

Narrowing the uncertainties in the effects of elevated CO₂ on crops

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1 Narrowing the uncertainties in the effects of 2 elevated CO₂ on crops

3

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39

40 *Plant responses to rising atmospheric carbon dioxide (CO₂) concentrations, together with*
41 *projected variations in temperature and precipitation will determine future agricultural*
42 *production. Estimates of the impacts of climate change on agriculture provide essential*
43 *information to design effective adaptation strategies, and develop sustainable food systems.*
44 *Here, we review the current experimental evidence and crop models on the effects of elevated*
45 *CO₂ concentrations. Recent concerted efforts have narrowed the uncertainties in CO₂-induced*
46 *crop responses so that climate change impact simulations omitting CO₂ can now be eliminated.*
47 *To address remaining knowledge gaps and uncertainties in estimating the effects of elevated*
48 *CO₂ and climate change on crops, future research should expand experiments on more crops*

49 *species under a wider range of growing conditions, improve the representation of responses to*
50 *climate extremes in crop models, and simulate additional crop physiological processes related*
51 *to nutritional quality.*

52
53

54 Many countries under the Paris Agreement have committed to increasing their resilience to
55 climate risks through adaptation and mitigation policies in their agricultural sectors. The
56 scientific community produce relevant scientific information for guiding the monitoring and
57 evaluation of national climate policies and increasing their ambition as stipulated by the Global
58 Stocktake component of the Paris Agreement².

59 Crop models are among the key tools to generate such scientific sources³. Process-based crop
60 models account for the impact of biophysical, climatic and environmental factors, including
61 elevated CO₂ concentration (*eCO₂*, hereafter) on plant growth processes⁴, crop yield quantity
62 and quality. Yet, despite decades of experiments robustly demonstrating the effects of *eCO₂*,
63 climate change impact assessments have continued to use scenarios both with and without CO₂-
64 *fertilization effects*⁵⁻⁷. Here we argue that this approach has produced more confusion than
65 clarity, whereas current knowledge is sufficiently robust to make the *without CO₂-fertilization*
66 scenario obsolete.

67

68 **Available experimental evidence of *eCO₂* effects**

69 The role of *eCO₂* in stimulating crop growth has been documented since 1804, when De
70 Saussure⁸ reported that peas exposed to *eCO₂* grew better than control plants in ambient air.
71 Since then, this effect has been exploited in commercial greenhouse production, while further
72 scientific work has continued through many CO₂ enrichment experiments using greenhouses,
73 growth chambers, gradient tunnels, open-top chambers (OTC), and Free-Air CO₂ Enrichment
74 (FACE) techniques (Supplementary Tables S1 and S2). The understanding of *eCO₂* effects on
75 plant growth derived from those experiments has been synthesized in several topical and
76 literature reviews as summarized below⁹⁻¹¹.

77 ***The effects of eCO₂ on crop productivity.*** Kimball et al.¹² assembled more than 70 reports and
78 tabulated 430 prior observations of eCO₂-driven productivity changes in crops, concluding that
79 yields of C₃ species under a full complement of water and nutrients significantly increase with
80 a doubling of ambient CO₂ concentration (*aCO₂*; since that time, the CO₂ mixing ratio has
81 increased from 340 ppm to 412 ppm, which affects the degree of response to an experimental
82 doubling). However, crop responses to eCO₂ vary by species and growing conditions⁴.
83 Elevation of CO₂ concentration in FACE experiments (from a CO₂ mixing ratio of 353 ppm to
84 550 ppm) with ample water and nutrients increased yields of C₃ grains (e.g., wheat, rice, barley)
85 on average by 19%⁴. In contrast, the yield of C₄ crops (e.g., maize, sorghum) did not change
86 significantly when the crops were grown under ample water supply conditions. Variation in
87 CO₂ responsiveness across genotypes within species¹³⁻¹⁵ has also been demonstrated in rice,
88 soybean, and wheat¹⁶⁻¹⁷.

89 Beyond stimulating photosynthesis and growth, eCO₂ also causes reduced stomatal
90 conductance by 19% to 22%^{12,18-19} and reduced crop transpiration^{4,20}. This leads to lower crop
91 evapotranspiration (ET), as demonstrated by the average 10% ET reduction in FACE
92 experiments for all investigated crops^{4,21} (Supplementary Material S.1.1). Improved water-use
93 efficiency under eCO₂ can enable crops to be more drought tolerant compared to crops grown
94 in *aCO₂*. This effect is particularly important for C₄ crops, for which yield increases have been
95 reported under water-limiting conditions in eCO₂. For example, FACE-sorghum²²⁻²³ and
96 FACE-maize²⁴ experiments had average yield increases of 15% and 41%, respectively.

97 While under ample water and nutrient conditions, yields of most C₃ crops increase by 10% to
98 30% under eCO₂ in experiments, yield stimulation due to eCO₂ is generally smaller or
99 insignificant when nutrients are limiting. Nutrient deficiencies, such as nitrogen (N) and
100 probably also phosphorus (P) deficiency, can minimize eCO₂ effects on crop productivity^{4,25}.

101 While eCO₂ improves water-use efficiency, the eCO₂ growth stimulus, which accelerates leaf

102 growth and may increase leaf area and root biomass, can lead to higher water use and nutrient
103 limitation later in the growing season²⁶. The modulating effects of N and seasonal rainfall on
104 plant responses to *eCO*₂ have recently been demonstrated for a temperate C₃-C₄ grassland²⁷.

105 ***The effects of eCO₂ on crop quality.*** While *eCO*₂ has the potential to partly offset (and in some
106 cases and conditions even compensate for) the negative effects of climate change on crop
107 productivity (especially for C₃ crops such as wheat, rice, and soybean²⁸), a substantial body of
108 work has shown that a CO₂-rich atmosphere also results in lowering food quality and potential
109 affecting nutrition security²⁹⁻⁴³ (Supplementary Material S.1.2).

110

111 A meta-analysis³³ of 228 pairs of experimental observations on barley, potato, rice, and wheat
112 reported reductions in protein concentrations ranging on average from -15.3% to -9.8% under
113 *eCO*₂, while the reduction was relatively small (-1.4%) in soybean³³. A larger meta-analysis⁴³
114 done on 7,761 pairs of observations covering 130 species and cultivars reported an average 8%
115 decline in mineral concentrations (except for Mn) and high agreement between FACE and non-
116 FACE experiments. N fertilization and climate conditions may play a role in modulating the
117 *eCO*₂-response in protein and mineral (Fe and Zn) concentrations⁴¹⁻⁴², entailing that processes
118 such as mineralization should be taken into account to better understand this modulating role⁴².

119

120 Declines in B vitamins (ranging from -30% to -13% for rice cultivars) under *eCO*₂ have been
121 identified as well³⁰ (Supplementary Material S.1.2). These changes in rice quality under *eCO*₂
122 may affect the nutrient status of about 600 million people³⁰ around the world.

123

124 Global-scale declines in mineral, such as Ca, Mg, protein concentrations, and carotenoids under
125 *eCO*₂ have been reported for many C₃ plants in general, including non-staple crops and
126 vegetables⁴³⁻⁴⁵. A meta-analysis⁴⁶ on legumes and leafy vegetables found no changes in Fe,

127 vitamin C, and flavonoid concentrations under eCO_2 ; whereas antioxidant concentration tended
128 to increase (although with high uncertainty). In another study, significant decreases in Fe
129 concentration under eCO_2 were reported for leafy vegetables (-31%), fruit (-19.2%), and root
130 vegetables (-8.2%), together with decreases in Zn concentration (-10.7% in stem vegetables, -
131 18.1% in both fruit and root vegetables)⁴⁴. Conversely, eCO_2 favors higher total antioxidant
132 capacity in leafy vegetables (72.5%) but not in fruit vegetables (-14.4%)⁴⁴.

133

134 Decreases in protein concentration under eCO_2 are likely caused by nitrogen uptake not
135 keeping up with carbon in biomass growth, an effect called ‘carbohydrate dilution’ or ‘growth
136 dilution’ (Supplementary Material S.1.3). However, recent studies have also found that lower
137 protein concentrations may be triggered by reduced photorespiration and lower N-demand
138 under eCO_2 ^{43,47-48}. Indeed, slower photorespiration may induce a decrease in NO_3^- assimilation
139 and eventually lower protein concentration^{48,49}. However, changes in the ratio of manganese-
140 magnesium may help to counterbalance this effect⁴⁸. Leaf protein concentration is determined
141 by the balance of Rubisco carboxylation-oxidation, with the former one favored by eCO_2 , and
142 by Rubisco content⁵⁰. The reduction of Rubisco content and activity over time, being more
143 pronounced under eCO_2 , leads to lower leaf protein concentration. To date, no adaptation in
144 agronomic management or phenotypic traits in FACE experiments⁵¹⁻⁵² has compensated for
145 reduced protein concentration.

146 Thus, the negative impacts of eCO_2 on protein and nutrient availability may be such as to
147 require important adjustments of future food systems^{53,54}.

148

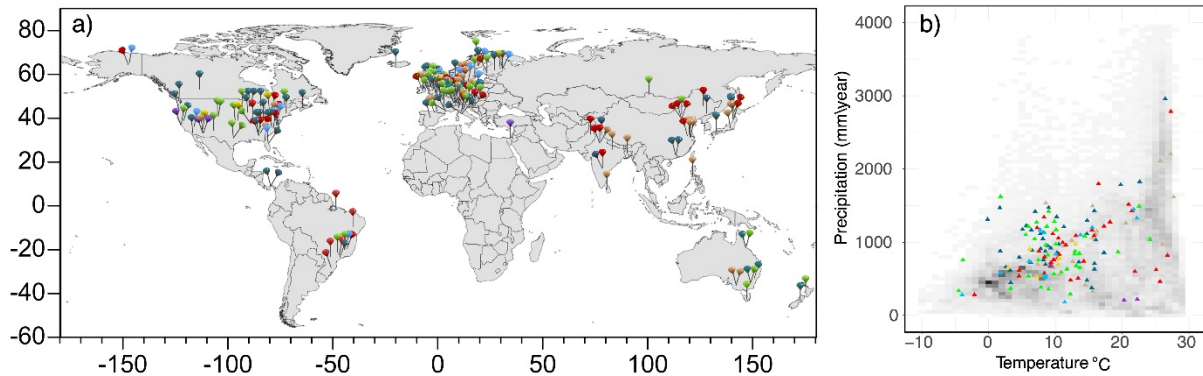
149 **Future directions to improve experimental coverage**

150 Although the overall number of eCO_2 -experiments is large and the findings of the main effects
151 on crops are unequivocal, more experimental work is still needed to improve the spatial

152 (geographical) representativeness, temporal (timing and duration) distribution, numbers of
153 crops and cultivars, and analyze components besides yield (e.g., water use and nutrient
154 concentrations).

155 As shown in Figure 1a, *eCO₂* experiments have been concentrated in Europe and the U.S., with
156 some significant multi-year, large-scale FACE studies in South America, Asia (Japan, China
157 and India), and Australia. There have been no *eCO₂* experiments in Africa, where agriculture
158 provides significant livelihoods. Furthermore, Figure 1b highlights the need for more
159 experiments in order to achieve a better coverage of the diverse climatic conditions around the
160 world. There is also a lack of multiple-year *eCO₂*-experiments, which are important for
161 grasslands and perennials, especially tree crops, and for understanding long-term effects on
162 soils and microbiota. A few long-term experiments have confirmed the ability of agro-
163 ecosystems to acclimate (i.e., reduced photosynthetic activity response compared to the initial
164 response, known as down-regulation) to a CO₂-rich environment⁵⁵ (Supplementary Material
165 S.1.4). Their results suggest that *eCO₂*-induced effects in grasslands and perennial crops are
166 highly dependent on climatic conditions and that acclimation may take more than 3-5 years⁵⁶⁻
167 ⁵⁹. Although acclimation is of less relevance for the main food crops, it is still an important
168 factor considering that it may act on shorter time scale and also looking at recent studies on
169 perennial grains⁶⁰ and the amplification of *eCO₂* positive effects through crop generations⁶¹.

170 Other types of experiments – including OTC, mini-FACE, climate control chambers and
171 enclosures – can be cheaper and faster. These experiments can significantly reduce
172 uncertainties by providing larger number of replicates and sample sizes, covering a larger range
173 of *eCO₂* well above 550ppm, and thus complementing and further supporting the evidence
174 provided by the more expensive and time-consuming FACE experiments. OTC and mini-
175 FACE may also help in addressing the role of *eCO₂* at night⁶², as many FACE experiments
176 only enrich during daylight hours.



178

179 **Figure 1. Overview of the eCO_2 experiments.** a). Global distribution of eCO_2 experiments on crops and
 180 grasslands. The distribution is derived from an updated version of the CLIMMANI Networking Group database
 181 (<https://climmani.org>, access date: October 2018; Table S2 in Supplementary Material) and other studies⁴³.
 182 Colors indicate different agricultural crops: green – grassland/forages, ochre – cereals (barley, maize, sorghum,
 183 wheat), purple – woody crops (cotton, grape), light blue – natural ecosystems, red – other crops (apple, banana,
 184 cassava, coffee, cucumber, lemon, orange, pea, peach, potato, radish, spinach), gold – artificial crops (single or
 185 multiple species mixtures without agricultural use). b). The mean annual temperature vs annual precipitation⁶³
 186 (1981-2010) of the experimental sites and of the global cropland⁶⁴ (grey area). The grey color gets darker
 187 according to the cropland area falling into the temperature/precipitation bin.

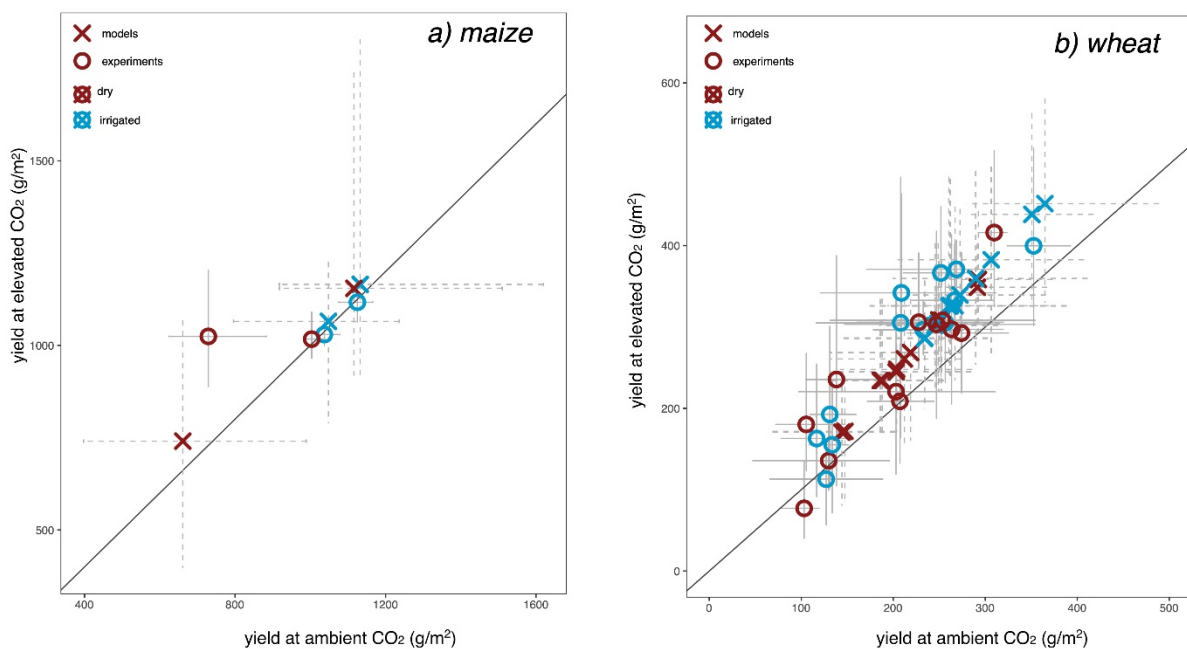
188

189 **Approaches for modeling primary production**

190 Crop growth models are key tools for scaling-up experimental evidence and assessing regional
 191 and global crop. We distinguish four basic types of approaches for modeling primary⁶⁵:
 192 complex with a biochemical basis; semi-complex involving leaf-level photosynthesis;
 193 radiation-use efficiency (RUE)-based; and transpiration-efficiency based⁶⁶. The choice of these
 194 modeling approaches largely determines how CO_2 responsiveness is implemented in crop
 195 models, either as simple response functions that scale productivity, or as components of the
 196 underlying mechanisms such as Rubisco kinetics⁶⁷ (Supplementary Material S.2).

197

198 While existing crop models include CO₂ responses in the simulation of primary production,
 199 they differ in the representation of transpiration and abiotic responses such as N stress⁶⁶.
 200 Many crop models have been tested against observations conducted with *eCO*₂ up to 600 ppm
 201 (FACE) and beyond (OTC). At the field scale under experimental conditions, crop models
 202 performed reasonably well⁶⁸ in reproducing the main effects of *eCO*₂ under both ample and
 203 limited water and N supplies, of higher temperatures on growth, harvestable yield, leaf area,
 204 water uptake, and of N dynamics for wheat⁶⁹⁻⁷¹, rice⁷², maize⁷³, cotton⁷⁴, potatoes⁷⁵⁻⁷⁶, and
 205 pasture⁷⁷. Figure 2 shows two examples of *eCO*₂ effects on yield of wheat and maize as
 206 simulated by crop models and measured in two dedicated experiments under different water
 207 and climatic conditions^{24,70,73,78}. Overall, good performance characterizes the modeling
 208 simulations, although some discrepancies remain (e.g. in the case of maize under dry
 209 conditions).



210
 211 **Figure 2. Yield responses (g/m²) to *eCO*₂ as measured in two FACE experiments^{24,78} and simulated by crop**
 212 **models^{70,73}.** a): maize yield responses to *eCO*₂ from a mixing ratio of 387 ppm to 550 ppm measured in the 2007-
 213 8 Braunschweig-FACE experiment²⁴ (northern Germany) under two levels of water supply: dry and irrigated.
 214 Uncertainty in measured crop yield response (given by replicates performed in the FACE experiment) is

215 *represented by grey solid lines. Uncertainty of the simulations, given by a 21-member ensemble of models⁷³, is*
216 *represented by grey dotted lines. b): wheat grain yield responses to eCO₂ from a mixing ratio of 365 ppm to 550*
217 *ppm measured in the 2007-9 Horsham-FACE experiment⁷⁸ (south-eastern Australia) under different water supply*
218 *conditions (dry and supplemental irrigation). Uncertainty in measured crop yield responses (given by replicates*
219 *performed in the FACE experiment) is represented by grey solid lines. Uncertainty of the simulations, given by a*
220 *6-member ensemble of models⁷⁰, is represented by grey dotted lines.*

221

222 Concerning the effects of N limitation in modulating the impacts of eCO₂, crop models in
223 general reproduce how the lack of adequate N reduces yield gains induced by eCO₂, although
224 uncertainties tend to be greater (Supplementary Figure S1). In most cases, crop models also
225 tend to underestimate yield gains induced by eCO₂ when N is adequate under experimental
226 conditions (Supplementary Figure S1).

227

228 **Scaling-up crop simulations from field experiments**

229

230 The high costs of running eCO₂ and climate change field experiments have prohibited the study
231 of a representative sample with respect to the crop genetics (G), environmental (E) conditions
232 and management (M) regimes (G×E×M) in which farmers produce crops. Process-based crop
233 models constitute an affordable solution to explore crop responses across a range of G×E×M
234 combinations and at any scale of interest. More than twenty global-scale crop models⁷⁹ have
235 been developed and many of them have been used in multi-model assessments^{28,80-82}. These
236 global crop models follow the same dynamic process approaches of field-based models and
237 have been increasingly used in economic and climate impact studies⁵⁻⁷ that contribute to policy
238 formulation^{7,83}. Large-scale crop simulations introduce additional uncertainty compared to
239 field-scale crop models due to lack of complete spatial and temporal data coverage on relevant
240 agronomic information. Simulation and scenario approaches are used to fill current data gaps⁸⁴⁻

241 ⁸⁹, and relevant global data are being marshalled to address these challenges. Trust in crop
242 modeling capacity has been gained over the past five decades since models were first
243 developed²⁸ based on widespread comparison of simulated yields and other variables against
244 available field data and from multi-model comparisons⁹¹⁻⁹³.

245

246 **The effects of *eCO*₂ in crop model simulations**

247 Past climate change assessments have routinely presented crop yield ‘with and without’ the
248 effects of *eCO*₂^{7,94-95}, under the implicit assumption that the no-*eCO*₂-effects scenario
249 represented an acceptable lower limit of the uncertainty range (Supplementary Table S3). That
250 extremely cautious approach has, however, generated unnecessary misunderstanding of
251 uncertainty regarding the current knowledge of *eCO*₂ on crops within climate change scenarios.
252 As a result, some studies⁹⁶⁻⁹⁷ have used crop modelling results based on both ‘with’ and
253 ‘without’ CO₂ simulations indistinguishably, potentially leading to misinterpretation of the
254 ensemble median, range, and causes for model (dis)agreement.

255

256 We demonstrate the issues in comparing crop model simulations with these different key
257 settings (i.e., with and without *eCO*₂) with global wheat and maize simulations under projected
258 climate changes (Supplementary Figure 2). The high uncertainties induced by the ‘without
259 CO₂’ lower bound ultimately reduce trust in the underlying crop models, whereas experimental
260 knowledge on the *eCO*₂ effect, as well as crop models’ ability to reproduce it, is substantial.

261

262 The large and growing body of experimental evidence has shown that current crop modeling
263 approaches are increasingly able to capture the main effects of *eCO*₂ on crop growth and yield
264 under a wide range of growing conditions at field scale. Hence, we argue that these effects
265 should be included by default in climate change impact assessments: there is no longer a

266 scientifically valid reason for expanding the range of model uncertainties to include a ‘without
267 *eCO₂*’ scenario (other than quantifying the isolated effect). Under optimal growing conditions,
268 ‘with *eCO₂*’ simulations should represent the upper bound of the uncertainty range. For the
269 lower bound, rather than using a ‘without *eCO₂*’ scenario, levels responding to observed
270 interactions of *eCO₂* with abiotic stresses affecting crop growth, e.g., soil N and water
271 availability⁷², temperature and O₃⁹⁸⁻⁹⁹ should be assessed.

272

273 **Knowledge gaps in model development**

274 Under complex growth-limiting environmental conditions, interactive processes are less well
275 understood. A recent experiment on maize indicated that crop model results corresponded well
276 to the observations under irrigated conditions^{73,100}. Nevertheless, some models had poor
277 performance under certain drought conditions (due to underestimation of *eCO₂* water savings),
278 and therefore underestimated the associated crop yield stimulation⁷³. Other nutrients, such as
279 phosphorus (P) and potassium (K), are often neither considered in crop models nor fully
280 measured or controlled in experiments, even though P is known to be a main limiting crop
281 nutrient in many soils, particularly in Africa¹⁰¹⁻¹⁰³.

282

283 A serious gap in crop modeling tools is the scarcity of models for fruits and vegetables⁶⁶. This
284 situation is now improving, but models for many more fruits and vegetables with the full range
285 of *eCO₂* responses are needed. In addition, most existing crop models do not account for
286 nutritional aspects other than protein concentration^{69,104}, while recent work on the socio-
287 economic impacts^{54,105} of reduced Fe and Zn concentration highlights the importance of
288 including other key nutritional aspects, such as mineral concentrations. Finally, the upper range
289 of projected CO₂ concentration by the end of the 21st century (e.g., up to a CO₂ mixing ratio of
290 936 ppm in RCP8.5) greatly exceeds *eCO₂* in current experiments. As the rate of C₃ crop

291 responses declines with eCO_2 approaching 600 ppm¹⁰⁶, and considering that the current
292 atmospheric concentration is currently about 412 ppm and increasing by 2-3 ppm *per* year, key
293 performance of crop models for long-term assessments will depend on the representation of
294 this saturating response in interaction with other environmental variables, especially
295 temperature,¹⁸ and possible physiological limitations¹⁰⁷.

296

297 **Key criteria for improving modeling protocols**

298 We argue that research and assessment should better focus on critical issues in projecting the
299 interactions of eCO_2 and climate change on crops. To this end, key criteria for selecting crop
300 models for climate change impact assessments should advance the representation as listed
301 below.

- 302 1. Concurrent and interactive effects of eCO_2 , temperature, water and nitrogen (CTWN) on crop
303 processes;
- 304 2. Evaluation of simulated responses to CTWN variation compared to a range of observations
305 from experiments (including at least crop cycle length, leaf area index, harvestable yield,
306 evapotranspiration) for C_3 and C_4 crops including staple grains, fruits, and vegetables;
- 307 3. Comparison with observations to identify systematic biases in simulated baseline (i.e., aCO_2)
308 crop yields, which should then be either bias-corrected or excluded from the crop model
309 ensemble.

310 The results of these evaluation tests should be made available as metadata in impact
311 assessments, and crop models should be assessed in standardized evaluation exercises¹⁰⁸. The
312 proposed criteria-based model could improve the robustness of multi-model impact
313 assessments.

314

315 **Roadmap to advance future research on eCO_2**

316 We outline here the main priorities for future research and point to existing barriers that must
 317 be addressed urgently to further improve scientific assessments of the effects of *eCO₂* and
 318 climate change on crop productivity and quality (Table 1). We propose that scientific
 319 community through international initiatives, such as the Agricultural Model Intercomparison
 320 and Improvement Project (AgMIP¹), plays an important role in delivering scientific resources
 321 that helps assess the potential biophysical and socio-economic consequences to support
 322 national and international agricultural policies.

323

324 **Table 1 Knowledge gaps, recommendations, and requirements for research progress on eCO₂ and climate**
 325 **change**

Data gaps and modeling inconsistencies	Recommendations	Main requirements to address
Data gap on crop nutritional quality, beyond N/protein	Include measurement of crop quality in experimental design.	Funding
Data gap on crop types and cropping systems	Expand FACE, mini-FACE, OTC, climate control chambers, and enclosures experiments to other crops and beyond high-input systems	Funding, Expertise, Infrastructure
Data gap in many agro-climatic regions of the world, especially Africa	Set up experiments in unstudied regions, especially in Africa	Funding, Expertise, Infrastructure
Data gap on interactions of <i>eCO₂</i> effects, weather conditions and extreme events	More long-term (>10 years) FACE studies incorporating climate variables	Funding; Infrastructure
Disparities in data measurements	Harmonization of measurement methods	Research method development
Limited sample sizes for testing experimental evidence	Increase replicates of experiments, especially non-FACE ones and those focused on nutrients.	Funding, Infrastructure
Lack of access to data	Set up and maintain an open-access data repository, e.g. within Copernicus and AgMIP	Funding, Communication, Database development
modeling uncertainty	<ul style="list-style-type: none"> - Use multi-model ensembles - Harmonization of variables and input data for modeling intercomparison exercises - Display and discuss additional measures other than the ensemble median - Use evaluation and validation criteria for inclusion of specific models 	Research method, Communication
Large uncertainty across scales	<ul style="list-style-type: none"> - Harmonize available input data sets - Identify an optimal set of global data to be used as input for large scale model runs - Create a common input data repository - Develop time-varying dataset of the main input parameters 	Research method, Funding, Infrastructure, Communication
Misleading scenarios using <i>without eCO₂</i> as plausible	For policy purpose, use results that fully include <i>eCO₂</i> effects (as well as N limitation) and are validated against recent <i>eCO₂</i> experiments	Research method, Communication
Effects on crop quality in modelling assessment are overlooked	<ul style="list-style-type: none"> - Development of modeling components to simulate protein and mineral concentrations - Set up AgMIP multi-modelling inter-comparison activity for coordinated 	Funding, Expertise, Research method

	model development and improvement that includes nutrient quality	
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327 First, new *eCO₂* experiments are needed for important crops in all agricultural regions of the
328 world, particularly for cropping systems and agro-climatic regions in Africa, in order to capture
329 the full diversity of responses. More experimental evidence on changes in crop quality and
330 nutrition is needed for a wider range of crops to represent the threat for human health. All new
331 studies describing results from specific CO₂-enrichment experiments should provide
332 comprehensive and detailed weather, soil and management information to be easily integrated
333 and used for crop model evaluation.

334 Synchronization of field experiments and modeling outputs should be enhanced to steadily
335 improve crop models. Building connections among scientific disciplines will contribute to
336 better access and use of experimental data to encourage continuous development of impact
337 modeling tools.

338 Secondly, crop model improvements should focus with high priority on capturing the complex
339 interactions of *eCO₂*, N, O₃, and varying climate/weather conditions, especially extreme events,
340 and nutritional aspects. This crop model development will be fostered by an international
341 initiative to be launched within AgMIP, but urgently requires research funding as well.

342 Thirdly, in addition to the inclusion of *eCO₂* by default in impact assessments, the use of multi-
343 model ensembles should be strongly encouraged to better capture modeling uncertainties⁸³.
344 Bias-correction techniques¹⁰⁹ should be applied to deal with potential biases in crop yield
345 baseline simulations²⁸

346 Finally, we propose to build an open-access web-repository (which could be hosted, for
347 example, in the Copernicus C3S data store in conjunction with AgMIP and other agricultural
348 modeling and data groups), containing information in standardized formats of experiments,

349 model metadata, and model simulations that are suitable for use in impact assessments, and to
350 be made accessible to stakeholders across the science and policy spheres.

351 This roadmap will contribute to further narrowing the uncertainties that have long hampered
352 actions on climate change mitigation and adaptation in agriculture, and facilitate major
353 improvements in the conduct and use of climate change impact assessments in the agricultural
354 sector.

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