5 is worse than what seems to be “business-as-  
113 usual” emissions<sup>27</sup>, but phasing out fossil fuels rapidly and deploying BECCS moves  
114 our projections close to the IPCC low-warming scenarios<sup>2</sup>. Cumulative emissions  
115 during 2021–2050 in our scenario with mitigation starting in 2030 are 380 Gt C from  
116 fossil fuel reduction alone, with additional negative emissions of –120 Gt C from  
117 BECCS by 2050 (**Fig. S2**). These net emissions (260 Gt C) are higher than SSP 1-1.9  
118 (150 Gt) but similar to SSP1-2.6 (250 Gt C)<sup>2</sup>, which meets the Paris goal of 2 °C<sup>1</sup>.

119 In our assumptions, the area of land converted from forests or marginal lands to  
120 cropland and the intensity of N fertilization depend on the food demand in 2030 (e.g. a  
121 higher food demand elicits more land conversion from forests or marginal lands to  
122 cropland). The impacts of transferring C associated with land-use change (LUC) from  
123 soils and vegetation to the atmosphere, and of the terrestrial emissions of methane and  
124 nitrous oxide (N<sub>2</sub>O) on climate change, were simulated using the OSCAR Earth system  
125 model<sup>9</sup>. We estimated the average growing-season temperature for maize, rice and  
126 wheat by country based on global crop calendar data (**Methods**). We considered a  
127 scenario where half of cropland expansions from forests and marginal lands<sup>28</sup> were used  
128 to grow new energy crops and the other half were used to grow food crops with the  
129 residues used for BECCS. Since technologies increase crop yields, we considered two  
130 scenarios, where the N use efficiency would be enhanced globally<sup>29</sup> or the growing  
131 season was brought forward or delayed by one month to increase the crop yield by  
132 country. Negative emissions from BECCS were estimated based on the amount of C  
133 produced as biomass and an efficiency of capturing 90% of the CO<sub>2</sub> emitted by BECCS  
134 plants<sup>30</sup>, while we examined the climate benefits for different types of bioenergy.  
135 Interactions between climate change and the global C cycle have been calibrated using  
136 the results of models in Coupled Model Intercomparison Project (CMIP)<sup>31</sup> Phase 5 and  
137 6. By running Monte Carlo simulations with OSCAR<sup>9</sup>, our results are representative of  
138 the CMIP ensembles<sup>31</sup> and the variation in the yield-climate relationships.

### 139 **Relationships between crop yields and climate**

140 We estimated the relationships between crop yields ( $Y$ ) and the average growing-season  
141 temperature ( $T_{am}$ ), atmospheric CO<sub>2</sub> concentration ( $X_{CO_2}$ ) and N fertilization ( $Z_{nit}$ )  
142 using global data. First, crop yield peaks at an optimal temperature ( $T_{opt}$ ) and decreases  
143 when temperatures increase beyond  $T_{opt}$  due to increasing water loss by  
144 evapotranspiration and lower enzymatic activity in foliar photosynthesis when  $T_{am}$   
145 exceeds a criterion<sup>7,32</sup> (**Fig. 2a,b**). In our central case, we used a quadratic function to  
146 fit the yields of wheat and maize from field-warming experiments and local process-  
147 based or statistical crop models (**Table S2** and **Supplementary Data Set 1**) by  
148 constraining  $T_{opt}$  (**Table S3**). We considered that the yield of wheat would be reduced  
149 to 1% of its maximum value when  $T_{am}$  exceeded 29 °C ( $T_{dam}$ )<sup>33</sup> to represent the effect  
150 of heat exposure over the whole growing season. Short exposures to temperatures above  
151 40 °C with low humidity may be lethal<sup>34</sup>, but the effect of extreme heat events is not  
152 considered due to the lack of direct evidence. Following this, we examined the impact

153 of increasing  $T_{opt}$  or  $T_{dam}$  by 1 °C or using data from field warming experiments only,  
154 which altered the  $Y-T_{atm}$  function moderately (**Fig. S3**). We examined the linear or  
155 nonlinear  $Y-T_{atm}$  functions to fit the sensitivity of wheat yield to temperature for  $T_{atm}$   
156  $\leq 15$  °C from field-warming experiments<sup>7</sup>, which led to a faster decline in crop yield for  
157  $T_{atm} < 25$  °C than our estimate (**Fig. S3**).

158 Second, elevated  $X_{CO_2}$  increases the rate of plant photosynthesis of C-3 crops and the  
159 yields of wheat and rice<sup>35</sup>. This effect saturates when  $X_{CO_2}$  exceeds 700 ppm (**Fig. 2c**),  
160 likely due to the co-limitation of soil nutrients and water<sup>36</sup>. We used a quadratic function  
161 to fit the saturating yield of wheat grown with ample water and nutrients at an optimal  
162 temperature in free-air  $CO_2$ -enrichment experiments<sup>37</sup> for  $X_{CO_2} < 700$  ppm ( $P < 0.001$ )  
163 and assumed a flat response for  $X_{CO_2} > 700$  ppm. This empirical sensitivity of  $Y$  to  $X_{CO_2}$   
164 is similar to the sensitivity obtained with crop models for wheat in the Netherlands and  
165 rice in Japan but is larger for maize as a C-4 crop in Tanzania that is exposed to higher  
166 temperatures<sup>38</sup> (**Fig. S3**). Third, N addition is beneficial for the growth of crops, but the  
167 effect decreases with excessive inputs<sup>39</sup>. We used a logarithmic function to fit the yields  
168 of rice, wheat, maize and soybeans<sup>40</sup> by region from 1961 to 2019 after adjusting for  
169 the impacts of  $T_{atm}$ ,  $X_{CO_2}$  and precipitation (**Fig. 2d** and **Fig. S4**). The yield of rice  
170 increases by six folds when N fertilization increases from 5 to 100 kg ha<sup>-1</sup> but by 12%  
171 when it increases further from 100 to 150 kg ha<sup>-1</sup>.

172 The yield-climate relationships are compared among five agriculturally important  
173 countries (**Fig. S5**). Crop yield is more sensitive to warming at lower latitudes and more  
174 sensitive to N inputs in the USA than in other countries<sup>38</sup>. We assumed that the  
175 dependencies of crop yield on air temperature,  $CO_2$  concentration and N fertilization  
176 for a limited set of species could be generalized to energy crops due to the lack of  
177 consistent data for those specific cultivars. We adopted the parameters calibrated in a  
178 previous study<sup>9</sup> to prescribe regional responses of yield to precipitation due to the lack  
179 of data to estimate the relationship between crop yield and precipitation. Similar to a  
180 previous study<sup>6</sup>, the impact of precipitation was estimated to be low in our model (**Fig.**  
181 **S6**), but the compound effect of temperature and precipitation on crop yield deserves  
182 attention<sup>7,20</sup>. Our yield model is different from previous studies (e.g. ref<sup>6</sup>) using national  
183 crop yield from the Food and Agriculture Organization (FAO) data set<sup>40</sup>. However,  
184 identifying the impact of climate change on national crop yield<sup>40</sup> can be prevented in  
185 some regions where the impact of historical climate change was not strong enough yet

186 to reduce crop yield significantly<sup>6</sup>. It is important to further improve our crop yield  
187 model when data from field-warming experiments become available in a broader range  
188 of countries or the regional impacts of climate change on crop yields are more  
189 significant under global warming.

#### 190 **Feedbacks of reduced BECCS capacity to climate change**

191 Our simulations indicated that global warming would reach 2.5 °C (2.3–2.9 °C as the  
192 range of 90% uncertainty) in 2050, 2.7 °C (2.4–3.1 °C) in 2100 and 1.7 °C (1.2–2.6 °C)  
193 in 2200 (Fig. 3a), if large-scale mitigation alongside BECCS was initiated in 2040  
194 (Methods). Cropland area is expanded to meet the caloric target<sup>41</sup> of 2 million calories  
195 per day (Mcal d<sup>-1</sup>) per capita in 2030 for countries where the supply is below this  
196 threshold, and cropland area is maintained for other countries. Due to the detrimental  
197 effects of climate change on crop yields, there is a decline in global average per capita  
198 calories from 2.2 Mcal d<sup>-1</sup> in 2030 to 1.8 (1.6–2.0) and 2.1 (1.8–2.2) Mcal d<sup>-1</sup> in 2100  
199 and 2200, respectively if the benefits of technology<sup>29</sup> were not considered (Fig. 3b). In  
200 contrast, global warming is estimated to reach 3.4 and 4.2 °C in 2100, followed by a  
201 decrease to 2.6 and 3.7 °C in 2200, if ambitious mitigation is delayed to 2050 and 2060,  
202 respectively, because of a longer maintenance of fossil emissions and reduced biomass  
203 feedstocks for BECCS. We provided the relationship between the quantity of bioenergy  
204 from agricultural residues and the projected level of global warming in 2050, 2100 and  
205 2200 (Fig. S7), which could be implemented into IAMs<sup>2-5</sup>.

206 If climate-induced feedbacks on crop yields are not considered by maintaining crop  
207 yields and BECCS capacity at their levels simulated with current climatology in 2020,  
208 global warming will decrease by 0.3, 0.6 and 0.8 °C in 2200 when ambitious mitigation  
209 with BECCS is initiated in 2040, 2050 and 2060, respectively, relative to our central  
210 cases (see Fig. S8 for the temporal evolutions of global warming and crop calories in  
211 all scenarios). In addition, global warming will be lower than our central case, if 50%  
212 of marginal lands are used to grow dedicated energy crops (e.g. *Miscanthus*) rather than  
213 agricultural crops whose residues are used for BECCS, because energy crops produce  
214 more bioenergy than do agricultural crops through the recovery of agricultural  
215 residues<sup>30</sup>. Further, if afforestation is considered in addition to BECCS by converting  
216 marginal lands to forests, global warming will be lower than in the BECCS-only  
217 scenarios without afforestation (Fig. 3). Lastly, if agricultural residues are used to  
218 produce liquid bioethanol to replace vehicle oils without CCS or if the gas-fired power  
219 plants were retrofitted for BECCS, the climate benefits of bioenergy would be lower

220 than retrofitting coal-fired power plants for BECCS, due to the higher CO<sub>2</sub> emissions  
221 incurred. If the biomass is used for liquid biofuel production with a high efficiency of  
222 energy conversion (47.5%)<sup>43</sup>, then bioenergy at biorefineries generates less climate  
223 benefits than BECCS power plants if only 15% of CO<sub>2</sub> released at a high purity during  
224 the fermentation process to manufacture bioethanol is subject to CCS<sup>43</sup>, but generates  
225 more benefits than BECCS power plants if 55% of CO<sub>2</sub> in the fermentation process can  
226 be captured<sup>43</sup>. Given different types of bioenergy, the impact of the yield-climate  
227 feedback remains robust, which could lead to a failure of meeting the 2 °C goal<sup>1</sup> (**Fig.**  
228 **S9**).

229 After propagation of uncertainties, the probability of meeting the 2 °C goal<sup>1</sup> by 2200  
230 would be reduced from 47 to 4% after considering agricultural feedbacks when  
231 mitigation is initiated in 2050. If mitigation is initiated in 2040, this probability only  
232 decreases from 93 to 75% by considering agricultural feedbacks. We examined the  
233 sensitivity of our results to the choice of yield-temperature functions fitted to  
234 experimental data only, fitting the  $Y-T_{am}$  function to the sensitivity of crop yields to  
235 temperature<sup>7</sup>, increasing  $T_{opt}$  or  $T_{dam}$  by 1 °C when constraining the  $Y-T_{am}$  function, and  
236 adopting the  $Y-X_{CO_2}$  relationship for maize in Tanzania, wheat in the Netherlands or rice  
237 in Japan from crop models<sup>38</sup> (**Fig. S3**). The impact of feedbacks on failure to meet the  
238 2 °C goal<sup>1</sup> due to delayed mitigation remains robust, but the crop caloric production  
239 could be increased or decreased using those alternative yield-climate relationships (**Fig.**  
240 **3**). We did not account for all possible factors that could further limit BECCS capacity  
241 such as soil degradation<sup>12</sup> or imbalanced nitrogen-phosphorus supplies<sup>44</sup>, so our model  
242 may be optimistic and meeting the Paris goals<sup>1</sup> may require even earlier or more  
243 ambitious mitigation than we estimated.

#### 244 **Implications for food security**

245 The previous section demonstrated a failure of delayed mitigation to meet the climate  
246 goal<sup>1</sup> of 2 °C as climate warming reduces crop yields and BECCS capacity, but the  
247 demand on crops for food need to be considered in addition to bioenergy production.  
248 We assessed whether enlarging cropland area by converting marginal lands and forests  
249 to cropland would ameliorate the conflict between food crops and BECCS by  
250 considering their impact on the global C cycle through LUC emissions. To do so, we  
251 assumed that first marginal lands and then forests are converted to cropland or that N  
252 fertilization is increased (see **Fig. S10** for the spatial distributions of per capita cropland  
253 area and N fertilization in 2019) to meet higher caloric targets in 2030. The food supply

254 then depends on the responses of crop yields to climate change (**Methods**).  
255 Global mitigation by 2050 is needed to match the increasing food demand in the face  
256 of decreasing crop yields (**Fig. 4**). Global warming will be higher in 2100 due to LUC  
257 emissions but lower in 2200 due to more BECCS negative emissions when mitigation  
258 is initiated earlier than 2050. We decomposed the changes in GHG emissions into its  
259 drivers. Total emissions during 2041–2200 to meet a reasonable per capita caloric  
260 target<sup>41</sup> of 2 Mcal d<sup>-1</sup> would be 28 Gt C from the reduced terrestrial C sink, 10 Gt C  
261 from emissions induced by land-use change and 92 Gt C from terrestrial emissions of  
262 N<sub>2</sub>O (converted to equivalent CO<sub>2</sub>) (**Methods**) when mitigation is initiated in 2040 (**Fig.**  
263 **S11**). Converting marginal lands, rather than forests, to cropland will slow warming  
264 (see **Fig. S12** for the difference between these scenarios) but increase the demand of  
265 fertilizers<sup>44</sup>. In contrast, if mitigation is delayed to 2060, cropland expansion will  
266 accelerate global warming due to LUC and N<sub>2</sub>O emissions, because the effect of  
267 cropland expansion to increase BECCS will be overcome by the reduction of BECCS  
268 capacity caused by global warming. The effect of intensifying N fertilization alone on  
269 slowing global warming is smaller than in the scenarios of increasing the area of  
270 cropland (**Fig. S13**) due to larger terrestrial emissions of N<sub>2</sub>O (**Fig. S11**), saturation of  
271 N fertilization (**Fig. 2d**) and potential co-limitations by water and phosphorus<sup>45</sup>.

#### 272 **Impact of agricultural feedbacks on the C budget**

273 The impact of deploying BECCS on allowable fossil emissions depends on the  
274 magnitude of agricultural feedbacks under climate change (**Fig. 5**). To meet the climate  
275 goal<sup>1</sup> of 2 °C in 2100 in our central estimate, allowable CO<sub>2</sub> emissions during 1850–  
276 2100 increases from 940 to 1400 Gt C by deploying BECCS without accounting for  
277 agricultural feedbacks, and to 1380 Gt C by including them. This negative emission  
278 service from BECCS (460 Gt C) agrees with previous model estimates (400–800 Gt  
279 C)<sup>46</sup>, but requires that global mitigation actions are initiated by 2030. The impact of  
280 agricultural feedbacks on the global C budget is larger in 2200 than 2100. Allowable  
281 CO<sub>2</sub> emissions during 1850–2200 for meeting the target of 2 °C in 2200 increase from  
282 1120 to 2040 Gt C by implementing large-scale BECCS when excluding agricultural  
283 feedbacks, but only to 1890 Gt C with them. The effects of agricultural feedbacks in  
284 reducing allowable CO<sub>2</sub> emissions will increase as the mitigation is delayed due to  
285 increasing feedbacks to climate warming. For example, agricultural feedbacks would  
286 reduce allowable CO<sub>2</sub> emissions by 150 and 270 Gt C to meet the targets of 2 and 3 °C  
287 in 2200, respectively. These reductions suggest that the ability to mitigate climate

288 change by BECCS will decrease as a result of delayed mitigation actions.

### 289 **Regional food gap under climate change**

290 Mitigating climate change requires global early actions through large-scale BECCS  
291 implementation<sup>2</sup>, but the impact of climate warming on crop yields varies among  
292 regions. Based on the yield-climate relationships, warming increases yields of wheat  
293 and maize over high-latitude regions with an average growing-season temperature  
294 lower than 10 and 19 °C, covering 4 and 30% of the global cropland area, respectively  
295 (**Fig. S14**). We define an index of food gap as one minus the ratio of per capita calories  
296 to a minimum undernutrition level of 1.5 Mcal d<sup>-1</sup>, where a higher positive food gap  
297 indicates a larger shortage of food crops. The effect of a delay from 2040 to 2060 of  
298 ambitious climate mitigation by deploying large-scale BECCS together with  
299 decarbonizing technologies in the SSP2-4.5 scenario<sup>2</sup> would be that the food gap in  
300 2100 will increase to >50% in India, Africa and Middle East without food trade (**Fig.**  
301 **6**). Many developing countries are located at lower latitudes and exposed to higher  
302 temperatures. Due to a delay of climate mitigation from 2040 to 2060, the number of  
303 developing countries where the food gap is positive will increase from 81 to 90 in 2100.  
304 In contrast, the food gap in 2100 remains negative in developed countries if ambitious  
305 mitigation is delayed from 2040 to 2060.

306 The gap of food supply in low-latitude developing countries may be alleviated by  
307 international trade of crops from temperate and northern countries to Central America,  
308 Africa and the Middle East. Export of food crops (e.g. wheat, rice and maize) from  
309 North America (417 Mt y<sup>-1</sup>), Europe (385 Mt y<sup>-1</sup>) and China (422 Mt y<sup>-1</sup>) to the  
310 remaining regions of the world is required to reduce the fraction of people with a  
311 positive food gap in 2100 from 65% to 30% when mitigation starts in 2060 (**Fig. S15**).  
312 The projected export of crops, however, would be 3, 2 and 80 times larger than the  
313 current levels<sup>40</sup> in 2019 for these three regions, respectively, indicating a large and  
314 likely implausible extent of increasing trade. Early climate mitigation<sup>10</sup> or population  
315 migration<sup>47</sup> may be the choice we have to make if the necessary food trade fails to occur.

### 316 **Implications**

317 Our results suggest that the negative impacts of climate change can reduce crop yields  
318 and thus the BECCS capacity, leading our exceeding the 2 °C Paris goal<sup>1</sup> and  
319 threatening food security. This process is absent in the future scenarios from current  
320 IAMs relying on large-scale deployment of BECCS during the second half of this  
321 century<sup>2-5,48,49</sup>. The capacity of BECCS could rapidly decrease after reaching a

322 threshold of climate warming. This would be the consequence of reduced biomass  
323 feedstocks in response to accelerated global warming due to a 20-year delay in  
324 mitigation from 2040 to 2060. The climate warming threshold, modeled here to occur  
325 in around 2050 when global warming exceeds 2.5 °C, is lower than many known  
326 ‘tipping points’ in the climate system that would lead to failure of the Paris goals<sup>1</sup>, such  
327 as triggering the melting of the Greenland ice sheet or the collapse of the Atlantic  
328 thermohaline circulation<sup>50</sup>. Exceeding the warming threshold above will jeopardize  
329 food security in the majority of developing countries, with a potential impact on  
330 developed countries. Accounting for these feedbacks improves our understanding of the  
331 food-climate-energy nexus, and reinforces the importance of early and ambitious  
332 mitigation<sup>10</sup> to meet the Paris goals<sup>2</sup>.

333 Delayed mitigation of CO<sub>2</sub> emissions inevitably requires a larger effort by deploying  
334 BECCS negative emissions, lasting for a longer time to offset the positive fossil  
335 emissions<sup>2</sup>. Food crises due to a unprecedented climate change may also lead to a shift  
336 of the growing season<sup>7</sup> and to population migration<sup>47</sup>. As a caveat, our study may  
337 overestimate future food shortages because we did not consider all potential benefits of  
338 advancing technologies and optimizing managements<sup>51</sup>. As half of the N added to  
339 cropland is currently lost to the environment<sup>52</sup> and in many countries N fertilization is  
340 already very high, food shortage could be alleviated by increasing the N use efficiency  
341 with better phosphorus and potassium fertilization so as to reach an adequate balance  
342 among these three fertilizers<sup>44</sup>. For example, if the N use efficiency was increased  
343 following a recent projection<sup>29</sup> to increase N uptake by region and reduce N<sub>2</sub>O  
344 emissions<sup>53</sup> for global croplands, per capita calories are projected to increase by 10%  
345 with a reduction of global warming by 0.2 °C in 2200 when mitigation is initiated in  
346 2050 (**Fig. S16**). We also projected an increase in per capita calories by 11% and a  
347 reduction of global warming by 0.3 °C in 2200 if we bring forward or delay the growing  
348 season for each country to optimize the crop yield under future, warmer climatology.

349 Assuming that humanity can moderate the rise of N fertilizers use and achieve a better  
350 N use efficiency (by crops taking up more N and getting more benefits from the N  
351 applied) by equilibrating fertilization<sup>44</sup>, improving water use and developing new crop  
352 varieties<sup>51</sup>, technologies will further alleviate the shortage of food and increase the  
353 capacity of BECCS. Even so, if ambitious mitigation of CO<sub>2</sub> emissions with a heavy  
354 reliance on BECCS is delayed, the impact of yield-climate feedbacks could still lead to  
355 a failure of meeting the 2 °C goal in the Paris Agreement<sup>1</sup> by considering the

356 interactions between crop yield and climate warming (**Fig. S16**). Accounting these  
357 feedbacks substantially undermines the feasibility of high allowable fossil-fuel  
358 emissions under overshoot scenarios<sup>13</sup> of delayed mitigation relying heavily on BECCS  
359 after 2050 to limit global warming below 2 °C<sup>2-5,48,49</sup>.

360 Our findings support the concerns of overshooting temperature targets by relying solely  
361 on BECCS and the assumption that BECCS production would remain insensitive to  
362 climate change<sup>3</sup>. They also indicate that irreversible climate change and serious food  
363 crises should be best avoided by accelerating supply-side decarbonization<sup>54</sup> if the  
364 reduced capacity of BECCS cannot be compensated by other negative-emission  
365 technologies. Although biophysical and technological barriers of BECCS have been  
366 widely recognized<sup>3,11,12,14,48,49</sup>, our results underscore an unrecognized drawback of  
367 BECCS due to agricultural feedbacks that limit BECCS capacity to mitigate climate  
368 change in cases of delayed mitigation. If the climate benefits of BECCS were to be  
369 attained, this technology should be deployed as early as possible, otherwise, the  
370 decreasing biomass feedstocks will reduce the BECCS efficacy and lead to failure of  
371 meeting the Paris goal of 2 °C<sup>1</sup> even by 2200. If the large-scale BECCS project cannot  
372 be put into place in the near term, these feedbacks will inevitably reduce the allowable  
373 emissions more than previously thought: demand-side decarbonization and other  
374 negative-emission technologies should undergo a more rapid deployment for human  
375 society to stay within the safe boundaries with regards to climate change.

376

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509 **Figure legends**

510 **Figure 1: Climate-yield feedbacks due to reduced biomass feedstocks of crop**  
511 **residues for bioenergy with carbon capture and storage (BECCS) and the**  
512 **potential impacts on food supply and land-use change (LUC).** This illustration  
513 shows the response of a social-ecological system relying on agricultural residues for  
514 bioenergy to a delay of mitigation with large-scale BECCS (from blue to red).

515 **Figure 2: Relationships between crop yield ( $Y$ ), climate and land management. a,**  
516 **b,** A quadratic function of average growing-season atmospheric temperature ( $T_{atm}$ , °C)  
517 is used to fit the yields of wheat (**a**) and maize (**b**). The yields are derived from field  
518 warming experiments and process-based or statistical models from 13 countries  
519 worldwide (**Table S2**), where the yields are normalized to 1 at 25 °C for different  
520 studies. Six outliers are excluded ( $P < 0.005$ ). We adopted the optimal temperature  
521 ( $T_{opt}$ ) for maize (19 °C) and wheat (9 °C) as an average in different countries or  
522 regions (**Table S3**) and assumed that the yield is reduced to 1% of its maximum value  
523 when  $T_{atm}$  exceeds 29 °C ( $T_{dam}$ )<sup>33,34</sup>. We used the yield-temperature functions fit to the  
524 local data to predict the crop yields by country if applicable and applied the functions  
525 fit to global data in the remaining regions of the world. The shaded area shows the  
526 90% interval range of the fitted function, which is adopted in our Monte Carlo  
527 simulations. **c,** A quadratic function of atmospheric CO<sub>2</sub> concentration ( $X_{CO_2}$ ) is used  
528 to fit the wheat yield<sup>37</sup> for  $X_{CO_2} < 700$  ppm. The yields are normalized to 1 at 350 ppm.  
529 A constant yield is predicted for  $X_{CO_2} \geq 700$  ppm, where the correlation between  $Y$  and  
530  $X_{CO_2}$  is not significant ( $P = 0.16$ ). **d,** A logarithmic function of N fertilization ( $Z_{nit}$ ) is  
531 used to fit the yield of rice as an example (see **Fig. S4** for the yields of wheat, maize  
532 and soybeans)<sup>40</sup> in the nine regions of the OSCAR model from 1961 to 2019. The  
533 yields in (**d**) have been adjusted for the impacts of  $T_{atm}$ ,  $X_{CO_2}$  and precipitation  
534 (**Methods**). The data used to fit the functions are listed in **Supplementary Data Set**  
535 **1**. The arrow in each panel shows the range of  $T_{atm}$ ,  $X_{CO_2}$  or  $Z_{nit}$  in the OSCAR model.

536 **Figure 3: Impact of agricultural feedbacks on climate warming and food supply.**

537 Violin plots of global warming relative to 1850–1900 (a) and global average per  
538 capita calories (b) in 2100 or 2200 when ambitious mitigation is initiated in 2040  
539 (blue), 2050 (yellow) or 2060 (orange), respectively by deploying large-scale BECCS  
540 together with decarbonizing technologies from the SSP2-4.5 scenario<sup>2</sup> after the year  
541 of mitigation onset. The results of scenarios without climate feedbacks on crop yields  
542 are obtained by maintaining the simulated capacity of BECCS for current climate  
543 (dashed violin plots). The results are estimated from Monte Carlo simulations  
544 combining uncertainties in the  $Y-T_{atm}$  functions with uncertainties in the Earth system  
545 model (Methods). The horizontal line in each violin plot shows the median estimate.  
546 The  $Y-T_{atm}$  function is derived from our central case, of which the sensitivity is  
547 examined to increasing  $T_{opt}$  (I) or  $T_{dam}$  by 1 °C (II), using experimental data only to fit  
548 the  $Y-T_{atm}$  function (III) and fitting the sensitivity<sup>7</sup> of  $Y$  to  $T_{atm}$  ( $sy-T$ ) to a linear (IV) or  
549 nonlinear (V) function (Fig. S3). The  $Y-X_{CO_2}$  function is derived from our central case  
550 or crop models for maize in Tanzania (VI), wheat in the Netherlands (VII) and rice in  
551 Japan (VIII)<sup>38</sup>. We also consider a case with 50% of the cropland expanded from  
552 marginal lands for growing energy crops (*Miscanthus*) rather than food crops (IX) and  
553 a case with marginal lands converted to forests in afforestation (X). The difference  
554 between two neighbouring violin plots is examined (\*\*\*) for  $P < 0.001$ .

555 **Figure 4: The nexus of bioenergy, climate warming and food security. a, b,** Global

556 warming in 2100 (a) and 2200 (b) relative to 1850–1900 when cropland area is  
557 increased by first converting marginal lands and then forests to cropland to meet the  
558 caloric targets of 1.5–2.5 Mcal d<sup>-1</sup> in 2030. Climate mitigation is initiated in 2040,  
559 2050 or 2060 by deploying large-scale BECCS with other decarbonizing technologies  
560 in the SSP2-4.5 scenario<sup>2</sup>. The higher caloric targets show the impact of larger  
561 cropland areas that increases not only BECCS negative emissions but also N<sub>2</sub>O  
562 emissions and CO<sub>2</sub> emissions due to land-use change (LUC). c, d, Global C budget  
563 with (unhatched) or without (hatched) feedbacks of reduced BECCS capacity due to

564 reduced crop yields when cropland area is expanded to meet the caloric target of 2  
565 Mcal d<sup>-1</sup> in 2030 and when global mitigation with large-scale BECCS is initiated in  
566 2040 (c) or 2060 (d). The cascading bars show a decomposition of the C budget into  
567 fossil-fuel (FF) emissions, emissions due to land-use change (LUC) and terrestrial  
568 emissions of N<sub>2</sub>O, BECCS, LUC emissions due to BECCS (LUC-B) and N<sub>2</sub>O  
569 emissions due to BECCS (N<sub>2</sub>O-B) from 1750 to 2200.

570 **Figure 5: Agricultural feedbacks impact the relationship between warming and**  
571 **cumulative CO<sub>2</sub> emissions.** Global warming in 2100 (a) or 2200 (b) relative to 1850–  
572 1900 is plotted against the cumulative CO<sub>2</sub> emissions by 2100 (a) or 2200 (b),  
573 respectively. Historical emissions are identical before 2020, but global climate  
574 mitigation starts in different years to deploy large-scale BECCS together with other  
575 decarbonizing technologies from the SSP2-4.5 scenario<sup>2</sup>. Global warming in these  
576 scenarios without agricultural feedbacks by maintaining the capacity of BECCS  
577 (orange line) is compared with the result with them (green line). The relationship  
578 between global warming and cumulative CO<sub>2</sub> emissions in IPCC-AR6<sup>2</sup> is indicated by  
579 the purple lines. The shaded area indicates the range of 90% uncertainty in Monte Carlo  
580 simulations varying climate parameters and yield-climate relationships (Methods).

581 **Figure 6: Contribution of climate mitigation to reduce the regional food gap. a,**  
582 Regional food gap, defined as one minus the ratio of per capita calories to a minimum  
583 undernutrition level of 1.5 Mcal d<sup>-1</sup>, in 2100. A higher food gap indicates a larger  
584 shortage of food crops. Ambitious mitigation is initiated in 2040 (solid line) or 2060  
585 (dotted line) by deploying large-scale BECCS together with other decarbonizing  
586 technologies from the SSP2-4.5 scenario<sup>2</sup>. The area of pie chart is proportional to  
587 current crop caloric production in 2019. Inserts show the food gap in 2100 when  
588 mitigation is initiated in different years. b, Food gap in 2100 when global climate  
589 mitigation starts in 2040. c, d, Plots of the food gap in 2100 when mitigation starts in  
590 2040 (c) and the change in food gap when the timing of mitigation is advanced from  
591 2060 to 2040 (d) against current per capita GDP in 2019 for developed (blue) and  
592 developing (red) countries, respectively.

593 **Methods**

594 **Earth system model**

595 We used a compact Earth system model, OSCAR 2.2, to simulate climate change during  
596 historical and future periods driven by emissions of greenhouse gases (GHGs) from  
597 human activities. Detailed descriptions of this model are provided by Li *et al.*<sup>55</sup>, Gasser  
598 *et al.*<sup>9,56</sup> and Fu *et al.*<sup>57</sup>. The interactions between climate change and the carbon (C)  
599 cycle in terrestrial systems were calibrated using the CMIP models<sup>31</sup>. In this study, we  
600 implemented the yield-climate relationships into the OSCAR model to simulate the  
601 interactions between climate change and agricultural development in assumed  
602 scenarios of cropland expansion and intensified N fertilization and to evaluate the  
603 impact of agriculture feedbacks on climate change under temperature overshoots<sup>13</sup>.  
604 Total anthropogenic CO<sub>2</sub> emissions from fossil-fuel combustion and cement production  
605 before 2010 were obtained from the CDIAC data set<sup>58</sup>; anthropogenic emissions of  
606 methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), nitrogen oxides (NO<sub>x</sub>), carbon monoxide (CO),  
607 volatile organic compounds (VOCs), sulfur dioxide (SO<sub>2</sub>), ammonia (NH<sub>3</sub>), 11  
608 hydrofluorocarbons (HFCs), eight perfluorocarbons (PFCs) and 16 ozone-depleting  
609 substances were obtained from the EDGAR inventory<sup>59</sup>; anthropogenic and natural  
610 emissions of organic carbon (OC) and black carbon (BC) were obtained from the  
611 ACCMIP inventory<sup>60</sup> and the GFED v3.1 inventory<sup>61</sup> and emissions of CO<sub>2</sub> and non-  
612 CO<sub>2</sub> GHGs due to land-use change (LUC) were obtained from the LUH1.1 data set<sup>62</sup>.  
613 Forcing data after 2010 were compiled from the Shared Socioeconomic Pathway (SSP)  
614 5-8.5 and SSP 2-4.5 (excluding the contribution of negative emissions)<sup>2</sup>, including data  
615 for anthropogenic emissions of CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, NO<sub>x</sub>, CO, VOCs, BC, OC, SO<sub>2</sub>, NH<sub>3</sub>,  
616 11 HFCs, eight PFCs and 16 ozone-depleting substances.

617 The model was run with active interactions and feedbacks between various Earth  
618 elements<sup>63</sup>, where the elements interacting with each other in the Earth system  
619 represented the responses of the climatic system to anthropogenic perturbations such as  
620 GHG emissions from industrial processes, cropland expansion, LUC and intensified N  
621 fertilization. Changes in global C budgets and GHG emissions were modeled using the  
622 terrestrial C sink, LUC emissions and the terrestrial emissions of N<sub>2</sub>O. This model  
623 configuration allowed us to simulate the feedbacks of both climate change to  
624 agricultural activities and of agricultural yields to climate change. Calculations of the  
625 changes in atmospheric concentrations of CO<sub>2</sub>, tropospheric and stratospheric  
626 chemistry, surface albedo, terrestrial C sinks, LUC emissions, air-sea gas exchanges

627 and the regional responses of atmospheric temperature and precipitation to the climatic  
 628 forcers in the OSCAR model were identical to those in previous studies<sup>9,55-57</sup> with a  
 629 limit to the simulated concentrations of N<sub>2</sub>O and CH<sub>4</sub> (420 ppb for N<sub>2</sub>O and 2200 ppb  
 630 for CH<sub>4</sub>).

### 631 **Net primary production in cropland**

632 The net primary production for cropland (*NPP*, g C y<sup>-1</sup>) in year *t* was represented by a  
 633 function of crop yield (*Y<sub>it</sub>*, g biomass ha<sup>-1</sup> y<sup>-1</sup>) and cropland area (*A<sub>it</sub>*, ha):

$$634 \quad NPP_t = \sum_{i=1}^8 \frac{A_{it} Y_{it} \mu_i f_i}{v_i I_i} \quad (1)$$

635 where *i* is the crop, *v<sub>i</sub>* is the fraction of shoots in the biomass, *μ<sub>i</sub>* is the fraction of dry  
 636 biomass, *f<sub>i</sub>* is the fraction of C in the dry biomass and *I<sub>i</sub>* is a harvest index, defined as  
 637 the ratio of the mass of the harvested yield to aboveground biomass. We divided all  
 638 crops into eight categories: cereals, roots and tubers, beans, oil crops, fiber crops, sugar  
 639 crops, primary fruits and primary vegetables. The values of the parameters *μ<sub>i</sub>*, *v<sub>i</sub>*, *f<sub>i</sub>* and  
 640 *I<sub>i</sub>* for these categories are listed in **Table S4**.

641 In our model, the crop yield (*Y<sub>it</sub>*) in year *t* was predicted:

$$642 \quad Y_{it} = Y_{i0} \frac{F^C(C_t) F^T(T_t) F^Z(Z_t) F^P(P_t)}{F^C(C_0) F^T(T_0) F^Z(Z_0) F^P(P_0)} \quad (2)$$

643 where *Y<sub>i0</sub>* (g biomass ha<sup>-1</sup> y<sup>-1</sup>) is the yield in 2019 and *C<sub>t</sub>*, *T<sub>t</sub>*, *Z<sub>t</sub>* and *P<sub>t</sub>* denote  
 644 atmospheric CO<sub>2</sub> concentration, average temperature during the growing season,  
 645 cropland intensity of nitrogen (N) fertilization and precipitation in a future year *t*,  
 646 respectively. *F<sup>C</sup>*, *F<sup>T</sup>*, *F<sup>Z</sup>* and *F<sup>P</sup>* were estimated from the relationships between observed  
 647 crop yields and atmospheric CO<sub>2</sub> concentration (*C<sub>t</sub>*, ppm), atmospheric mean growing-  
 648 season temperature (*T<sub>t</sub>*, °C), intensity of N fertilization (*Z<sub>t</sub>*, kg N ha<sup>-1</sup>) and precipitation  
 649 (*P<sub>t</sub>*, mm y<sup>-1</sup>), respectively:

$$650 \quad F^C(C_t) = \beta^C C_t^2 + \gamma^C C_t + \alpha^C \quad (3)$$

$$651 \quad F^T(T_t) = \beta^T T_t^2 + \gamma^T T_t + \alpha^T \quad (4)$$

$$652 \quad F^Z(Z_t) = \gamma^Z \ln(Z_t) + \alpha^Z \quad (5)$$

$$653 \quad F^P(P_t) = \exp(\gamma^P \Delta P_t) \quad (6)$$

654 where the coefficients *α<sup>C</sup>*, *β<sup>C</sup>*, *γ<sup>C</sup>*, *α<sup>T</sup>*, *β<sup>T</sup>*, *γ<sup>T</sup>*, *α<sup>Z</sup>* and *γ<sup>Z</sup>* were determined by fitting these  
 655 functions to data (**Supplementary Data Set 1**). We compiled the yield data for maize  
 656 and wheat from both field-warming experiments and local process-based or statistical  
 657 models (**Table S2**). After excluding data with a narrow range of growing-season  
 658 temperature or without controlling the impact of confounding variables, our data set

659 covers 13 countries globally distributed in Africa, East Asia, South Asia, West Asia,  
660 North America, South and Central America, where the average growing-season  
661 temperature ranges from 12 to 34 °C. As the environments for these experiments are  
662 different, it is necessary to normalize the variance of the yields between different  
663 studies. This is done by dividing the yields by the average yields measured around 25  
664 °C using 10% of data. To constrain the yield-temperature functions, we compiled the  
665 optimal growing temperature ( $T_{opt}$ ) for maize and wheat growing in different countries  
666 or regions (**Table S3**). We fit the yield-temperature functions to the local data in the  
667 USA, India, Sudan, Mexico, China, Pakistan and Africa using the local  $T_{opt}$  if applicable  
668 or using the average  $T_{opt}$  (**Fig. S3**), and we fit the global yield-temperature functions to  
669 all data applying the average  $T_{opt}$  (**Fig. 2**).

670 In our Earth system model, we used the yield-temperature functions fit to the local data  
671 to predict the future crop yields in these countries if applicable and used the yield-  
672 temperature functions fit to the global data in the remaining regions of the world. We  
673 did not find long-term data for other crops and assumed that the yield-temperature  
674 function for other crops is similar to that of wheat. We estimated uncertainties in the  
675 fitted functions (**Fig. 2** and **Fig. S3**), which were considered in our Monte Carlo Earth  
676 system model simulations to estimate the climate impact of deploying BECCS. We  
677 performed additional experiments to examine the sensitivity of the yield-temperature  
678 relationship to using only experimental data, increasing the optimal growing  
679 temperature ( $T_{opt}$ ) or the dampening temperature ( $T_{dam}$ ) by 1 °C, using a linear or  
680 nonlinear function to fit the sensitivity of wheat yield to temperature change<sup>7</sup> (**Fig. S3**),  
681 which are considered to examine the sensitivity of the climate benefits of BECCS to  
682 these factors (**Fig. 3**).

683 The fitted parameters  $\alpha^T, \beta^T, \gamma^T$  using all data and the fitted  $\alpha^C, \beta^C, \gamma^C, \alpha^Z$  and  $\gamma^Z$  are listed  
684 by region in **Table S5**. Different from the parameters in the response of crop yields to  
685 changes in temperature, atmospheric CO<sub>2</sub> and intensity of N fertilization, the parameter  
686  $\gamma^P$  in the response of crop yield to change in precipitation was determined by a previous  
687 study<sup>9</sup>. In that study, crop yield was simulated using seven Earth system models<sup>31,63</sup> in  
688 a case using a fully coupled configuration with an increase of atmospheric CO<sub>2</sub> of +1%  
689 yr<sup>-1</sup>, in a case using the fixed climate and in a case using the fixed carbon cycle,  
690 respectively. For each region, an exponential function was used to fit the simulated crop  
691 yields based on the decadal moving averages of the relevant variables in the seven  
692 models, where the best fit returned the parameter  $\gamma^P$  in the response of crop yield to

693 precipitation in each region. As a caveat,  $\gamma^P$  was not determined as other parameters due  
694 to the lack of field experiments measuring the response of crop yield to precipitation  
695 change, but, similar to a previous study<sup>6</sup>, the impact of precipitation on crop yields in  
696 the future was estimated at a lower magnitude than temperature, atmospheric CO<sub>2</sub> and  
697 intensity of N fertilization in our model (**Fig. S6**).

698 For future scenarios, we predicted the yields of eight crops (cereals, roots and tubers,  
699 beans, oil crops, fiber crops, sugar crops, primary fruits and primary vegetables) ( $Y_t$ )  
700 based on the yield of each crop for the year 2019 from the Food and Agriculture  
701 Organization (FAO) data set<sup>40</sup> and the changes in N fertilization, CO<sub>2</sub> concentrations  
702 and the average growing-season temperature and precipitation over croplands from  
703 2019 to a future year during 2020–2200 by country. The crop yields ( $Y_{2019}$ ), N  
704 fertilization ( $Z_{2019}$ ), CO<sub>2</sub> concentration ( $C_{2019}$ ), and the average growing-season  
705 temperature and precipitation over cropland ( $T_{2019}$  and  $P_{2019}$ ) for 167 countries in 2019  
706 are listed in **Supplementary Data Set 2**. For dedicated energy crops, the average yield  
707 (8.5 t ha<sup>-1</sup>) in 2020 was derived from a previous study<sup>64</sup> as a conservative estimate. The  
708 yield of dedicated energy crops under climate change is predicted by **Eqs. 2–6** using the  
709 functions of atmospheric CO<sub>2</sub> concentration, atmospheric surface temperature, N  
710 fertilization and precipitation as of wheat crop.

### 711 **Terrestrial C sink**

712 The terrestrial C sink, which is one of the drivers of changes in atmospheric CO<sub>2</sub>  
713 concentration, responds to changes in atmospheric CO<sub>2</sub> concentration and other  
714 environmental changes. The OSCAR model<sup>9</sup> divided global land into five categories:  
715 bare soil, forest, grassland and shrubland, cropland and pasture. The change in the  
716 terrestrial C sink ( $\Delta E_{\downarrow land}$ , Gt C y<sup>-1</sup>) for each biome relative to the preindustrial period  
717 (1850–1900) was estimated:

$$718 \quad \Delta E_{\downarrow land} = (\Delta e_t^{fire} + \Delta rh_t^{litter} + \Delta rh_t^{soil} - \Delta NPP_t)(A_0 + \Delta A_t) \quad (7)$$

719 where  $A_0$  is the preindustrial area for this biome,  $\Delta A_t$  is the change in area relative to the  
720 preindustrial period,  $\Delta e_t^{fire}$  is the change in the flux of C from biomass burnt in wildfires,  
721  $\Delta rh_t^{litter}$  is the change in the flux of C from biomass to the atmosphere when C in litter  
722 is oxidized by heterotrophic respiration,  $\Delta rh_t^{soil}$  is the change in the flux of C from soil  
723 to the atmosphere when soil C is oxidized by heterotrophic respiration and  $\Delta NPP_t$  is the  
724 intensive change in net primary production.  $\Delta e_t^{fire}$  was calculated as a function of the  
725 fire intensity and the amount of living biomass, where the fire intensity was represented

726 as a function of surface air temperature, precipitation and atmospheric CO<sub>2</sub>  
 727 concentration<sup>9</sup>.  $\Delta rh_t^{litt}$  was calculated as a function of the litter C concentration, annual  
 728 mean atmospheric temperature and precipitation<sup>57</sup>.  $\Delta rh_t^{soil}$  was calculated as a function  
 729 of the soil C concentration, annual mean atmospheric temperature and precipitation<sup>35</sup>.  
 730  $\Delta NPP_t$  was calculated for cropland using Eq. 1 and for other biomes as a function of  
 731 atmospheric CO<sub>2</sub> concentration, annual mean atmospheric temperature and  
 732 precipitation<sup>9</sup>.

### 733 **LUC emissions of CO<sub>2</sub>**

734 The conversion of marginal lands first and then forests to cropland to meet the  
 735 increasing food targets leads to additional LUC emissions of CO<sub>2</sub> by affecting the stock  
 736 of C in living biomass, litter and soil C pools and harvested wood products. LUC  
 737 emissions ( $\Delta E_{LUC}$ ) depend on the changes in C stocks in different pools:

$$738 \quad \Delta E_{LUC} = -\frac{d}{dt} (\Delta C_{veg} + \Delta C_{litt} + \Delta C_{soil} + \sum_p \Delta C_{hwp}^p) \quad (8)$$

739 where  $p$  is the use of a wood product (1 for fuel wood, 2 for pulp-based products and 3  
 740 for hardwood-based products) and  $\Delta C_{veg}$ ,  $\Delta C_{litt}$ ,  $\Delta C_{soil}$  and  $\Delta C_{hwp}$  indicate the stocks of  
 741 C in living biomass, litter, soil and harvested wood products, respectively.  $\Delta C_{veg}$ ,  $\Delta C_{litt}$ ,  
 742  $\Delta C_{soil}$  and  $\Delta C_{hwp}$  were calculated based on the changes in the area from one biome to  
 743 another biome and on the C concentration in each pool. The C concentration in each  
 744 pool was simulated using the dynamic scheme that is calibrated by the flux of C in the  
 745 CMIP5 model<sup>63</sup>. The total LUC emissions from 1800 to 2020 are estimated of 137 Gt  
 746 C, which is in the range of the estimates since 1800 (100–180 Gt) by Erb *et al.*<sup>65</sup>.

### 747 **N<sub>2</sub>O emissions**

748 N<sub>2</sub>O was treated as a well-mixed GHG in the OSCAR model. Anthropogenic sources  
 749 of N<sub>2</sub>O include direct and indirect emissions from agriculture, energy production,  
 750 industry, waste and wildfires<sup>59,66,67</sup>. Natural sources of N<sub>2</sub>O include emissions from  
 751 tropical soils<sup>68</sup> and emissions from the application of N fertilizers<sup>69</sup>. N<sub>2</sub>O in the  
 752 atmospheric is mainly removed by stratospheric photolysis, the rate of which is a  
 753 function of the stratospheric N<sub>2</sub>O concentration due to the autocatalytic feedback of  
 754 N<sub>2</sub>O by reducing the concentration of stratospheric ozone<sup>70</sup>. For the future simulations,  
 755 we modeled the agricultural practice of N fertilization with the average length of  
 756 growing season (153 d)<sup>69</sup>. N<sub>2</sub>O emissions were converted to equivalent CO<sub>2</sub> emissions  
 757 using a constant ratio of 81.3 g C to 1 g N<sub>2</sub>O<sup>69</sup>. For the future scenarios, N<sub>2</sub>O emissions  
 758 converted to equivalent CO<sub>2</sub> emissions ( $\Delta E_{N_2O-fertilizer}$ , t C y<sup>-1</sup>) due to agricultural N

759 fertilization in cropland were represented by an exponential function<sup>69</sup>:

$$760 \quad \Delta E_{N_2O-fertilizer} = 4.93 \cdot D \cdot A \cdot \sigma_{N_2O} \cdot \exp(0.0134 \cdot Z) \quad (9)$$

761 where  $Z$  is the intensity of N fertilization in the cropland ( $\text{kg ha}^{-1}$ ),  $D$  is the duration of  
762 N fertilization,  $A$  is the area of cropland and  $\sigma_{N_2O}$  is the coefficient for converting  $N_2O$   
763 emissions to equivalent  $\text{CO}_2$  emissions.

#### 764 **Average growing-season temperature in cropland**

765 We used the OSCAR model to simulate the average atmospheric temperature ( $T_{jt}$ ) in  
766 cropland in region  $j$  in year  $t$  during the growing season based on the preindustrial  
767 temperature for cropland in region  $j$  during the growing season ( $T_{j0}$ ) and degree of  
768 global warming relative to the preindustrial period (1850–1900) ( $\Delta T_{jt}$ ):

$$769 \quad T_{jt} = T_{j0} + \omega_j \Delta T_t \quad (10)$$

770 where  $j$  is the region (1 for North America, 2 for South and Central America, 3 for  
771 Europe, 4 for the Middle East and northern Africa, 5 for tropical Africa, 6 for the former  
772 Soviet Union, 7 for China, 8 for southern and southeastern Asia and 9 for the developed  
773 Pacific region) and  $\omega_j$  is the ratio of regional to global warming, calibrated for each  
774 region from an ensemble of CMIP models<sup>31</sup>. Atmospheric surface temperature differs  
775 between cropland and other land types and between the growing and non-growing  
776 seasons in a region, so we assumed that the change in atmospheric growing-season  
777 temperature was homogeneous in a region. We estimated the average growing-season  
778 temperature by country based on global crop calendar data<sup>71</sup> (**Supplementary Data Set**  
779 **3**).

780 The degree of global warming ( $\Delta T_t$ ) was simulated as a function of anthropogenic  
781 radiative forcing ( $\Delta RF$ ) of GHGs, ozone precursors, aerosols and aerosol precursors  
782 and the natural forcings caused by various anthropogenic activities:

$$783 \quad \tau \frac{d}{dt} \Delta T_t = \lambda \Delta RF - \Delta T_t - \theta (\Delta T_t - \Delta D_t) \quad (11)$$

784 where  $\tau$  is the temporal inertia of global mean atmospheric temperature,  $\lambda$  is the  
785 equilibrium climate sensitivity,  $\theta$  is the coefficient determining exchange of energy  
786 between the Earth surface and deep oceans and  $\Delta D$  is the change in temperature of deep  
787 oceans. These parameters are identical to those determined by previous studies<sup>55-57</sup>. In  
788 the OSCAR model, we calibrated the preindustrial surface air temperature in the  
789 growing season over cropland ( $T_{j0}$ ) in country  $j$  using the observed average temperature  
790 in the growing season in cropland for 2016–2019 ( $T_{j,2016-2019}$ ) in country  $j$  and the  
791 simulated change in atmospheric surface temperature in this country in 2019 relative

792 the average of 1850–1900 ( $\Delta T_{j,1900-2019}$ ). Atmospheric temperature in the growing  
793 season in cropland for 2016–2019 by country ( $T_{j,2016-2019}$ ) was estimated from the global  
794 gridded daily temperature re-analysis data set of the Global Forecast System released  
795 by the National Centers for Environmental Prediction<sup>72</sup>.

### 796 **Global data of crop yields, cropland area and N fertilization**

797 We compiled the yields of crops by country for 1961–2019 from the FAO global  
798 agricultural data set<sup>40</sup>. We simulated the national crop yields for 2020–2200 using Eqs.  
799 2–6 based on the simulated atmospheric CO<sub>2</sub> concentration, the simulated average  
800 growing-season temperature, the simulated precipitation and the targeted intensity of N  
801 fertilization. We compiled the national areas of cropland growing cereals, roots and  
802 tubers, beans, oil crops, fiber crops, sugar crops, primary fruits and primary vegetables  
803 for 1961–2019 from the FAO global agricultural data set of cropland area<sup>40</sup>. The area  
804 of marginal lands is derived from a previous study<sup>73</sup>. We applied the per capita cropland  
805 area in 2020 to the period from 2020 to 2200 as a constant in the scenario without  
806 cropland expansion. In the scenarios of cropland expansion, we increased the per capita  
807 cropland area in 2020 to a specific area (0.16, 0.17, ..., 0.24 ha) to meet the caloric  
808 targets of 1.5–2.5 Mcal d<sup>-1</sup> in 2030 in countries where the cropland area is below this  
809 threshold, while the cropland area is maintained at the 2020 level for countries above  
810 this threshold. We assumed that first marginal lands and then forests in the expansion  
811 of cropland were converted to cropland<sup>74</sup>. We estimated the impact of a higher per capita  
812 food demand by adopting the national population in 2020<sup>75</sup> to estimate the total area of  
813 croplands based on the per capita cropland area by country for years after 2020, so we  
814 took population as a control variable to estimate the impact of increasing per capita  
815 food demand on cropland area<sup>76</sup>. We estimated the amount of synthetic N fertilizer  
816 applied to the cropland in 167 countries for 1961–2019 by subtracting the amount of  
817 synthetic N fertilizer applied to pastures<sup>77</sup> from the amount of synthetic N fertilizer  
818 applied to both pastures and cropland from the FAO data set of fertilizers<sup>78</sup>. In the future  
819 scenarios of intensified N fertilization, we considered that the intensity of N fertilization  
820 increases to a specific level (100, 110, ..., 300 kg ha<sup>-1</sup>) during 2020–2030 in countries  
821 where the intensity is below this threshold, while N fertilization is maintained at the  
822 2020 level for countries above this threshold.

### 823 **Calculation of calories in crops**

824 We calculated the calories in cereal crops based on the production of wheat, rice and  
825 maize in the OSCAR model. We estimated the calories in a crop ( $L$ ) based on the crop

826 yield ( $Y_i$ ) and the cropland area ( $A_i$ ):

$$827 \quad L = \sum_{i=1}^3 \chi A_i Y_i \eta_i (1 - \omega_i) E_i \quad (12)$$

828 where  $i$  is a crop,  $\chi$  is the fraction of food loss and waste (56% for developed countries  
829 and 44% for developing countries)<sup>79</sup>,  $\eta_i$  is a factor for converting the agricultural  
830 product produced to the part that is edible<sup>80</sup>,  $\omega_i$  is the fraction of crops used for animal  
831 feed and other non-food purposes and  $E_i$  is the caloric content by weight for each crop.  
832 The fraction of crops used for animal feed and other non-food purposes was derived  
833 from the FAO global food-balance data set<sup>81</sup>. Caloric contents were compiled for wheat,  
834 rice and maize from the Calories data set<sup>82</sup>. For each country, we considered the calories  
835 provided by the animal products compiled from the FAO global food-balance data set<sup>75</sup>  
836 as a constant, which were added to the calories provided by crops. The parameters  $\chi$ ,  $\eta_i$ ,  
837  $\omega_i$  and  $E_i$  by crop are listed in **Table S6**.

### 838 **Negative emissions from BECCS**

839 We estimated the negative emissions from BECCS based on the quantity of agricultural  
840 residues that is harvested from crop production. Negative emissions from BECCS  
841 included the reduction in CO<sub>2</sub> emissions by substituting coal to produce the same  
842 amount of electricity in power plants and the sequestration of C in biomass to geological  
843 repositories<sup>19</sup>. We assumed that BECCS was deployed by retrofitting coal-fired power  
844 plants. We estimated the negative emissions from BECCS as a function of crop yield  
845 ( $Y_i$ , g biomass ha<sup>-1</sup> y<sup>-1</sup>) and cropland area ( $A_i$ , ha) at an efficiency of C capture and  
846 storage of 90%:

$$847 \quad \Delta E_{BECCS} = - \left[ \sum_{i=1}^8 Y_i A_i \mu_i f_i \frac{(1-I_i)}{I_i} \cdot 90\% + Y_i A_i \mu_i V_i \frac{(1-I_i)}{I_i} \frac{\eta_{bio}}{V_{coal} \eta_{coal}} \xi \right] \quad (13)$$

848 where  $i$  is a crop (i.e. cereals, roots and tubers, beans, oil crops, fiber crops and sugar  
849 crops),  $\mu_i$  is the fraction of dry biomass,  $f_i$  is the concentration of C in dry biomass,  $I_i$  is  
850 the harvest index, defined as the ratio of the mass of the harvested yield to total  
851 aboveground biomass,  $V_i$  is the ratio of bioenergy to dry biomass (5 MWh (g biomass)<sup>-1</sup>)<sup>83</sup>,  
852  $V_{coal}$  is the energy content of coal (7.44 MWh (g coal)<sup>-1</sup>)<sup>84</sup>,  $\xi$  is the emission factor  
853 of coal (0.67 g C (g coal)<sup>-1</sup>)<sup>85</sup>, and  $\eta_{coal}$  and  $\eta_{bio}$  are the efficiencies of power generation  
854 in coal-fired power plants (39.3%) and BECCS plants (27.8%), respectively<sup>86</sup>. The  
855 parameters  $\mu_i$ ,  $f_i$  and  $I_i$  are listed by crop in **Table S4**.

856 We assumed that BECCS was used for retrofitting coal-fired power plants (e.g., that is  
857 to substitute up to 57%, 83% and 85% of electricity generated by coal in Asia, Europe  
858 and North America, respectively in 2030) before retrofitting oil-fired and gas-fired

859 power plants. We considered four scenarios to examine the impacts of alternative  
 860 bioenergy applications (**Fig. S9**). First, we considered that BECCS was used for  
 861 substituting oil or gas rather than coal, where less emissions were abated due to a higher  
 862 power generation efficiency (41% and 47% for oil and gas<sup>87</sup>, respectively, versus 39%  
 863 for coal<sup>86</sup>) and a lower CO<sub>2</sub> emission factor (0.7 and 0.4 tCO<sub>2</sub> MWh<sup>-1</sup> for oil and gas<sup>88</sup>,  
 864 respectively, versus 0.85 tCO<sub>2</sub> MWh<sup>-1</sup> for coal<sup>85</sup>) in power plants. Second, there are  
 865 technological and market barriers for using bioenergy in transportation<sup>89,90</sup>, which make  
 866 it difficult to equip CCS on vehicles<sup>91</sup>. We considered a scenario where biomass  
 867 produces bioethanol with a 16% of energy loss in production<sup>92</sup> to substitute vehicle oils  
 868 without CCS. Third, we considered a scenario, where the efficiency of energy  
 869 conversion was increased from 27.8% for BECCS power plants in our central case to  
 870 47.5% in biorefinery plants<sup>43</sup>, but 15% of CO<sub>2</sub> released at a high purity during the  
 871 fermentation process can be captured<sup>43</sup>. Lastly, we considered an optimistic scenario  
 872 where the efficiency of energy conversion was improved from 27.8% to 47.5% in  
 873 biorefinery plants, but 55% of CO<sub>2</sub> released during the fermentation process in  
 874 gasification can be captured at a high purity<sup>43</sup>.

875 Our method for estimating the quantity of agricultural residues for BECCS differed  
 876 from those in previous studies (e.g. ref<sup>93</sup>) based on crop NPP, which scaled as the  
 877 assumed fraction of agricultural residues that can be harvested in the field. We derived  
 878 the quantity of agricultural residues from the quantity of the harvested grain using the  
 879 crop-specified straw-to-grain ratio for above-ground biomass (excluding the difficult-  
 880 to-obtain biomass like roots). The quantity of the collected agricultural residues for  
 881 bioenergy ( $q_{straw}$ ) could be computed:  $q_{straw} = x_{straw} \cdot \eta_{straw} = [x_{grain} \cdot (1 - I_i) / I_i] \cdot \eta_{straw}$   
 882  $= [q_{grain} / \eta_{grain} \cdot (1 - I_i) / I_i] \cdot \eta_{straw} = [q_{grain} \cdot (1 - I_i) / I_i] \cdot (\eta_{straw} / \eta_{grain})$ , where  $x_{straw}$  is the quantity of  
 883 agricultural residues from all crops growing in the field,  $\eta_{straw}$  is the fraction of  
 884 agricultural residues that can be harvested for use as bioenergy,  $I_i$  is the harvest index,  
 885 defined as the ratio of the mass of the harvested grain to total aboveground biomass  
 886 (**Table S4**),  $q_{grain}$  is the quantity of harvested grain and  $\eta_{grain}$  is the fraction of grown  
 887 grain that can be harvested for food. In the literature,  $\eta_{grain}$  varies from 80 to 95%<sup>94,95</sup>  
 888 and  $\eta_{straw}$  varies from 83 to 90%<sup>96,97</sup>, which both depend on the locations, type of crop  
 889 and technology of pretreatment. We considered that the pretreatment of straw can  
 890 improve  $\eta_{straw}$  (e.g., by reducing the volume of straw<sup>96</sup>), while the emissions of CO<sub>2</sub>  
 891 from diesel in the pretreatment estimated in our previous study<sup>19</sup> have been considered  
 892 in this study. Therefore, we converted the quantity of harvested grain ( $q_{grain}$ ) to the

893 quantity of harvested residue ( $q_{straw}$ ) by assuming that it is possible to be equally  
894 efficient in harvesting grain and residue. However, this calculation may lead to an upper  
895 estimate of the effect of BECCS in mitigation, because sustaining a high  $\eta_{straw}$  for long  
896 time may reduce soil fertility and require more fertilizer applications, which deserves  
897 attention<sup>98</sup>.

### 898 **Uncertainty analyses**

899 We estimated the uncertainty in global warming and crop calories by running valid  
900 Monte Carlo simulations 1000 times using the OSCAR model<sup>9</sup>, randomly drawing  
901 parameters from their uncertainty distributions<sup>99</sup>. Parameters that varied in the Monte  
902 Carlo simulations were: (i) anthropogenic emissions of CO<sub>2</sub>, methane and N<sub>2</sub>O, LUC  
903 emissions of CO<sub>2</sub>, emissions of halogenated compounds, ozone precursors (NO<sub>x</sub>, CO),  
904 VOCs, aerosols (BC, OC, sulfate and nitrate) and aerosol precursors (SO<sub>2</sub>, NO<sub>x</sub>, O<sub>3</sub>,  
905 NH<sub>3</sub>), (ii) natural radiative forcings, (iii) parameters governing the processes in oceans,  
906 biospheres, wildfires, land uses, hydroxyl groups, wetlands, photolysis, tropospheric  
907 ozone, stratospheric ozone, sulfate formation, nitrate formation, secondary organic  
908 aerosols, direct and indirect radiative forcings of aerosols, changes in surface albedo,  
909 temperature changes, precipitation and ocean acidification and (iv) the fitted  
910 coefficients  $\alpha^C$ ,  $\beta^C$ ,  $\gamma^C$ ,  $\alpha^T$ ,  $\beta^T$ ,  $\gamma^T$ ,  $\alpha^Z$  and  $\gamma^Z$  in the relationships between crop yields and  
911 atmospheric growing-season temperature, atmospheric CO<sub>2</sub> concentration and intensity  
912 of N fertilization. The standard deviations of these fitted coefficients as normal  
913 distributions were derived from the regression models, which are listed in **Table S5**.  
914 We used the interquartile range and the range of 90% uncertainty from Monte Carlo  
915 simulations to indicate the uncertainties in the simulated global warming, crop  
916 production and per capita calories.

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1042 **Author contributions**

1043 R.W. conceived the research, designed the study and wrote the first version of  
1044 manuscript. S.Q.X. compiled data, performed the research and prepared graphs. T.G.  
1045 provided the OSCAR model; P.C., T.G., J.P., Y.B., O.B., I.A.J., J.S., J.H.C., J.J.C.,  
1046 R.H.Z. provided tools analyzing the relationship between climate change and food  
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1050 the agronomy. All coauthors interpreted the results and contributed to the writing.

1051 **Declaration of Interests**

1052 The authors declare no competing interests.

1053 **Availability of data and material**

1054 Additional material is available in Supplementary Materials. Code and data used for  
1055 our analyses are available on the GitHub repository: [https://github.com/rongwang-](https://github.com/rongwang-fudan/OSCAR_Agriculture_Global)  
1056 [fudan/OSCAR\\_Agriculture\\_Global](https://github.com/rongwang-fudan/OSCAR_Agriculture_Global).

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