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Shifting from a fertilization-dominated to a warming-dominated period

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

Humans strongly fertilize the planet. Human activities result in increasing atmospheric concentrations of carbon dioxide (CO_2)[1] and nitrogen (N) inputs to ecosystems[2]. This leads to increased availability of biospheric carbon (C) and N and, enhanced metabolism of organism. In addition warming[1] is lengthening the growing seasons in the northern hemisphere[3,4]. Plants can consequently grow more. This enhanced plant growth is a driver of carbon sinks but it is not sufficient: there must also be ecosystem compartments where carbon is retained before being cycled back to the atmosphere, and plants must allocate carbon to these long-lived compartments. In fact, the magnitude of carbon sinks and their duration depend both on the rate of increase of carbon inputs and on the residence time of the carbon being taken up by ecosystems. Changes in these two processes will affect the future evolution of sinks and thus in return, of atmospheric CO_2 and climate. For instance, if the input to land carbon pools from primary productivity slows down and eventually saturates, e.g. because of emerging nutrient constraints on plant productivity, and if the residence time of excess carbon remains constant, sinks will slowly decrease and eventually disappear. If instead the carbon residence time becomes shorter, e.g. in the case of increased biomass mortality or an increasing allocation of carbon to short-lived pools such as fine roots and leaves, then ecosystems lose part of their sink capacity even if their productivity continues to increase. Examples of the latter case occur when disturbances such as fire lead to the long-term reduction of forest biomass and soil carbon or to the exposure to decomposition of previously protected soil carbon. In the case of an irreversible disturbance not followed by a recovery of carbon stocks, there is not only an initial source of CO_2 to the atmosphere, but the replacement of a slow turnover system by a fast turnover one that reduces the sink capacity in the long term; an example is the conversion of forest lands to croplands. Changes in residence times are function of changes in land use and land management, disturbances, changes in carbon allocation, decomposition, and changes in ecosystem structure. Past, current and future changes in land carbon sinks thus result from the interplay between an overall change in productivity and/or changes in the residence times of carbon in ecosystem pools. Both productivity and residence times respond to changing CO_2, climate and nutrient availability[5].

Current evidence suggests that land C storage and therefore land C sinks are increasing at global scale and that human-induced CO_2 and N fertilization and warming (and changes in other climate variables) play a key role in this increase. This land sink has grown rapidly in the past five decades consistent with the rapid increase of CO_2 emissions from fossil fuel use and with the recorded land use change[6]. At local scale, estimates from long-term flux tower records show that gross primary productivity (GPP) and net ecosystem production (NEP) have increased by 1% annually from 1995 to 2011 across 23 forests in Europe and the USA[7]. Satellite observations show a widespread greening trend in 25-50% of vegetated areas during the last 30 years as compared to only 4% of the areas showing decreased greenness[8]. Some studies on forest inventories also report increasing carbon storage in intact tropical forests[9] and other forests[10]. Attribution studies suggest that increasing atmospheric CO_2 is the most likely factor associated with the increasing strength of the carbon sink. This is the case for the flux-tower sites in Europe and the USA[7] and also for global greening trends[8], where factorial simulations with global ecosystem models suggest that CO_2 fertilization explains 70% (4.7-9.5% increase in global mean LAI) of the observed trend in greening; nitrogen deposition contributed 9%, climate change 8%, and land-cover change 4%. The relatively small global effect of climate change is because the effects of climate regionally oppose each other whereas the CO_2 fertilization effect is more uniform and consistent across biomes. Analyses of forest inventory data have also concluded that the current increase in biomass carbon stocks in European and North American forests can only be explained with a contribution of rising CO_2 increasing productivity[11,12]. These data, together with results from short-term experiments on elevated CO_2, nutrient fertilization and warming, despite their shortcomings, support enhanced productivity in response to elevated CO_2[13–15]. The fact that the global residual land sink has increased in the past three decades, that long term flux towers show increases of NEP, and that remote sensing and forest inventory data show an increased sink in most regions suggests that the residence time of excess carbon has not been reduced significantly over the last decades with a magnitude sufficient to offset productivity induced carbon storage.

However, there are now indications that these trends of increasing sinks may be slowing down. Here, we point out these indications to thereafter discuss the likely limitations for fertilization-enhancement of carbon sinks underlying them (limitations by key nutrients such as P, reduced sensitivity to warming, negative responses to Tmin and heatwaves, droughts, fires, land use changes and their legacy, harvests, and climatic and human disturbances leading to reductions of C residence times). This discussion finally drive us to hypothesize that a long term weakening of the natural land sink relative to fossil fuel CO_2 emissions may be driving to the beginning of an anthropocenic transition from a vegetation fertilization-dominated period to a period dominated by nutrient and climate constraints on further plant growth, and larger climate change impacts.

Indications of slowing down of trends of increasing sinks

All over the world, and particularly in northern latitudes, the difference between the annual minimum and maximum concentrations of CO_2 (the amplitude) has been increasing since the 1960s. This seems mainly due to increasing plant growth in the North. The strong seasonality of gross primary productivity and ecosystem respiration causes a larger average CO_2 amplitude in northern high latitudes than in low latitudes. The analyses of these long-term atmospheric CO_2 concentration records of the stations at Mauna Loa in Hawaii and Point Barrow in Alaska shows that the sensitivity of the annual peak-to-peak amplitude of CO_2 for an increase of 1 ppm CO_2 decreased to 0 in 2015, while the sensitivity per °C warming decreased to 0 already in the early 1990s and is now negative, particularly in Northern latitudes (Fig. 1a-d). These trends suggest that terrestrial ecosystems are responding at a decline rate to the continued increase of atmospheric CO_2 (fertilization effect). And likewise, that the positive effects of warming in the high latitudes leading to higher rates of carbon uptake are also declining.

Between the first and the last 20 years of the Mauna Loa record, used as two end points, which helps to filter quasi-decadal variability, the ratio of the residual land sink to land-use and fossil-fuel emissions decreased from 0.34 ± 0.08 to 0.28 ± 0.05 ($p = 0.09$), suggesting a slightly decreased efficiency of natural ecosystems to absorb emissions (Table 1). This decline in the efficiency of land sinks occurred in spite of the Pinatubo eruption (that caused a short lived increase of carbon sinks). Although C sinks are still increasing, the combined land–ocean CO_2 sink flux per unit of excess atmospheric CO_2 above preindustrial levels has declined by 1/3 over 1959-2012[16], implying that CO_2 sinks increased more slowly than excess CO_2. Using a very simple carbon–climate model, Raupach et al[16] attributed this slower increase to slower-than-exponential CO_2 emissions growth (~ 35 % of the trend), accidents of history causing short-lived increases of sinks like volcanic eruptions (~ 25 %), sink responses to climate change (~ 20 %), and nonlinear responses to increasing CO_2, mainly oceanic (~ 20 %)[16].

An analysis of tree-ring $\delta^{13}C$ and growth over the last 40 years at 47 sites covering all major types of forest biomes, including boreal, wet temperate, Mediterranean, semi-arid and tropical biomes, also shows that tree growth at those sites did not increase significantly, despite an increase in atmospheric CO_2 concentrations of over 50 ppm and a 20.5% increase in intrinsic water-use efficiency[17]. This suggests that other factors are counteracting the potential growth benefits of a CO_2-rich world at many of the studied sites[17]. Similar results were reported for tropical trees[18]. There are also other studies based on forest inventories suggesting a declining sink rate in European forests[19], in tropical intact forests[10], and in the biomass accumulation of Amazon forests[20]. Possible explanations for this decline are higher night time temperatures in the tropics driving higher ecosystem respiration[21] and increased biomass mortality[20]. Piao et al[22,23] have also reported a weakening temperature control on the interannual variations of spring carbon uptake across northern lands in the last 17 years and suggest that it is attributable to the declining temperature response of spring net primary productivity (NPP) rather than to changes in heterotrophic respiration or in atmospheric transport patterns. Reduced chilling during dormancy and emerging light limitation are possible mechanisms contributing to the loss of NPP response to warming. Furthermore, the legacy effects of land use changes have a limited duration and therefore need to be taken into account in this consideration of saturation and even reversal of carbon sinks. A remaining question is whether in regions where carbon sinks may be slowing down, this is due to stalling productivity or to reducing residence times.

Ecological studies have not fully proved the universality of the CO_2 fertilization effect, while several studies have documented well the negative effects on ecosystem carbon storage due to warming and drought (Fig. 2). The impacts of warming and drought on terrestrial ecosystems are negative when the increased evaporative demand and the decreased soil water availability increase drought stress effect and mortality. In the tropics there is also the negative impact of the likely rise of temperatures above the optimum that decreases GPP and NPP. In fact, optimum temperatures[24] are close to current values for tropical forests. In mid-latitudes and boreal regions, additional possible negative impact comes from increased fire risk in dry seasons., although fire risks would not necessarily be increasing with warming[25]. In the boreal and arctic regions, with large soil carbon stocks, warming increases soil respiration and soil carbon loss from frozen carbon stocks. For one degree of warming, about 30 petagrams of soil carbon are now estimated to be released into the atmosphere, or about 2-3 times as much as is emitted annually due to human-related activities. These losses are largely driven by the losses of carbon in these most sensitive boreal and arctic regions[26,27]. Loss of permafrost carbon can only be partially compensated by beneficial temperature increases on tree growth in boreal forests, woody encroachment and longer growing seasons due to strong warming in those regions.

The two largest and most vulnerable carbon stocks are tropical forest biomass vulnerable to drought[28] and rising T[29] (although controversial[30]) and the boreal and arctic soil carbon stocks vulnerable to warming and thawing[31]. Tropical forest biomass and soil carbon hold about 400 Pg C, while tropical peatlands in South-east Asia, vulnerable to fire hold about 100 Pg C[32]. Frozen carbon stocks are about 1600 Pg C, among which 130 to 160 Pg C vulnerable to climate-induced loss[31,33]. Compared to these large and potentially vulnerable carbon pools, temperate forests biomass hold only 41 Pg C and pan-boreal forests 50 Pg C[10]. Thus the plausible loss of 10% of tropical forest biomass or 37-174 PgC by 2100 of high latitude frozen carbon[33] represents an amount of carbon comparable with the implausible loss of 100% of temperate and boreal forest biomass.

All these observational data suggest a decrease in the efficiency of carbon sinks to remove excess atmospheric CO_2 albeit a continue increase in the magnitude of sinks. Together with the experimental evidence on the effects of rising atmospheric CO_2 on plant growth also often showing saturation of the CO_2 fertilization effect[34,35] suggest limits to the buffering capacity of the biosphere. They suggest a slowdown of the CO_2 and N fertilization effects on ecosystem carbon sequestration and a rapid emergence of negative ecosystem impacts from global climate change that might drive a shift from a period dominated by fertilization to another period characterized by saturated fertilization and strong climate change. That is, the impacts of warming on the land sinks are likely to be larger in the future than the benefits from CO_2 fertilization because of nutrient and climate constraints, management and disturbance that reduce the increase in carbon stocks and thus the sequestration potential.

Likely limitations for enhancement of carbon sinks.

Key nutrients

The anthropogenic increases in CO_2 and atmospheric nitrogen deposition are not matched by a similar increase in the inputs of other key nutrients such as phosphorus (P) and/or potassium (K). A simple mass-balance approach of the NPP-based and C stock-based demands indicates that limited P availability and the corresponding N:P imbalances will result in a smaller CO_2 removal by terrestrial ecosystems during this century than currently predicted by biogeochemical and Earth system models[36,37]. Changes in mineralization with climate change, and other processes governing the recycling of nutrients, are a large source of uncertainty in the amount of nutrients available for the accumulation of new biomass[36]. However, an increasing biological P demand is likely to outpace exogenous P inputs, suggesting that an accelerated cycling of existent P pools will be critical to sustain productivity and carbon sinks. An increase in the amount of new P from weathering is also possible under conditions of strong warming, but the effects of climatic warming on P dynamics are even less known. Thus, the changes in the future availability of P are uncertain, but current evidence suggest an overall shortage of P which will act as a limiting factor to meet the increasing demand for plant growth[36–38]. A better understanding of the factors that regulate exchanges between pools of "available" and "unavailable" soil P is critically needed. Furthermore, a better quantification of how N limitation restricts C sinks from CO_2 fertilization both by limiting NPP increase and by resulting in a lower wood allocation as plants are forced to allocate below ground to obtain N for NPP is also warranted.

Reduced sensitivity to warming and negative responses to Tmin and heatwaves

Warming is lengthening the growing seasons in the northern latitudes[3] but the apparent response of leaf unfolding to climatic warming (expressed in days of advance of leaf unfolding per °C warming) has decreased by 40% from 1980 to 2013 for deciduous forests in Europe[39]. The reduction in sensitivity is likely to be partly attributable to reduced winter chilling and other mechanisms, such as photoperiod limitation[40], that may become ultimately limiting when leaf unfolding occurs too early in the season, together resulting in a slowdown in the advance of spring tree phenology.

Furthermore, the satellite-derived normalized difference vegetation index (NDVI), an indicator of vegetation greenness, is negatively correlated with T_{min} in boreal regions of the Northern Hemisphere[41]. Similar patterns were detected in maps of terrestrial net CO_2 exchange obtained from a relatively high-resolution atmospheric inversion[41]. In addition, the analysis of the long-term records of atmospheric CO_2 concentration from the Point Barrow station (71°N) in Alaska suggests that the peak-to-peak amplitude of CO_2 increased by 28±11% for a +1 °C anomaly in T_{max} from May to September over land north of 51°N, but decreased by 34±14% for a +1 °C anomaly in T_{min}. This asymmetry is especially important because temperature data for the last century shows faster warming at night (T_{min}) than during the day (T_{max})[1], although this effect is uncertain for the future given strong aerosol reductions as suggested by RCP scenarios. These multiple lines of evidence suggest that asymmetric diurnal-nocturnal warming is an important process affecting terrestrial ecosystems. Higher nocturnal temperatures enhance night respiration, with important implications for carbon cycling.

Severe regional heatwaves are also likely to become more frequent in a changing climate[42,43] (Fig. 3), and their negative impact on terrestrial carbon sequestration may thus also become important. For example, the 2003 drought and heatwave decreased European gross primary productivity by 30%, which resulted in a strong anomalous net source of carbon dioxide (0.5 Pg C y^{-1}) to the atmosphere; this effect is the equivalent of reversing four years of net ecosystem carbon sequestration in the European continent[44]. Heatwaves are often co-occurring with droughts in mid-latitudes which may explain some of the impacts[45,46]. The 2003 summer was both characterized by dry and hot conditions. For the carbon cycle, it is more likely that it was the drought conditions that affected the net carbon anomalies[47].

Droughts

A number of major droughts in mid-latitudes might have also contributed to the weakening of the growth rate of terrestrial carbon sinks in recent decades[44,48]. These large-scale droughts have reduced seasonal NPP in these areas and weakened the terrestrial carbon sink. However, summer productivity losses can be offset by productivity gains in spring[45] and autumn[46] so that the response of NPP to drought depends on the timing of drought during the growing season, and on ecosystem properties of resistance to drought (e.g. deep rooting, efficient stomatal controls). There is an inherent difficulty in quantifying droughts and a wide likelihood-range of drought projections, but there are regions where drought is consistently expected to increase. In other regions, wide likelihood-range should not be equated with low drought risk, since potential scenarios include large drought increases in key agricultural and ecosystem regions[49]. In fact, vulnerability of tree mortality and forest die-off to hotter and drier conditions are expected to increase[50]. Beyond the signs of drought-induced constrains on land carbon sinks in mid latitudes, tropical regions, and particularly the Amazon, have been subject to unprecedented levels of drought over the past decade with an associated reduction in the growth of carbon sinks[51,52].

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

Human caused climate change and elevated CO_2 can also shorten residence times through complex and poorly understood pathways. For instance, there is evidence to show that, under future global warming, fire disturbances will increase in several regions such as those with Mediterranean climate, leading to reduced soil carbon residence time and thereby reduced sink capacity of the land biosphere.

Future higher atmospheric CO_2 can reduce residence times by accelerating competition and mortality in forest stands, and by priming soil carbon decomposition through fresh organic matter input[53]. Elevated CO_2 increases turnover rates of new soil carbon, thus limiting the potential for additional soil C sequestration[54]. CO_2 fertilization effect produces soil organic matter of lower nutritional quality (higher C:N and C:P ratios), hindering decomposition but further increasing nutrient limitation on plant carbon uptake. In addition to enhanced above-ground growth, several FACE experiments observed a below ground C allocation increase[35], thus not an storage in long-lived carbon compartment despite fine-root litter being in part converted to soil organic matter which also includes long-lived components. These experiments are, however, of short duration, so that long-term storage changes could not really be quantified.

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

Modelling

The potential saturation or slower increase of the sink capacity of terrestrial ecosystems, or even its transition into a source of CO_2, beyond what is reflected in several earth system models, shows the exceptional relevance to climate policy now focused to achieve the temperature targets agreed in COP21. For instance, ESMs and the climate projections of the IPCC could be improved by a better quantification of land carbon sinks with more realistic constraints from nutrient limitation. Models and projections could also be improved by a better quantification of the natural ecosystem responses to the different aspects of warming (e.g. contrast between nocturnal and diurnal warming) and drought / climate extremes or the interaction between environmental pollution (e.g. ozone, heavy metals, or organic pollutants) and increasing atmospheric CO_2 concentrations. In addition to the role of terrestrial ecosystems in CO_2 uptake, other influences on climate of biogeochemical and biophysical processes of terrestrial ecosystems such as exchanges of biogenic volatile organic compounds, CH_4 and N_2O, latent and sensitive heat, albedo and roughness must be quantified[57,58]. Biochemical, optical and gaseous signals of the energetic status and structure and functioning of plants and ecosystems[59] could be useful at this regard. Such improved models could then help understanding the responses to different levels of global warming (especially in the range 1.5-3°C according to the Paris agreement and current intended policies).

Arguably, some ESM already incorporate several of these processes (eg chilling, or different effects of T_{min} and T_{max}). Currently, there is also a lot of modelling work on the dynamics of terrestrial sinks into the future that includes some experiments with and without nutrient limitations, with and without Land Use Change, with and without permafrost thawing, with different sensitivities to changes in rainfall and temperature, etc. These are not the big ensembles reported in the IPCC, but there are plenty of advancements at the individual model level, and several of these processes will be considered in the upcoming CMIP6 experiments (e.g.[60,61]). However, there are other mechanisms still missing in ESM, for example the legacy effects of land use changes, disturbance and extreme climate events on carbon sink activity[21] and the factors that control stand structure, density, management and disturbance in the Northern Hemisphere. Similarly, the effect of increased competition in tropical forests in which CO_2 fertilization could increase individual growth but cause in turn more self-thinning and increase biomass carbon turnover[20] and sink capacity is missing. Current climate models do not necessarily well represent extreme events due to coarse resolution (eg. extreme precipitation, wind storms and tropical cyclones)[42,43] or to insufficiently constrained soil-atmosphere interactions[62]. Likewise, many models show effectively a slowdown of the growth in sinks, some saturate and a few have even declining terrestrial sinks[1,63]. Adding more processes to models will only make complex, poorly understood models into even more complex and poorly understood models so we advocate for modellers to increase their focus on process-oriented model evaluation, based on hypothesis that can be discriminated by data. For instance, rather than benchmarking process-based models for stocks and fluxes, estimating sensitivities of fluxes and stocks to variable drivers such as elevated CO_2 and climate, can be achieved to enable a comparison with both local manipulative experiments (e.g. FACE experiments, warming, altered rainfall and nutrient fertilization experiments) and global observation-based estimates of carbon variables[64,65].

Shift from a fertilization to a warming period. Final remarks

Here we thus hypothesize that a long term weakening of the natural land sink relative to fossil fuel CO_2 emissions may be driving to the beginning of a transition between a vegetation fertilization-dominated period to a period dominated by nutrient and climate constraints on plant growth, and larger climate change impacts.

The CO_2 and N fertilization effects are two main drivers of the increase of the natural land sink[53]. However, the future strength of these fertilization drivers in the coming decades is uncertain, in presence of emerging nutrient limitations that progressively limit the effect of elevated CO_2 on increased carbon storage, as observed at some long term FACE experiments[34,35]. In contrast, the continuous warming and the associated reduction in water availability in several regions are gaining significance resulting in growing negative impacts on the biosphere. Compared to the historical period, future warming and drought and their impacts are thus likely to be larger than the benefits gained from the effects of CO_2 and N fertilization because of nutrient and climatic constraints, intensified land management and shifts in disturbance regimes that reduce carbon stocks and thus the sequestration capacity of terrestrial ecosystems. There are many unknowns in the timing of this transition, so in light of the recent Paris COP21 agreement, a better understanding of the impacts of climate change on carbon stocks remains paramount to understand the level of climate mitigation required to achieve the agreed temperature goals.

In addition, it must also be noticed that the effect of CO_2 on photosynthesis is one of diminishing returns, and that CO_2 fertilization only leads to enhanced plant growth and storage as long as atmospheric CO_2 increases. Even if the CO_2 effect would not be reduced until well into the second half of this century because plants would be able to use excess CO_2 to meet the carbon costs for getting access to extra N and P[66], e.g. through increased below ground, root allocation and mycorrhizae association[67] or increased biological nitrogen fixation, our hypothesis will hold as the climate continues to warm and extremes become more extreme. This dynamic underscores the importance to investigate climate change impacts on carbon sinks more than to hope for the benefits of CO_2 fertilization, which will become smaller particularly in the low temperature scenarios set under the Paris Climate Agreement.

Although the climate has not yet changed dramatically in the Anthropocene, the coming decades will undoubtedly be different: atmospheric CO_2 levels will remain high, but the climate will have no analogue in recent human history, even for so called «safe» scenarios. The lower panels of Fig. 3 show that a warming of 2 °C would slightly increase the frequency of 2003-like heatwaves in Northern France. A warming of 3 °C would instead produce very different conditions, with one summer like that of 2003 occurring every two or three years, which would therefore affect the forests carbon sink in Europe much more than in the past.

In addition to the trends described in this paper, there is also the possibility of low probability but high impact phenomena which would lead to rapid positive feedbacks to the climate system[68]. These include, among others, potential for rapid regional transitions in the climate system, massive dieback of Amazon rainforest because of reduced rainfall, dramatic temperature drop in the North Atlantic because of the collapse of the ocean current that carries warm surface water north, ice sheet collapse, or/and permafrost carbon decomposition[68]. The occurrence of these phenomena is highly uncertain, particularly for low temperature scenarios. However, it is much more certain that we are currently entering a new warming period where ecosystems are put under increasing stresses. The extreme and record temperatures of 2015 are illustration of such transition with unprecedented levels of fires in Southeast Asia, coral bleaching in Australia, drought in Africa, and floods in South America, all associated with one of the largest El Niño events in history. Consistent with the high temperatures, 2015 also recorded the largest annual atmospheric CO_2 growth rate since atmospheric observations began in Mauna Loa in 1959 (NOAA/ESRL and Scripps Institution of Oceanography).

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Author contributions

J.P. designed the study. J.P., P.C., M.F-M. R.V., and J.S. conducted the analyses with support 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., J.C., M.O., and S.P contributed to the interpretation of the results and to the text.

Additional information

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Competing interests

The authors declare no competing financial interests

Table 1. Mean (Pg C y^{-1}) fossil fuel emissions, land use change emissions, residual land sink, and the ratio of the residual land sink to land use and fossil fuel emissions, at the 1960s-1970s and at the last 20 years. Standard deviations for the four five-year windows of each period are given between brackets. The change in the ratio of residual land sink to 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)*

Data from ref 1 and 6

Figure 1. **CO_2 and temperature sensitivity of annual amplitude (AMP) at Point Barrow and (a,c) Mauna Loa (b,d) stations.** The AMP is the difference between the annual minimum and maximum atmospheric concentrations of CO_2. To conduct this sensitivity analyses, we used monthly average atmospheric CO_2 concentration for Mauna Loa (1958 – 2015) and Point Barrow (1974 – 2015) observatories, provided by the Scripps Institution of Oceanography (Scripps CO_2 program) and by NOAA, Earth System Research Laboratory and Global Monitoring Division: http://www.esrl.noaa.gov/gmd) respectively. We calculated annual CO_2 amplitude (AMP) as the difference in CO_2 concentration between the month with the highest CO_2 concentration and the month with the lowest CO_2 concentration within the same year. We also downloaded global land monthly average temperature record from the Complete Berkeley Dataset (http://berkeleyearth.org/land-and-ocean-data/) and the northern hemisphere land-ocean monthly average temperature from the NASA GISS surface temperature database (http://data.giss.nasa.gov/gistemp/). For both temperature datasets, we calculated spring (March – May) and summer (June – August) temperatures. Then we fitted generalized least squares models (GLS) in which the response variable was AMP and the predictor variables were mean annual CO_2 concentrations, and spring and summer temperatures, while accounting for temporal autocorrelation for lag 1. We repeatedly performed these models for a time-span moving window of 10 years from the beginning to the end of the time series of each observatory. For every time-span window of 10 years analysed, we extracted the model estimates for CO_2 (i.e., sensitivity of AMP to increasing CO_2) and for spring and summer temperatures (i.e., sensitivity of AMP to warming). We then used these estimates as response variables in fitted GLS models correcting for temporal autocorrelation to calculate the trends in the sensitivities of CO_2 and temperature. For Mauna Loa we used temperature data from the Berkeley dataset (global), while for Point Barrow we used NASA GISS (northern hemisphere).

625

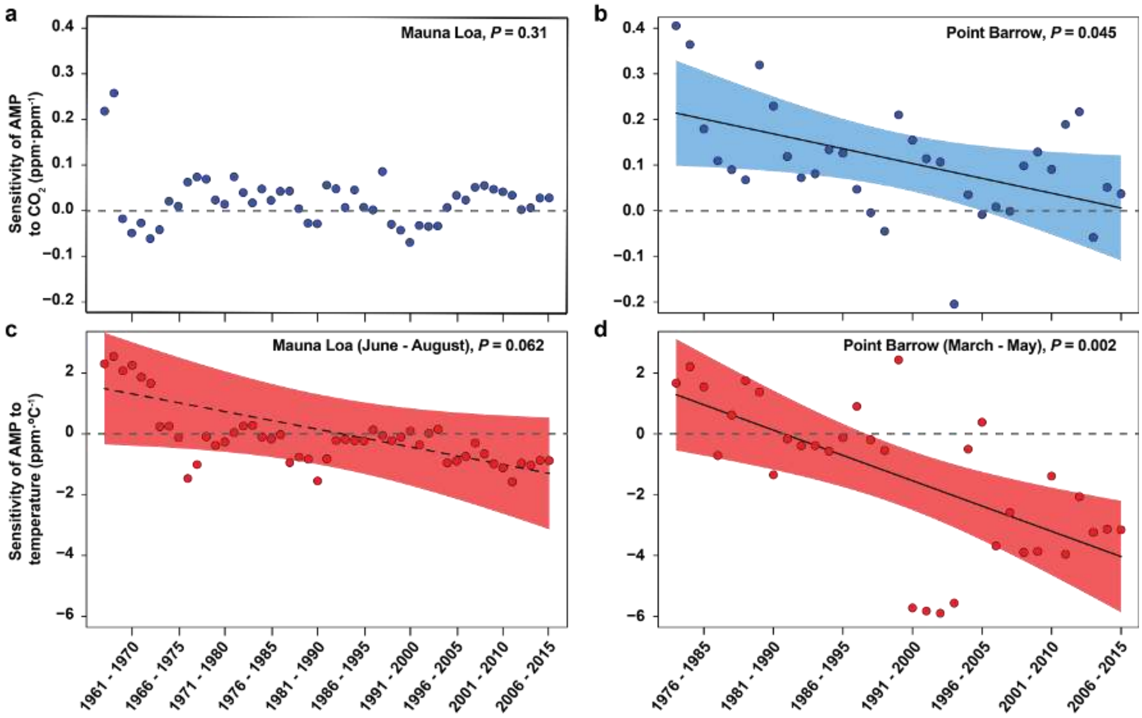
a
Mauna Loa, P = 0.31
Sensitivity of AMP to CO2 (ppm·ppm-1)
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
b
Point Barrow, P = 0.045
c
Mauna Loa (June - August), P = 0.062
Sensitivity of AMP to temperature (ppm·°C-1)
2
0
−2
−4
−6
1961 - 1970
1966 - 1975
1971 - 1980
1976 - 1985
1981 - 1990
1986 - 1995
1991 - 2000
1996 - 2005
2001 - 2010
2006 - 2015
d
Point Barrow (March - May), P = 0.002

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

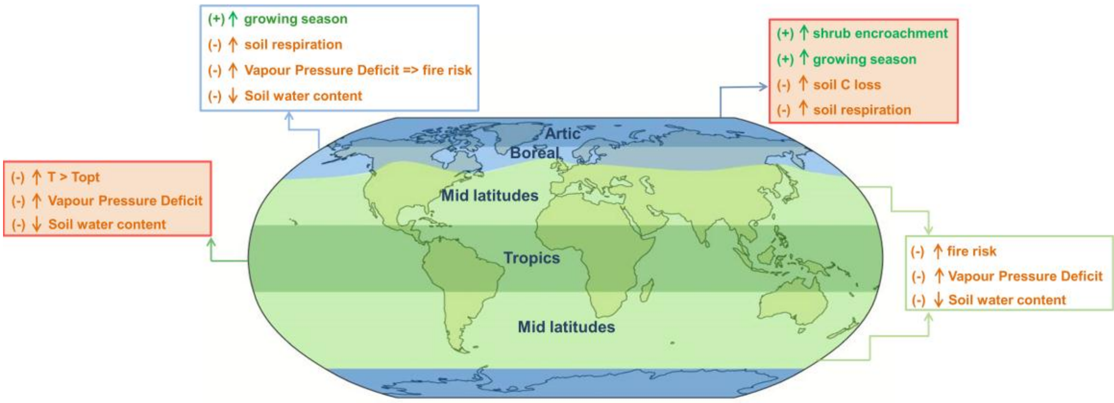

Figure 3**. Schematics for the impacts and feedbacks of the drivers of global change on carbon sinks by affecting productivity and C residence time.** Solid lines indicate how we currently assume they operate, and dashed lines indicate how they actually operate or could change in the future toward saturation. The drivers may help to keep the climate within sustainable limits, depending on their respective strengths, and help to avoid abrupt shifts such as, for example, passing from a scenario of 2 °C warming in which the summer climate of Europe would still have rare 2003-like heatwaves (6%), to a scenario of 3 °C warming, with one summer 2003-like heatwave occurring every four years The lower panel of the figure shows observations (E-OBS[69]) and regional climate projections (EURO-CORDEX[70]) of mean summer temperatures in the Paris area, the temperature periods being defined according to the methodology used for the IMPACT2C project, described in Vautard et al. (2014)[71]. See also the IMPACT2C atlas (https://www.atlas.impact2c.eu/en/).