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1 **Shifting from a fertilization-dominated to a** 2 **warming-dominated period**

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31 **Carbon dioxide and nitrogen fertilization effects on ecosystem carbon sequestration**
32 **may slow down in the future because of emerging nutrient constraints, climate**
33 **change reducing the effect of fertilization, and expanding land use change and land**
34 **management and disturbances. Further, record high temperatures and droughts are**
35 **leading to negative impacts on carbon sinks. We suggest that, together, these two**
36 **phenomena might drive a shift from a period dominated by the positive effects of**
37 **fertilization to a period characterized by the saturation of the positive effects of**
38 **fertilization on carbon sinks and the rise of negative impacts of climate change. We**
39 **discuss the evidence and processes likely leading to this shift.**

40

41 Humans strongly fertilize the planet. Human activities result in increasing atmospheric
42 concentrations of carbon dioxide (CO₂)¹ and nitrogen (N) inputs to ecosystems². This leads
43 to increased availability of biospheric carbon (C) and N and, enhanced metabolism of
44 organism. In addition warming¹ is lengthening the growing seasons in the northern
45 hemisphere^{3,4}. Plants can consequently grow more. This enhanced plant growth is a driver
46 of carbon sinks but it is not sufficient: there must also be ecosystem compartments where
47 carbon is retained before being cycled back to the atmosphere, and plants must allocate
48 carbon to these long-lived compartments. In fact, the magnitude of carbon sinks and their
49 duration depend both on the rate of increase of carbon inputs and on the residence time of
50 the carbon being taken up by ecosystems. Changes in these two processes will affect the
51 future evolution of sinks and thus in return, of atmospheric CO₂ and climate. For instance, if
52 the input to land carbon pools from primary productivity slows down and eventually
53 saturates, e.g. because of emerging nutrient constraints on plant productivity, and if the
54 residence time of excess carbon remains constant, sinks will slowly decrease and eventually
55 disappear. If instead the carbon residence time becomes shorter, e.g. in the case of increased
56 biomass mortality or an increasing allocation of carbon to short-lived pools such as fine
57 roots and leaves, then ecosystems lose part of their sink capacity even if their productivity
58 continues to increase. Examples of the latter case occur when disturbances such as fire lead
59 to the long-term reduction of forest biomass and soil carbon or to the exposure to
60 decomposition of previously protected soil carbon. In the case of an irreversible disturbance
61 not followed by a recovery of carbon stocks, there is not only an initial source of CO₂ to the
62 atmosphere, but the replacement of a slow turnover system by a fast turnover one that

63 reduces the sink capacity in the long term; an example is the conversion of forest lands to
64 croplands. Changes in residence times are function of changes in land use and land
65 management, disturbances, changes in carbon allocation, decomposition, and changes in
66 ecosystem structure. Past, current and future changes in land carbon sinks thus result from
67 the interplay between an overall change in productivity and/or changes in the residence
68 times of carbon in ecosystem pools. Both productivity and residence times respond to
69 changing CO₂, climate and nutrient availability⁵.

70 Current evidence suggests that land C storage and therefore land C sinks are
71 increasing at global scale and that human-induced CO₂ and N fertilization and warming (and
72 changes in other climate variables) play a key role in this increase. This land sink has grown
73 rapidly in the past five decades consistent with the rapid increase of CO₂ emissions from
74 fossil fuel use and with the recorded land use change⁶. At local scale, estimates from long-
75 term flux tower records show that gross primary productivity (GPP) and net ecosystem
76 production (NEP) have increased by 1% annually from 1995 to 2011 across 23 forests in
77 Europe and the USA⁷. Satellite observations show a widespread greening trend in 25-50%
78 of vegetated areas during the last 30 years as compared to only 4% of the areas showing
79 decreased greenness⁸. Some studies on forest inventories also report increasing carbon
80 storage in intact tropical forests⁹ and other forests¹⁰. Attribution studies suggest that
81 increasing atmospheric CO₂ is the most likely factor associated with the increasing strength
82 of the carbon sink. This is the case for the flux-tower sites in Europe and the USA⁷ and also
83 for global greening trends⁸, where factorial simulations with global ecosystem models
84 suggest that CO₂ fertilization explains 70% (4.7-9.5% increase in global mean LAI) of the
85 observed trend in greening; nitrogen deposition contributed 9%, climate change 8%, and
86 land-cover change 4%. The relatively small global effect of climate change is because the
87 effects of climate regionally oppose each other whereas the CO₂ fertilization effect is more
88 uniform and consistent across biomes. Analyses of forest inventory data have also
89 concluded that the current increase in biomass carbon stocks in European and North
90 American forests can only be explained with a contribution of rising CO₂ increasing
91 productivity^{11,12}. These data, together with results from short-term experiments on elevated
92 CO₂, nutrient fertilization and warming, despite their shortcomings, support enhanced
93 productivity in response to elevated CO₂¹³⁻¹⁵. The fact that the global residual land sink has
94 increased in the past three decades, that long term flux towers show increases of NEP, and
95 that remote sensing and forest inventory data show an increased sink in most regions
96 suggests that the residence time of excess carbon has not been reduced significantly over
97 the last decades with a magnitude sufficient to offset productivity induced carbon storage.

98 However, there are now indications that these trends of increasing sinks may be
99 slowing down. Here, we point out these indications to thereafter discuss the likely
100 limitations for fertilization-enhancement of carbon sinks underlying them (limitations by
101 key nutrients such as P, reduced sensitivity to warming, negative responses to Tmin and
102 heatwaves, droughts, fires, land use changes and their legacy, harvests, and climatic and
103 human disturbances leading to reductions of C residence times). This discussion finally
104 drive us to hypothesize that a long term weakening of the natural land sink relative to fossil
105 fuel CO₂ emissions may be driving to the beginning of an anthropocenic transition from a
106 vegetation fertilization-dominated period to a period dominated by nutrient and climate
107 constraints on further plant growth, and larger climate change impacts.

108

109 **Indications of slowing down of trends of increasing sinks**

110 All over the world, and particularly in northern latitudes, the difference between the annual
111 minimum and maximum concentrations of CO₂ (the amplitude) has been increasing since
112 the 1960s. This seems mainly due to increasing plant growth in the North. The strong
113 seasonality of gross primary productivity and ecosystem respiration causes a larger average
114 CO₂ amplitude in northern high latitudes than in low latitudes. The analyses of these long-
115 term atmospheric CO₂ concentration records of the stations at Mauna Loa in Hawaii and
116 Point Barrow in Alaska shows that the sensitivity of the annual peak-to-peak amplitude of
117 CO₂ for an increase of 1 ppm CO₂ decreased to 0 in 2015, while the sensitivity per °C
118 warming decreased to 0 already in the early 1990s and is now negative, particularly in
119 Northern latitudes (Fig. 1a-d). These trends suggest that terrestrial ecosystems are
120 responding at a decline rate to the continued increase of atmospheric CO₂ (fertilization
121 effect). And likewise, that the positive effects of warming in the high latitudes leading to
122 higher rates of carbon uptake are also declining.

123 Between the first and the last 20 years of the Mauna Loa record, used as two end
124 points, which helps to filter quasi-decadal variability, the ratio of the residual land sink to
125 land-use and fossil-fuel emissions decreased from 0.34 ± 0.08 to 0.28 ± 0.05 ($p = 0.09$),
126 suggesting a slightly decreased efficiency of natural ecosystems to absorb emissions (Table
127 1). This decline in the efficiency of land sinks occurred in spite of the Pinatubo eruption (that
128 caused a short lived increase of carbon sinks). Although C sinks are still increasing, the
129 combined land–ocean CO₂ sink flux per unit of excess atmospheric CO₂ above preindustrial
130 levels has declined by 1/3 over 1959-2012¹⁶, implying that CO₂ sinks increased more slowly
131 than excess CO₂. Using a very simple carbon–climate model, Raupach et al¹⁶ attributed this

132 slower increase to slower-than-exponential CO₂ emissions growth (~ 35 % of the trend),
133 accidents of history causing short-lived increases of sinks like volcanic eruptions (~ 25 %),
134 sink responses to climate change (~ 20 %), and nonlinear responses to increasing CO₂,
135 mainly oceanic (~ 20 %)16.

136 An analysis of tree-ring δ¹³C and growth over the last 40 years at 47 sites covering
137 all major types of forest biomes, including boreal, wet temperate, Mediterranean, semi-arid
138 and tropical biomes, also shows that tree growth at those sites did not increase significantly,
139 despite an increase in atmospheric CO₂ concentrations of over 50 ppm and a 20.5% increase
140 in intrinsic water-use efficiency17. This suggests that other factors are counteracting the
141 potential growth benefits of a CO₂-rich world at many of the studied sites17. Similar results
142 were reported for tropical trees18. There are also other studies based on forest inventories
143 suggesting a declining sink rate in European forests19, in tropical intact forests10, and in the
144 biomass accumulation of Amazon forests20. Possible explanations for this decline are higher
145 night time temperatures in the tropics driving higher ecosystem respiration21 and increased
146 biomass mortality20. Piao et al22,23 have also reported a weakening temperature control on
147 the interannual variations of spring carbon uptake across northern lands in the last 17 years
148 and suggest that it is attributable to the declining temperature response of spring net
149 primary productivity (NPP) rather than to changes in heterotrophic respiration or in
150 atmospheric transport patterns. Reduced chilling during dormancy and emerging light
151 limitation are possible mechanisms contributing to the loss of NPP response to warming.
152 Furthermore, the legacy effects of land use changes have a limited duration and therefore
153 need to be taken into account in this consideration of saturation and even reversal of carbon
154 sinks. A remaining question is whether in regions where carbon sinks may be slowing down,
155 this is due to stalling productivity or to reducing residence times.

156 Ecological studies have not fully proved the universality of the CO₂ fertilization
157 effect, while several studies have documented well the negative effects on ecosystem carbon
158 storage due to warming and drought (Fig. 2). The impacts of warming and drought on
159 terrestrial ecosystems are negative when the increased evaporative demand and the
160 decreased soil water availability increase drought stress effect and mortality. In the tropics
161 there is also the negative impact of the likely rise of temperatures above the optimum that
162 decreases GPP and NPP. In fact, optimum temperatures24 are close to current values for
163 tropical forests. In mid-latitudes and boreal regions, additional possible negative impact
164 comes from increased fire risk in dry seasons., although fire risks would not necessarily be
165 increasing with warming25. In the boreal and arctic regions, with large soil carbon stocks,
166 warming increases soil respiration and soil carbon loss from frozen carbon stocks. For one

167 degree of warming, about 30 petagrams of soil carbon are now estimated to be released into
168 the atmosphere, or about 2-3 times as much as is emitted annually due to human-related
169 activities. These losses are largely driven by the losses of carbon in these most sensitive
170 boreal and arctic regions^{26,27}. Loss of permafrost carbon can only be partially compensated
171 by beneficial temperature increases on tree growth in boreal forests, woody encroachment
172 and longer growing seasons due to strong warming in those regions.

173 The two largest and most vulnerable carbon stocks are tropical forest biomass
174 vulnerable to drought²⁸ and rising T²⁹ (although controversial³⁰) and the boreal and arctic
175 soil carbon stocks vulnerable to warming and thawing³¹. Tropical forest biomass and soil
176 carbon hold about 400 Pg C, while tropical peatlands in South-east Asia, vulnerable to fire
177 hold about 100 Pg C³². Frozen carbon stocks are about 1600 Pg C, among which 130 to 160
178 Pg C vulnerable to climate-induced loss^{31,33}. Compared to these large and potentially
179 vulnerable carbon pools, temperate forests biomass hold only 41 Pg C and pan-boreal
180 forests 50 Pg C¹⁰. Thus the plausible loss of 10% of tropical forest biomass or 37-174 PgC
181 by 2100 of high latitude frozen carbon³³ represents an amount of carbon comparable with
182 the implausible loss of 100% of temperate and boreal forest biomass.

183 All these observational data suggest a decrease in the efficiency of carbon sinks to
184 remove excess atmospheric CO₂ albeit a continue increase in the magnitude of sinks.
185 Together with the experimental evidence on the effects of rising atmospheric CO₂ on plant
186 growth also often showing saturation of the CO₂ fertilization effect^{34,35} suggest limits to the
187 buffering capacity of the biosphere. They suggest a slowdown of the CO₂ and N fertilization
188 effects on ecosystem carbon sequestration and a rapid emergence of negative ecosystem
189 impacts from global climate change that might drive a shift from a period dominated by
190 fertilization to another period characterized by saturated fertilization and strong climate
191 change. That is, the impacts of warming on the land sinks are likely to be larger in the future
192 than the benefits from CO₂ fertilization because of nutrient and climate constraints,
193 management and disturbance that reduce the increase in carbon stocks and thus the
194 sequestration potential.

195

196 **Likely limitations for enhancement of carbon sinks.**

197 *Key nutrients*

198 The anthropogenic increases in CO₂ and atmospheric nitrogen deposition are not matched
199 by a similar increase in the inputs of other key nutrients such as phosphorus (P) and/or

200 potassium (K). A simple mass-balance approach of the NPP-based and C stock-based
201 demands indicates that limited P availability and the corresponding N:P imbalances will
202 result in a smaller CO₂ removal by terrestrial ecosystems during this century than currently
203 predicted by biogeochemical and Earth system models^{36,37}. Changes in mineralization with
204 climate change, and other processes governing the recycling of nutrients, are a large source
205 of uncertainty in the amount of nutrients available for the accumulation of new biomass³⁶.
206 However, an increasing biological P demand is likely to outpace exogenous P inputs,
207 suggesting that an accelerated cycling of existent P pools will be critical to sustain
208 productivity and carbon sinks. An increase in the amount of new P from weathering is also
209 possible under conditions of strong warming, but the effects of climatic warming on P
210 dynamics are even less known. Thus, the changes in the future availability of P are uncertain,
211 but current evidence suggest an overall shortage of P which will act as a limiting factor to
212 meet the increasing demand for plant growth³⁶⁻³⁸. A better understanding of the factors that
213 regulate exchanges between pools of "available" and "unavailable" soil P is critically needed.
214 Furthermore, a better quantification of how N limitation restricts C sinks from CO₂
215 fertilization both by limiting NPP increase and by resulting in a lower wood allocation as
216 plants are forced to allocate below ground to obtain N for NPP is also warranted.

217 *Reduced sensitivity to warming and negative responses to T_{min} and heatwaves*

218 Warming is lengthening the growing seasons in the northern latitudes³ but the apparent
219 response of leaf unfolding to climatic warming (expressed in days of advance of leaf
220 unfolding per °C warming) has decreased by 40% from 1980 to 2013 for deciduous forests
221 in Europe³⁹. The reduction in sensitivity is likely to be partly attributable to reduced winter
222 chilling and other mechanisms, such as photoperiod limitation⁴⁰, that may become
223 ultimately limiting when leaf unfolding occurs too early in the season, together resulting in
224 a slowdown in the advance of spring tree phenology.

225 Furthermore, the satellite-derived normalized difference vegetation index (NDVI), an
226 indicator of vegetation greenness, is negatively correlated with T_{min} in boreal regions of the
227 Northern Hemisphere⁴¹. Similar patterns were detected in maps of terrestrial net CO₂
228 exchange obtained from a relatively high-resolution atmospheric inversion⁴¹. In addition,
229 the analysis of the long-term records of atmospheric CO₂ concentration from the Point
230 Barrow station (71°N) in Alaska suggests that the peak-to-peak amplitude of CO₂ increased
231 by 28±11% for a +1 °C anomaly in T_{max} from May to September over land north of 51°N, but
232 decreased by 34±14% for a +1 °C anomaly in T_{min}. This asymmetry is especially important
233 because temperature data for the last century shows faster warming at night (T_{min}) than
234 during the day (T_{max})¹, although this effect is uncertain for the future given strong aerosol

235 reductions as suggested by RCP scenarios. These multiple lines of evidence suggest that
236 asymmetric diurnal-nocturnal warming is an important process affecting terrestrial
237 ecosystems. Higher nocturnal temperatures enhance night respiration, with important
238 implications for carbon cycling.

239 Severe regional heatwaves are also likely to become more frequent in a changing
240 climate^{42,43} (Fig. 3), and their negative impact on terrestrial carbon sequestration may thus
241 also become important. For example, the 2003 drought and heatwave decreased European
242 gross primary productivity by 30%, which resulted in a strong anomalous net source of
243 carbon dioxide (0.5 Pg C y⁻¹) to the atmosphere; this effect is the equivalent of reversing four
244 years of net ecosystem carbon sequestration in the European continent⁴⁴. Heatwaves are
245 often co-occurring with droughts in mid-latitudes which may explain some of the
246 impacts^{45,46}. The 2003 summer was both characterized by dry and hot conditions. For the
247 carbon cycle, it is more likely that it was the drought conditions that affected the net carbon
248 anomalies⁴⁷.

249 *Droughts*

250 A number of major droughts in mid-latitudes might have also contributed to the weakening
251 of the growth rate of terrestrial carbon sinks in recent decades^{44,48}. These large-scale
252 droughts have reduced seasonal NPP in these areas and weakened the terrestrial carbon
253 sink. However, summer productivity losses can be offset by productivity gains in spring⁴⁵
254 and autumn⁴⁶ so that the response of NPP to drought depends on the timing of drought
255 during the growing season, and on ecosystem properties of resistance to drought (e.g. deep
256 rooting, efficient stomatal controls). There is an inherent difficulty in quantifying droughts
257 and a wide likelihood-range of drought projections, but there are regions where drought is
258 consistently expected to increase. In other regions, wide likelihood-range should not be
259 equated with low drought risk, since potential scenarios include large drought increases in
260 key agricultural and ecosystem regions⁴⁹. In fact, vulnerability of tree mortality and forest
261 die-off to hotter and drier conditions are expected to increase⁵⁰. Beyond the signs of
262 drought-induced constrains on land carbon sinks in mid latitudes, tropical regions, and
263 particularly the Amazon, have been subject to unprecedented levels of drought over the past
264 decade with an associated reduction in the growth of carbon sinks^{51,52}.

265 *Fire, land use changes, harvests, and climatic and human disturbances: Reductions of* 266 *residence times*

267 Human caused climate change and elevated CO₂ can also shorten residence times through
268 complex and poorly understood pathways. For instance, there is evidence to show that,

269 under future global warming, fire disturbances will increase in several regions such as those
270 with Mediterranean climate, leading to reduced soil carbon residence time and thereby
271 reduced sink capacity of the land biosphere.

272 Future higher atmospheric CO₂ can reduce residence times by accelerating
273 competition and mortality in forest stands, and by priming soil carbon decomposition
274 through fresh organic matter input⁵³. Elevated CO₂ increases turnover rates of new soil
275 carbon, thus limiting the potential for additional soil C sequestration⁵⁴. CO₂ fertilization
276 effect produces soil organic matter of lower nutritional quality (higher C:N and C:P ratios),
277 hindering decomposition but further increasing nutrient limitation on plant carbon uptake.
278 In addition to enhanced above-ground growth, several FACE experiments observed a below
279 ground C allocation increase³⁵, thus not an storage in long-lived carbon compartment
280 despite fine-root litter being in part converted to soil organic matter which also includes
281 long-lived components. These experiments are, however, of short duration, so that long-
282 term storage changes could not really be quantified.

283 In addition to atmospheric and climatic changes, most land use changes, fires, and
284 harvests, which are expected to increase in the future^{55, 1, 56} reduce residence times, thereby
285 reducing the sink capacity of the land biosphere.

286 **Modelling**

287 The potential saturation or slower increase of the sink capacity of terrestrial ecosystems, or
288 even its transition into a source of CO₂, beyond what is reflected in several earth system
289 models, shows the exceptional relevance to climate policy now focused to achieve the
290 temperature targets agreed in COP21. For instance, ESMs and the climate projections of the
291 IPCC could be improved by a better quantification of land carbon sinks with more realistic
292 constraints from nutrient limitation. Models and projections could also be improved by a
293 better quantification of the natural ecosystem responses to the different aspects of warming
294 (e.g. contrast between nocturnal and diurnal warming) and drought / climate extremes or
295 the interaction between environmental pollution (e.g. ozone, heavy metals, or organic
296 pollutants) and increasing atmospheric CO₂ concentrations. In addition to the role of
297 terrestrial ecosystems in CO₂ uptake, other influences on climate of biogeochemical and
298 biophysical processes of terrestrial ecosystems such as exchanges of biogenic volatile
299 organic compounds, CH₄ and N₂O, latent and sensitive heat, albedo and roughness must be
300 quantified^{57,58}. Biochemical, optical and gaseous signals of the energetic status and structure
301 and functioning of plants and ecosystems⁵⁹ could be useful at this regard. Such improved
302 models could then help understanding the responses to different levels of global warming

303 (especially in the range 1.5-3°C according to the Paris agreement and current intended
304 policies).

305 Arguably, some ESM already incorporate several of these processes (eg chilling, or
306 different effects of T_{\min} and T_{\max}). Currently, there is also a lot of modelling work on the
307 dynamics of terrestrial sinks into the future that includes some experiments with and
308 without nutrient limitations, with and without Land Use Change, with and without
309 permafrost thawing, with different sensitivities to changes in rainfall and temperature, etc.
310 These are not the big ensembles reported in the IPCC, but there are plenty of advancements
311 at the individual model level, and several of these processes will be considered in the
312 upcoming CMIP6 experiments (e.g.^{60,61}). However, there are other mechanisms still missing
313 in ESM, for example the legacy effects of land use changes, disturbance and extreme climate
314 events on carbon sink activity²¹ and the factors that control stand structure, density,
315 management and disturbance in the Northern Hemisphere. Similarly, the effect of increased
316 competition in tropical forests in which CO₂ fertilization could increase individual growth
317 but cause in turn more self-thinning and increase biomass carbon turnover²⁰ and sink
318 capacity is missing. Current climate models do not necessarily well represent extreme
319 events due to coarse resolution (eg. extreme precipitation, wind storms and tropical
320 cyclones)^{42,43} or to insufficiently constrained soil-atmosphere interactions⁶². Likewise,
321 many models show effectively a slowdown of the growth in sinks, some saturate and a few
322 have even declining terrestrial sinks^{1,63}. Adding more processes to models will only make
323 complex, poorly understood models into even more complex and poorly understood models
324 so we advocate for modellers to increase their focus on process-oriented model evaluation,
325 based on hypothesis that can be discriminated by data. For instance, rather than
326 benchmarking process-based models for stocks and fluxes, estimating sensitivities of fluxes
327 and stocks to variable drivers such as elevated CO₂ and climate, can be achieved to enable a
328 comparison with both local manipulative experiments (e.g. FACE experiments, warming,
329 altered rainfall and nutrient fertilization experiments) and global observation-based
330 estimates of carbon variables^{64,65}.

331

332 **Shift from a fertilization to a warming period. Final remarks**

333 Here we thus hypothesize that a long term weakening of the natural land sink relative to
334 fossil fuel CO₂ emissions may be driving to the beginning of a transition between a
335 vegetation fertilization-dominated period to a period dominated by nutrient and climate
336 constraints on plant growth, and larger climate change impacts.

337 The CO₂ and N fertilization effects are two main drivers of the increase of the natural
338 land sink⁵³. However, the future strength of these fertilization drivers in the coming decades
339 is uncertain, in presence of emerging nutrient limitations that progressively limit the effect
340 of elevated CO₂ on increased carbon storage, as observed at some long term FACE
341 experiments^{34,35}. In contrast, the continuous warming and the associated reduction in water
342 availability in several regions are gaining significance resulting in growing negative impacts
343 on the biosphere. Compared to the historical period, future warming and drought and their
344 impacts are thus likely to be larger than the benefits gained from the effects of CO₂ and N
345 fertilization because of nutrient and climatic constraints, intensified land management and
346 shifts in disturbance regimes that reduce carbon stocks and thus the sequestration capacity
347 of terrestrial ecosystems. There are many unknowns in the timing of this transition, so in
348 light of the recent Paris COP21 agreement, a better understanding of the impacts of climate
349 change on carbon stocks remains paramount to understand the level of climate mitigation
350 required to achieve the agreed temperature goals.

351 In addition, it must also be noticed that the effect of CO₂ on photosynthesis is one of
352 diminishing returns, and that CO₂ fertilization only leads to enhanced plant growth and
353 storage as long as atmospheric CO₂ increases. Even if the CO₂ effect would not be reduced
354 until well into the second half of this century because plants would be able to use excess CO₂
355 to meet the carbon costs for getting access to extra N and P⁶⁶, e.g. through increased below
356 ground, root allocation and mycorrhizae association⁶⁷ or increased biological nitrogen
357 fixation, our hypothesis will hold as the climate continues to warm and extremes become
358 more extreme. This dynamic underscores the importance to investigate climate change
359 impacts on carbon sinks more than to hope for the benefits of CO₂ fertilization, which will
360 become smaller particularly in the low temperature scenarios set under the Paris Climate
361 Agreement.

362 Although the climate has not yet changed dramatically in the Anthropocene, the
363 coming decades will undoubtedly be different: atmospheric CO₂ levels will remain high, but
364 the climate will have no analogue in recent human history, even for so called «safe»
365 scenarios. The lower panels of Fig. 3 show that a warming of 2 °C would slightly increase
366 the frequency of 2003-like heatwaves in Northern France. A warming of 3 °C would instead
367 produce very different conditions, with one summer like that of 2003 occurring every two
368 or three years, which would therefore affect the forests carbon sink in Europe much more
369 than in the past.

370 In addition to the trends described in this paper, there is also the possibility of low
371 probability but high impact phenomena which would lead to rapid positive feedbacks to the
372 climate system⁶⁸. These include, among others, potential for rapid regional transitions in
373 the climate system, massive dieback of Amazon rainforest because of reduced rainfall,
374 dramatic temperature drop in the North Atlantic because of the collapse of the ocean
375 current that carries warm surface water north, ice sheet collapse, or/and permafrost carbon
376 decomposition⁶⁸. The occurrence of these phenomena is highly uncertain, particularly for
377 low temperature scenarios. However, it is much more certain that we are currently entering
378 a new warming period where ecosystems are put under increasing stresses. The extreme
379 and record temperatures of 2015 are illustration of such transition with unprecedented
380 levels of fires in Southeast Asia, coral bleaching in Australia, drought in Africa, and floods in
381 South America, all associated with one of the largest El Niño events in history. Consistent
382 with the high temperatures, 2015 also recorded the largest annual atmospheric CO₂ growth
383 rate since atmospheric observations began in Mauna Loa in 1959 (NOAA/ESRL and Scripps
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385

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582 **Author contributions**

583 J.P. designed the study. J.P., P.C., M.F-M. R.V., and J.S. conducted the analyses with support
584 by J.C., I.J., J.C., M.O., and S.P. The paper was drafted by JP and P.C., M.F-M. R.V., J.S. J.C., I.J.,
585 J.C., M.O., and S.P contributed to the interpretation of the results and to the text.

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587 **Additional information**

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591 **Competing interests**

592 The authors declare no competing financial interests

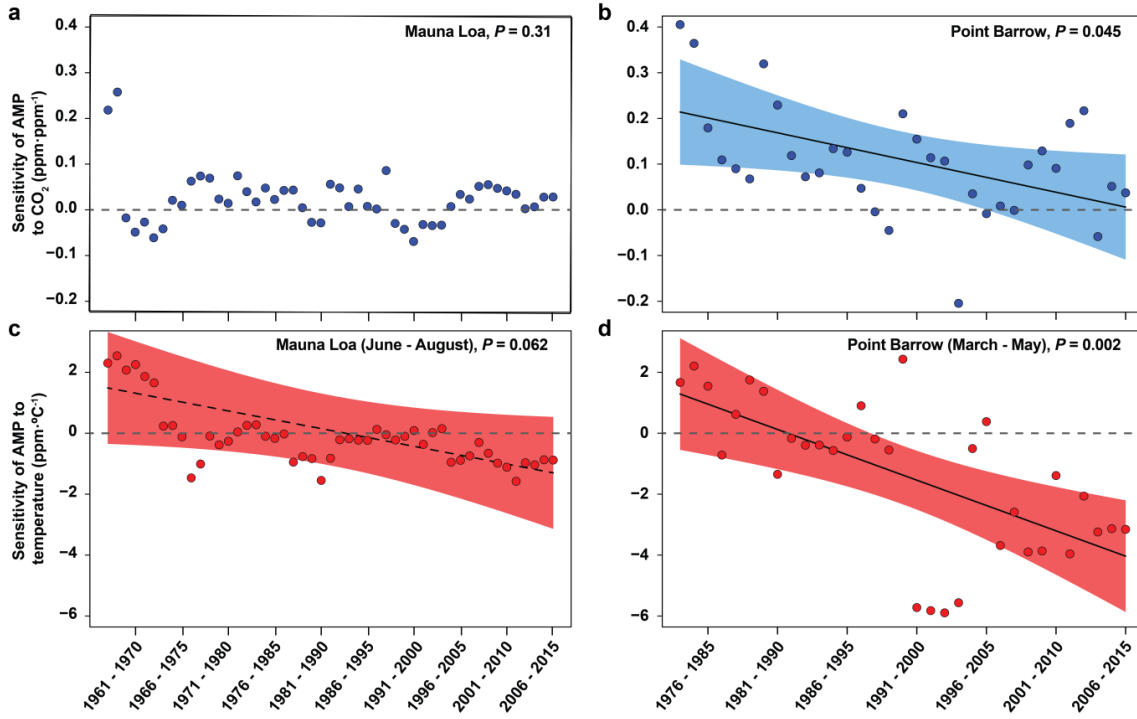
593 Table 1. Mean (Pg C y⁻¹) fossil fuel emissions, land use change emissions, residual land sink,
 594 and the ratio of the residual land sink to land use and fossil fuel emissions, at the 1960s-
 595 1970s and at the last 20 years. Standard deviations for the four five-year windows of each
 596 period are given between brackets. The change in the ratio of residual land sink to
 597 emissions is significant at * $P = 0.09$ (t-test).

| | FOSSIL FUEL EMISSIONS | LAND USE CHANGE EMISSIONS | RESIDUAL LAND SINK | RATIO OF RESIDUAL LAND SINK TO TOTAL EMISSIONS |
|------------------|----------------------------------|--|-------------------------------|---|
| 1960-1979 | 3,88 (0.14) | 1,44 (0.35) | 1,71 (0.49) | 0,32 (0.08) |
| 1996-2015 | 8,42 (0.35) | 1,50 (0.35) | 2,68 (0.57) | 0,28 (0.05)* |

598 Data from ref 1 and 6

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600 **Figure 1. CO₂ and temperature sensitivity of annual amplitude (AMP) at Point Barrow**
601 **and (a,c) Mauna Loa (b,d) stations.** The AMP is the difference between the annual
602 minimum and maximum atmospheric concentrations of CO₂. To conduct this sensitivity
603 analyses, we used monthly average atmospheric CO₂ concentration for Mauna Loa (1958 –
604 2015) and Point Barrow (1974 – 2015) observatories, provided by the Scripps Institution
605 of Oceanography (Scripps CO₂ program) and by NOAA, Earth System Research Laboratory
606 and Global Monitoring Division: <http://www.esrl.noaa.gov/gmd>) respectively. We
607 calculated annual CO₂ amplitude (AMP) as the difference in CO₂ concentration between the
608 month with the highest CO₂ concentration and the month with the lowest CO₂ concentration
609 within the same year. We also downloaded global land monthly average temperature record
610 from the Complete Berkeley Dataset (<http://berkeleyearth.org/land-and-ocean-data/>) and
611 the northern hemisphere land-ocean monthly average temperature from the NASA GISS
612 surface temperature database (<http://data.giss.nasa.gov/gistemp/>). For both temperature
613 datasets, we calculated spring (March – May) and summer (June – August) temperatures.
614 Then we fitted generalized least squares models (GLS) in which the response variable was
615 AMP and the predictor variables were mean annual CO₂ concentrations, and spring and
616 summer temperatures, while accounting for temporal autocorrelation for lag 1. We
617 repeatedly performed these models for a time-span moving window of 10 years from the
618 beginning to the end of the time series of each observatory. For every time-span window of
619 10 years analysed, we extracted the model estimates for CO₂ (i.e., sensitivity of AMP to
620 increasing CO₂) and for spring and summer temperatures (i.e., sensitivity of AMP to
621 warming). We then used these estimates as response variables in fitted GLS models
622 correcting for temporal autocorrelation to calculate the trends in the sensitivities of CO₂ and
623 temperature. For Mauna Loa we used temperature data from the Berkeley dataset (global),
624 while for Point Barrow we used NASA GISS (northern hemisphere).

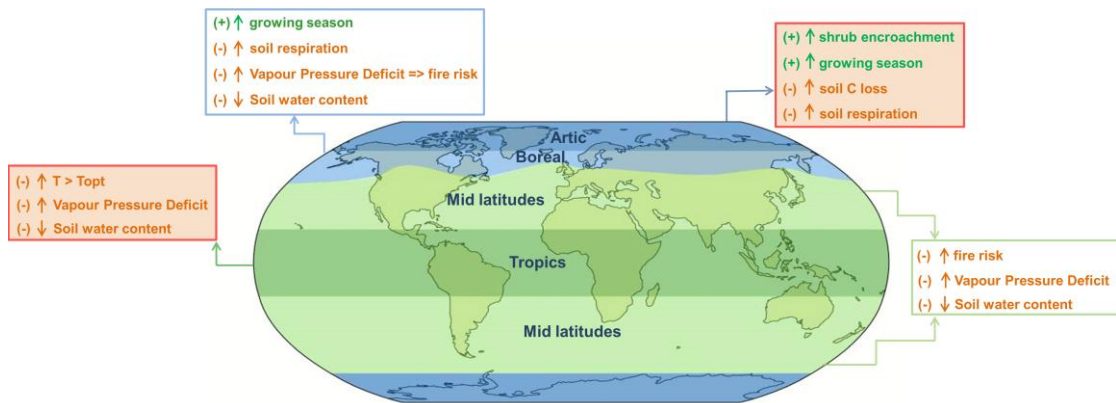


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626 Figure 2. **Warming impacts on C storage in the Tropics, mid latitudes, boreal and arctic**
 627 **zones.** Positive impacts in green, negative impacts in red. Topt Optimum temperature.
 628 Tropical forest biomass and peatlands and high latitude frozen carbon are highlighted in
 629 red rectangles since they accumulate much larger amounts of C, so small percentages of loss
 630 there represent larger total amounts of carbon losses than implausible huge percentages of
 631 losses of temperate and boreal forest biomass.

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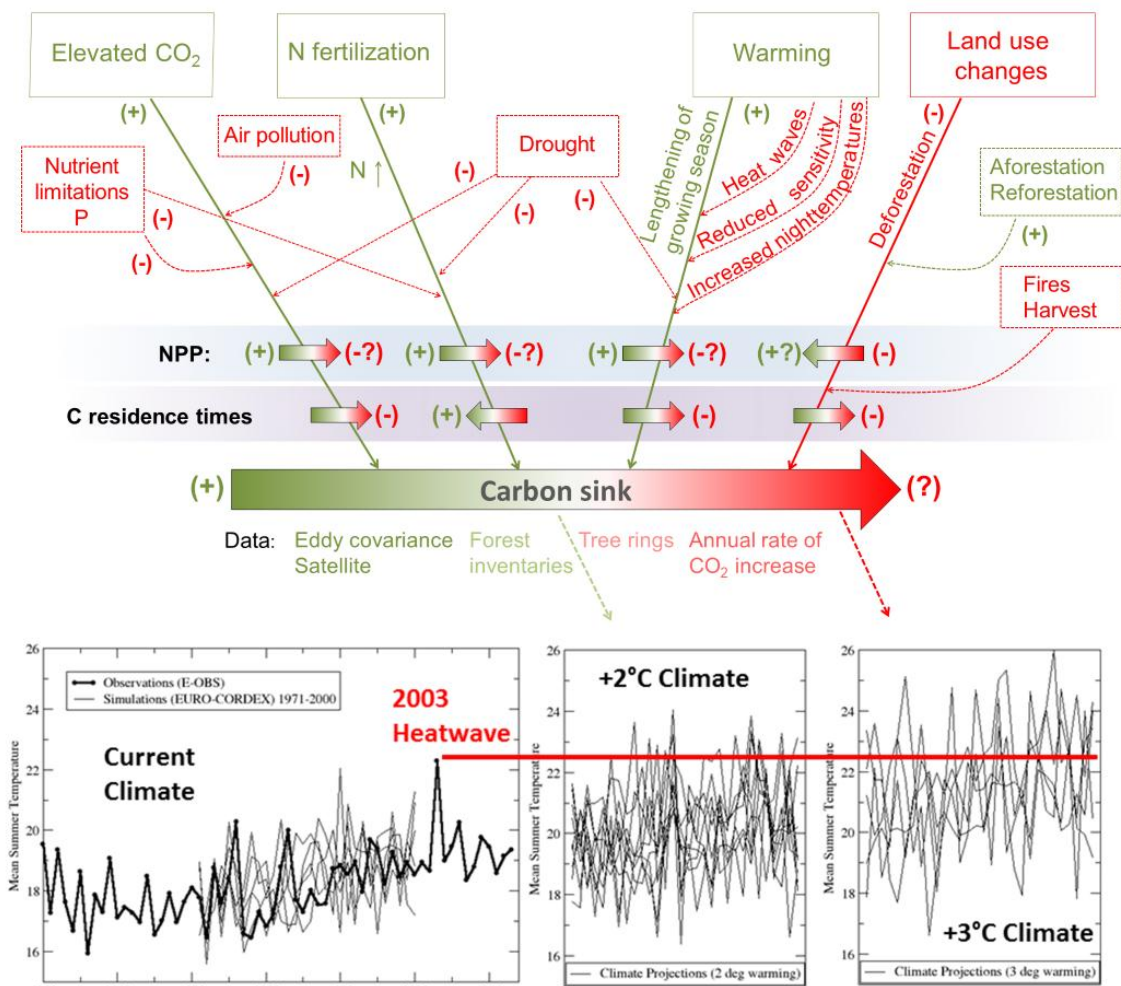
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644 Figure 3. **Schematics for the impacts and feedbacks of the drivers of global change on**
 645 **carbon sinks by affecting productivity and C residence time.** Solid lines indicate how
 646 we currently assume they operate, and dashed lines indicate how they actually operate or
 647 could change in the future toward saturation. The drivers may help to keep the climate
 648 within sustainable limits, depending on their respective strengths, and help to avoid abrupt
 649 shifts such as, for example, passing from a scenario of 2 °C warming in which the summer
 650 climate of Europe would still have rare 2003-like heatwaves (6%), to a scenario of 3 °C
 651 warming, with one summer 2003-like heatwave occurring every four years The lower panel
 652 of the figure shows observations (E-OBS⁶⁹) and regional climate projections (EURO-
 653 CORDEX⁷⁰) of mean summer temperatures in the Paris area, the temperature periods being
 654 defined according to the methodology used for the IMPACT2C project, described in Vautard
 655 et al. (2014)⁷¹. See also the IMPACT2C atlas (<https://www.atlas.impact2c.eu/en/>).



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