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1 **INCREASING IMPACTS OF EXTREME DROUGHTS ON VEGETATION**
2 **PRODUCTIVITY UNDER CLIMATE CHANGE**

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24 **Abstract:** Terrestrial gross primary production (GPP) is the basis of food production and
25 vegetation growth globally¹, and plays a critical role in regulating atmospheric CO₂ through its
26 impact on ecosystem carbon balance. Even though higher CO₂ concentrations in future decades
27 can increase GPP², low soil water availability, heat stress, and disturbances associated with
28 droughts could reduce the benefits of such CO₂ fertilization. Here we analyzed outputs of 13
29 Earth System Models (ESMs) to show an increasingly stronger impact on GPP by extreme
30 droughts than mild and moderate droughts over the 21st century. Due to a dramatic increase in
31 the frequency of extreme droughts, the magnitude of globally-averaged reductions in GPP
32 associated with extreme droughts was projected to be nearly tripled by the last quarter of this
33 century (2075–2099) relative to that of the historical period (1850–1999) under both high and
34 intermediate greenhouse gas emission scenarios. In contrast, the magnitude of GPP reduction
35 associated with mild and moderate droughts was not projected to increase substantially. Our
36 analysis indicates a high risk of extreme droughts to the global carbon cycle with atmospheric
37 warming; however, this risk can be potentially mitigated by positive anomalies of GPP
38 associated with favorable environmental conditions.

39

40 The terrestrial biosphere absorbed ~30% of anthropogenic carbon emissions from fossil
41 fuels during 1990–2007³, making it a critical component of the global carbon sink that mitigates
42 fossil fuel CO₂ emissions and associated climate warming. GPP is a measure of fixation of CO₂
43 into an ecosystem through photosynthesis and plays a key role in the net carbon balance of the
44 terrestrial biosphere and the terrestrial CO₂ absorption. However, despite our knowledge of CO₂
45 fertilization effects on plant productivity², the future trend of GPP under elevated CO₂ levels
46 remains highly uncertain due to the impact of many factors such as nutrient limitation⁴ and
47 increasing frequency and intensity of drought⁵. Drought is already the most widespread factor
48 affecting GPP⁶ via direct physiological impacts such as water limitation and heat stress⁷, and
49 through its indirect impacts on increased frequency and intensity of disturbances such as fire and
50 insect outbreaks⁸ that release large amounts of carbon back into the atmosphere. In agreement
51 with such trends, several modeling studies have showed an increasing risk of a greater frequency
52 and intensity of droughts in many regions during the 21st century⁹⁻¹², which could affect the
53 magnitude of future GPP and lead to high uncertainty in projecting the future of terrestrial
54 carbon sink. Previous studies have assessed the importance of different climate factors for carbon
55 flux extremes^{13,14}, but few studies have specifically quantified future drought impacts on GPP at
56 the global scale.

57 To better understand how future drought will affect GPP at the global scale, we analyzed
58 the climate and GPP projections from 13 ESMs in the Coupled Model Intercomparison Project
59 Phase 5 (CMIP5)¹⁵. The models were selected based on the criteria that they reported both soil
60 water content at different depths and GPP, to quantify the potential impacts of droughts on future
61 terrestrial GPP. Given that plant responses to water stress depend on their historical climate
62 conditions¹⁶, we defined location (i.e., grid cell for ESMs) and model-specific droughts during

63 the historical period of 1850–1999 as months when plant accessible soil water (PASW: vertical
64 integral of soil water weighted by the fraction of roots in a soil column at different depths) was
65 less than the 10th percentile for each location. These percentile-defined droughts may not have an
66 impact on GPP at very wet sites, therefore, we only used the 10th percentile to define droughts if
67 GPP during these drought months was significantly lower (with a significance level of 0.01) than
68 that of the non-drought months (see Methods and Extended data Fig. 1 for details). We classified
69 droughts into extreme, moderate, and mild so that PASW was less than the 2nd percentile during
70 extreme droughts, between the 5th and 2nd percentiles during moderate droughts, and between the
71 10th and 5th percentiles during mild droughts. Projected future droughts were sorted into these
72 categories using the grid-cell-, model-, and month-specific historical simulations. The drought-
73 associated change in GPP was calculated based on the deviations (or anomalies) of GPP from the
74 mean for each month of a specific location during 1850–2099 (See Methods and Extended data
75 Fig. 1 for details). Positive deviations from the mean indicate that droughts stimulate GPP and
76 negative deviations indicate that droughts reduce GPP.

77 Our analysis showed that drought events defined by low PASW were projected to
78 become more frequent under future climates (Fig. 1). The frequency of extreme droughts per
79 year was projected to increase by a factor of ~3.8 (p-value < 0.001) under the high greenhouse
80 gas emission scenario (RCP 8.5¹⁵) and by a factor of ~3.1 (p-value < 0.001) under the
81 intermediate greenhouse gas emission scenario (RCP 4.5¹⁵) (Fig. 1a, b) during 2075–2099,
82 compared to the historical period of 1850–1999. The mean frequency of moderate droughts per
83 year was projected to increase by a factor of ~1.2 (not significant with p-value > 0.2) under
84 scenario RCP8.5 (Fig. 1d) and by a factor of ~1.5 (p-value < 0.01) under scenario RCP4.5 (Fig.
85 1c). One reason for the relatively lower increase of moderate drought frequency under scenario

86 RCP8.5 in comparison to scenario RCP 4.5 was that drought events became more extreme under
87 scenario RCP8.5 and thus there was a smaller proportion of moderate drought events under this
88 scenario (Extended data Fig. 2). These droughts were widely distributed with particularly high
89 risks for the Amazon, South Africa, Mediterranean Basin, Australia, and southwest USA (Fig.
90 2). The risk of mild droughts did not change significantly in the future (Fig. 1e, f). The drought
91 events were typically associated with low humidity (Extended data Fig. 3), low precipitation
92 (Extended data Fig. 4), high temperature (Extended data Fig. 5), high radiation (Extended data
93 Fig. 6), and increased carbon release from fire disturbances (Extended data Fig. 7).

94 The magnitude of annual GPP reductions associated with droughts was also projected to
95 increase substantially in the future (Fig. 3). In terms of absolute carbon fluxes, the magnitude of
96 forecasted mean reductions in global GPP associated with droughts will rise from ~2.8 Pg C per
97 year during 1850–1999 to ~4.5 and ~4.7 Pg C per year (p-value <0.01) during 2075–2099 under
98 emission scenario RCP8.5 and RCP 4.5, respectively (Extended data Fig. 8). Drought-associated
99 reductions in GPP (Figs. 3 and 4) can arise in two main ways: 1) via an increased intensity of
100 droughts (in terms of GPP impact), or 2) via an increased drought frequency. Our analysis
101 showed that the ensemble mean of absolute GPP reduction per drought event was not projected
102 to be significantly larger in the future (Extended data Fig. 9). This could result from the effect of
103 CO₂ fertilization for the both drought and non-drought months (see next paragraph for details).
104 Therefore, the increasing impact of drought upon GPP mainly resulted from the increased
105 frequency of drought events. Due to the relatively large increase in the frequency of extreme
106 droughts (Fig. 1), the magnitude of GPP reductions associated with extreme droughts increased
107 much more than that associated with moderate and mild droughts in the future (Fig. 3).
108 Specifically, the magnitude of annual GPP reduction associated with extreme droughts during

109 2075–2099 was projected to increase by a factor of ~ 2.9 (p -value < 0.001) and ~ 2.7 (p -value $<$
110 0.001) under emission scenarios of RCP8.5 and RCP4.5, respectively (Fig. 3 a, b), compared to
111 their historical mean values during 1850–1999. In contrast, no significant increase in the
112 magnitude of mean GPP reduction was detected for mild and moderate droughts except for the
113 moderate droughts under RCP4.5 (Fig. 3 c-e). Therefore, the proportion of total GPP reduction
114 contributed by extreme droughts was projected to increase from $\sim 28\%$ during 1850–1999 to ~ 56
115 and 49% during 2075–2099 under emission scenarios RCP 8.5 and RCP4.5, respectively
116 (Extended data Fig. 10). The projected GPP reductions associated with droughts were correlated
117 with changes in several environmental drivers including PASW, temperature, humidity and
118 radiation, and vegetation states with each variable contributing ~ 10 – 30% on average
119 (Supplementary Fig. 1 and Supplementary Fig. 2).

120 The GPP reduction associated with droughts can be viewed in the context of rising GPP
121 under future CO_2 fertilization, which was included in all selected Earth system model
122 projections. Due to CO_2 fertilization and higher temperature for high latitudes, the globally-
123 averaged mean GPP was projected to be $\sim 50\%$ and $\sim 31\%$ higher for year 2075–2099 compared
124 to the historical period (1850–1999) under emission scenarios of RCP 8.5 and RCP 4.5,
125 respectively (Supplementary Fig. 3). Similarly, the GPP in drought periods was also projected to
126 increase significantly for mild and moderate droughts (p -value < 0.02) but not significantly for
127 extreme droughts (Supplementary Fig. 4). To better understand the drought impacts in relative
128 terms, we calculated the impacts of droughts as the percentages reduction in GPP associated with
129 droughts. The percentage reduction averaged across all models showed no significant change
130 during 2075–2099 compared to the historical period during 1850–1999 under RCP 8.5
131 (Supplementary Fig. 5 a). Under the emission scenario of RCP 4.5, percentage reduction of GPP

132 by droughts was projected to have a slight increase from ~1.8% per year during 1850–1999 to
133 ~2.3% per year (p-value < 0.01) in 2075–2099 (Supplementary Fig. 5b). Relative to RCP 4.5, the
134 lower percentage reduction in GPP during 2075–2099 under RCP 8.5 could result from the
135 beneficial impact of higher CO₂ concentrations on plant production during moderate and mild
136 droughts (e.g., higher photosynthetic rate and increased water use efficiency with lower stomata
137 conductance²) (Supplementary Fig. 6 c-e). For both mild and moderate droughts, the magnitude
138 of percentage reduction in GPP decreased except for moderate drought under RCP4.5
139 (Supplementary Fig. 6 c-e). However, for extreme droughts, the percentage reduction in GPP
140 was projected to be doubled (p-value < 0.001) under both emission scenario RCP 8.5 and RCP
141 4.5 (Supplementary Fig. 6 a, b). This suggests that the magnitude of extreme-drought-associated
142 GPP reduction increases faster than the mean GPP in the future.

143 There was a large latitudinal variation in the projected impact of drought on GPP. The
144 drought impacts on GPP for years 2075–2099 (measured by the grid-cell-specific GPP reduction
145 relative to the historical period of 1850–1999) were much larger in tropical and temperate
146 regions and smaller at high latitudes (Fig. 4; see Supplementary Fig. 7 for a reference over years
147 1975–1999). The uncertainty was also relatively lower for tropical and temperate regions as
148 measured by the relative amount of deviation from the ensemble mean (Supplementary Fig. 8
149 and Supplementary Fig. 9). The large increase in the magnitude of drought-associated reduction
150 in GPP projected for tropical and temperate regions (Fig. 4) is in agreement with recent
151 observations of drought-associated vegetation changes in Europe¹⁷, the Amazon basin¹⁸, Western
152 US^{19,20}, and the global assessment of drought-induced plant production reduction during 1999–
153 2009 using remote-sensing-based estimates²¹. The small impacts of droughts on GPP at high
154 latitudes could result from their relatively low GPP and beneficial consequences of higher

155 temperature (Extended data Fig. 5) and radiation (Extended data Fig. 6) during the drier months
156 in these colder regions²², where relatively high antecedent soil moisture buffers vegetation
157 against stress-inducing drought levels despite experiencing statistically dry conditions. However,
158 this projection of small GPP reductions at high latitudes could be too optimistic given that all the
159 current ESMs do not explicitly consider insect dynamics, which are influenced by drought and
160 warming climate and have substantial impacts on regional to global carbon cycles^{23,24}. Long-
161 term observational data also showed that drought had already led to substantial tree mortality
162 across Canada from 1963–2008²⁵.

163 The ESMs projected not only an increase of mean GPP in the future due to CO₂
164 fertilization (Supplementary Fig. 3), but also an increase of variability in GPP (Supplementary
165 Fig. 10). This suggests that magnitude of both positive and negative anomalies around the mean
166 of GPP will increase in the future¹⁴. The GPP reduction associated with drought represents one
167 of the key drivers of negative abnormalities for the simulated GPP in ESMs; however, at global
168 scale, these negative anomalies could be mitigated by the positive anomalies of GPP related to
169 wet conditions, favorable temperature and radiation, and enhanced water use efficiency due to
170 elevated CO₂ concentration². Zscheischler et al¹⁴ pointed out that the dominance of large
171 negative carbon extremes (e.g., deviation of GPP from the mean) could be changed toward
172 dominance of large positive carbon extremes in GPP in the 21st century. Thus, it is possible that
173 the high risk of increasing impact of extreme droughts on GPP could be mitigated by the positive
174 impacts on GPP in the future under favorable environmental conditions of temperature, soil
175 moisture and radiation.

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238

239 *Methods*

240 We selected 13 ESM simulations (Supplementary Table 1) from CMIP5 archive, based
241 on the criteria that they reported both soil water at different soil depths and GPP. There are
242 multiple simulations for each ESM under each specific greenhouse gas emission scenarios. In
243 this study, we selected only the first reported simulation for each model, given that multiple
244 inclusions of the same model might lead to its over-representation in our analysis²⁶. We also
245 collected additional climate variables including precipitation, radiation, temperature and relative
246 humidity to identify the deviations in climate for drought months from the same CMIP5 archive.
247 In this study, we only considered two emission scenarios: RCP8.5 and RCP4.5. This was
248 justified by the fact that these scenarios generally capture the potential range of future
249 greenhouse gas releases and that fewer simulations are available for other emission scenarios.

250 There are many ways to define droughts¹¹. Because our goal was to understand impacts
251 of drought on GPP, we used plant accessible soil water (PASW) as an indicator of drought.
252 PASW was defined as the sum of soil water weighted by the fractions of plant roots at different
253 soil depths (see Supplementary Note 1 for details). Because drought tolerance of plants depends
254 on their historical climate conditions¹⁶, we defined droughts based on the site-specific PASW.
255 Specifically, we defined a month in a specific year as a month of mild, moderate, and extreme
256 drought if its PASW was less than (or equal to) the 10th but larger than the 5th percentile, less
257 than (or equal to) the 5th but large than the 2nd percentile, and less than (or equal to) the 2nd
258 percentile for the same month during 1850–1999, respectively (Extended data Fig. 1a). These
259 percentiles were then used to identify months of different levels of droughts during 2000–2099
260 based on the projected PASW. Even if PASW of a certain month was relatively low (e.g., <10th
261 percentile) for a specific year, it may not have an impact on plant production if the site was very

262 wet. Thus, we used these percentiles to define droughts only if GPP values of a specific month
263 for the years with PASW less than the 10th percentile were significantly lower than the rest of
264 years during 1850–2099 (see Supplementary Note 1, Supplementary Fig. 11, and Supplementary
265 Fig. 12 for details).

266 In most models, each grid cell can contain more than one plant functional type (PFT)
267 with differing root distributions. Ideally, we could have defined droughts based on whether the
268 PASW of a PFT had a significant impact on the PFT-specific GPP; however, the CMIP5
269 database only has a single total GPP for each specific grid cell. In this study, droughts were thus
270 defined by PASW of different PFTs as long as GPP during the defined drought months was
271 significantly lower than that during non-drought months (see Supplementary Note 1 for details of
272 statistical tests). This does not affect our analysis because all the droughts defined by PASW of
273 different PFTs had a significant impact on the lumped GPP. If a specific month was set as
274 drought month by PASW of multiple PFTs, however, we defined the drought category based on
275 the PASW of the PFT that had the most significant impact on GPP (see Supplementary Note 1
276 for details).

277 To quantify drought impacts on GPP, we first fitted a smooth spline over noisy
278 simulations of GPP for a specific month (e.g., May) during 1850–2099 (Extended data Fig. 1b).
279 See Supplementary Note 2 for details of smooth spline estimations. This spline was then used to
280 represent the mean GPP for the month of interest. For each drought month, the deviation (or
281 anomaly) of its GPP from the estimated spline was used to quantify the monthly impact of
282 drought on GPP (Supplementary Note 3 and Extended data Fig. b). Finally, we summed these
283 deviations across months and spatial locations to estimate impacts of the drought on GPP at the
284 global scale. The corresponding standard errors were estimated based on the standard errors of

285 the estimated spline (see Supplementary Note 2 for details). Statistical tests were used to test for
286 significant differences in drought risks and associated GPP reductions (see Supplementary Note
287 5 for details). Our approach might underestimate drought impacts, because drought-associated
288 GPP reduction could plausibly extend past the end of the duration of drought defined based on
289 soil moisture^{13,27}. Further studies based on specific model experiments are needed to identify
290 these lag impacts, because it is difficult to confirm if the follow-on reductions in GPP result from
291 the lag effects of droughts or other environmental condition changes (e.g., low radiation) in the
292 CMIP5 archive.

293 It is important to point out that the PASW is only one indicator of drought. The impact of
294 droughts on GPP can be attributed to different climate variables such as temperature, humidity,
295 radiation, precipitation, and PASW, and to different vegetation states such as PFT compositions,
296 height, and leaf area index. To understand the importance of different climate variables and
297 vegetation states on GPP reductions associated with droughts, we fitted multilinear regressions to
298 estimated GPP deviations with explanatory variables of PASW, daily temperature, incoming
299 solar radiation, relative humidity, and mean GPP (as an indicator of overall vegetation status) for
300 all the drought events for a specific month for the 25-year periods during 1850–2099 (see
301 Supplementary Note 4 for details).

302 ***Data Availability***

303 The ESM output data that support the findings of this study are available from the CMIP5 site
304 (<https://esgf-node.llnl.gov/projects/cmip5/>).

305 ***Code availability***

306 The processing R codes are available from corresponding author upon request.

307

308 ***METHODS REFERENCES***

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314

315

316 **ENDNOTES**

317 Please contact Chonggang Xu (cxu) for correspondence and requests for materials.

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334 the Global Organization for Earth System Science Portals.

335

336 **Author Contributions**

337 All authors contributed to the manuscript writing. CX and NGM initially designed the
338 experiment. CX implemented the analysis. LW helped data exploration for evaluating the
339 results; RAF, SS, BOC and RM provide suggestions for improvement of the experimental design
340 and analysis. EW provided support on water limitation functions and PFT mapping on GFDL
341 and NOAA models.

342 **Competing Interests statement**

343 We declare that no competing interests are present in the manuscript.

344

345 **Figure legends**

346 **Fig. 1 Temporal changes in annual drought frequency relative to the historical period of**
347 **1850–1999.** The relative frequencies were calculated on a model-specific basis, dividing the
348 projected mean annual drought frequency (drought events/year) for a specific period (e.g., years
349 2075–2099) by that over the historical period. Values <1 indicate that the drought frequency
350 decreases while values >1 indicate that the drought frequency increases compared to the
351 historical period. The P-values were calculated using the bootstrap sampling (see Supplementary
352 Note 5.2 for details) to test if the mean frequency across different models during 2075–2099
353 were significantly higher than the historical period. The gray horizontal line represents the
354 ensemble mean for 2075–2099. See Supplementary Table 1 for the abbreviations of 13 selected
355 Earth system models.

356 **Fig. 2 Spatial distribution of drought frequency during 2075–2099 relative to the historical**
357 **period of 1850–1999.** The relative frequencies were averaged over the ensemble of 13 Earth
358 system models. They were calculated on a model- and grid-cell-specific basis, dividing the mean
359 drought frequency per year (drought events/year) during 2075–2099 by that over the historical
360 period. Values <1 indicate the drought frequency decreases while values >1 indicate that the
361 drought frequency increases compared to the historical period. The frequencies projected by
362 different models were interpolated to a reference spatial resolution [1.125° (longitude) x 0.9375°
363 (latitude)] for mapping purposes.

364 **Fig. 3 Temporal changes in GPP anomalies associated with droughts relative to the**
365 **historical period of 1850–1999.** The relative anomalies were calculated on a model-specific
366 basis, dividing the mean annual GPP anomaly associated with droughts ($\text{kg C/m}^2/\text{year}$) for a
367 specific period (e.g., years 2075–2099) by that for the historical period (see Methods and

368 Supplementary Note 3). They were multiplied by (-1) to indicate that droughts decrease GPP,
369 with -1 indicating the reference drought-associated GPP anomaly for the historical period.
370 Hence, values < -1 indicate that the magnitude of GPP reduction becomes larger relative to the
371 historical period, while values > -1 indicate that the magnitude of GPP reduction becomes
372 smaller. The dotted line shows the mean relative anomaly during 2075–2099 across all models.
373 The P-values were calculated using the bootstrap sampling (see Supplementary Note 5.2 for
374 details) to test if the mean magnitude of GPP reduction during 2075–2099 across different
375 models becomes significantly larger than that during the historical period. See Supplementary
376 Table 1 for the abbreviations of 13 selected Earth system models.

377 **Fig. 4 Spatial distribution of GPP anomalies associated with droughts during 2075–2099**
378 **relative to the historical period of 1850–1999.** The relative anomalies were averaged over the
379 ensemble of 13 Earth system models. They were calculated on a model basis, dividing the grid-
380 cell-specific mean annual GPP anomalies ($\text{kg C/m}^2/\text{year}$) during 2075–2099 by the global mean
381 annual GPP reduction ($\text{kg C/m}^2/\text{year}$) for the historical period. The relative anomalies were
382 multiplied by (-1) to indicate that droughts decrease GPP, with -1 indicating the reference global
383 mean GPP reduction for the historical period. Hence, values < -1 (shades of red) indicate that the
384 magnitude of GPP reduction was larger than the global mean GPP reduction during the historical
385 period, while values > -1 (light blue) indicate that the magnitude of GPP reduction was smaller.
386 The drought-associated changes in GPP projected by different models were interpolated to a
387 reference spatial resolution [1.125° (longitude) \times 0.9375° (latitude)] for mapping purposes.