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Perspective

Heat and drought extremes likely to stress ecosystem productivity equally or more in a warmer, CO_2 rich future

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Abstract
Reduced carbon uptake caused by recent heat and drought extremes raises concerns about biospheric feedbacks that amplify global warming. However, elevated carbon dioxide is expected to boost terrestrial ecosystem productivity over the 21st century, potentially alleviating some of the adverse carbon impacts of climate extremes. Using CMIP5 earth system model (ESM) results, Ian Williams and colleagues (2014 *Environ. Res. Lett.* **9** 094011) find that the carbon impacts of heat and drought extremes in the future are likely to be similar to those seen in today's climate only shifted toward fluctuations around a higher average temperature. However, they also find that extremes may become more frequent and longer lived, causing further reductions in carbon uptake. Considering that ESMs generally miss a host of heat and drought induced mortality mechanisms that could exacerbate adverse carbon impacts, it is logical to expect that the impacts of today's heat and drought extremes are likely underestimates of what we can expect in the future with a high fossil emissions pathway.

Keywords: gross primary productivity, water stress, climate change, heat wave

Recent heat waves and droughts have caused large-scale reductions in ecosystem carbon uptake around the world (Ciais *et al* 2005, Allen *et al* 2010, Zhao and Running 2010, Schwalm *et al* 2012). Extremes of this nature are expected to intensify with global warming (Easterling *et al* 2000), raising concerns about increased ecosystem stress, reduced biospheric productivity, and carbon cycle feedbacks that beget further warming (Luo 2007, Reichstein *et al* 2013). But before today's responses can be used to infer likely future impacts it is important to examine how ongoing global environmental changes may alter the sensitivity of the carbon cycle to climate and thus modify the impacts of heat waves and droughts in the future.

For the past half century terrestrial ecosystems have sequestered about a quarter of anthropogenic carbon emissions (Le Quéré *et al* 2009), much of it in forests (Pan *et al* 2011) fueled by some combination of growth enhancement from CO_2 and nitrogen fertilizations, longer growing seasons, and changes in light and moisture conditions. Such stimulation of terrestrial productivity is expected to continue and even increase over the coming century particularly as elevated atmospheric carbon dioxide promotes greater rates of carbon fixation and uptake in spite of carbon releases caused by warming and changes in moisture regimes (Cox *et al* 2000, Friedlingstein *et al* 2006, Arora *et al* 2013, Ciais *et al* 2013). It is therefore reasonable to wonder if the processes stimulating productivity might diminish the adverse carbon impacts of droughts and heat waves in the future.

A new study by Ian Williams and co-authors (Williams *et al* 2014) used CMIP5 coupled carbon-climate earth system model (ESM) experiments (Taylor *et al* 2012) to examine if CO_2 fertilization or changes in temperature and moisture patterns with global warming alter productivity declines from heat extremes. The study emphasizes growing season months over the 21st century under a high carbon emissions scenario (the IPCC Fifth Assessment Report's Representative Concentration Pathway 8.5). Results show the expected increase in gross primary productivity (GPP) over the 21st century despite a decline in average soil moisture because of the overwhelming influence of CO_2 fertilization. This is true in most regions except where (i) soil moisture suffers the largest declines, (ii) water is already severely limiting, or (iii) cold temperature limitation is strong. Interestingly, Williams *et al* (2014) also find that GPP stimulation is greatest during warm events when precipitation actually increases. Williams *et al* (2014) attribute this to an increase in the surface temperature needed to trigger moist convection in a warmer atmosphere shifting convective precipitation onset to a higher temperature. The combined effect of these changes is to increase the temperature at which GPP is maximum as well as the temperature at which GPP experiences declines from heat and water stress.

One might expect this shift to diminish the sensitivity of GPP to future heat waves. To the contrary, Williams *et al* (2014) show that the key to examining impacts of warm events and droughts in a future climate is to shift the lens to account for the drift in the temperature optimum for GPP, thus separating climate variability from trend. When doing so, they find that GPP declines are just as large or even larger for a given temperature anomaly in the future compared to the present. In other words, the sensitivity of GPP to heat waves and droughts is largely unaltered by GPP stimulation, adjustments in soil moisture with temperature, or other modeled responses to global warming. This makes a compelling case for using today's observational anecdotes about the carbon impacts of heat waves and droughts as guides to what can be expected in the future. However, Williams *et al* (2014) also show that future heat extremes are expected to be more frequent and longer lived with continued global warming, exacerbating productivity declines. From this perspective, today's measured impacts may offer an overly optimistic view of what is to come.

While recognizing the significance of these findings, it is also worth considering processes missed or poorly represented in the current generation of biophysical/biogeochemical ESMs that contributed to the CMIP5 ensemble. For example, considerable uncertainty remains regarding the degree to which ecosystem productivity can be stimulated by elevated atmospheric CO_2 concentrations and there is reason to believe it may be overestimated by such models which tend to miss possible limitation by other factors, particularly nitrogen availability (Luo *et al* 2004, Norby *et al* 2010), though stimulation of N uptake or N use efficiency may be able to sustain CO_2-enhanced productivity (Finzi *et al* 2007). More relevant for drought and heat extremes, water stress induced mortality processes such as hydraulic failure or carbon starvation are largely missing from ESMs despite their known importance (Allen *et al* 2010, McDowell 2011). Recent work suggests that many trees operate at or near their tolerance limit for water stress, suggesting widespread vulnerability to not just water shortages but also temperature driven increases in vapor pressure deficit (Williams *et al* 2012) and may not be able to acclimate or acclimate fast enough to keep pace with the changing climate. Even if such stresses do not directly kill trees themselves, they can increase vulnerability to mortality from pests as witnessed by the large-scale forest dieback from bark beetle outbreaks taking place across North America (Kurz *et al* 2008, Hicke *et al* 2013). Warming could also create longer, more damaging wildfire seasons causing further carbon releases (Westerling *et al* 2006) though see also Krawchuk *et al* (2009). In addition, plant distributions and ecosystem assemblages are capable of gradual or even abrupt shifts in response to changing climate and environmental conditions (e.g. Allen and Breshears 1998). These and other processes are absent from the current generation of ESMs used in global simulation of coupled carbon-climate dynamics, contributing to uncertainties surrounding the use of current climate responses to predict impacts of future climate. Solving this challenge relies on expanded observations to improve process understanding for regional and global parameterization. But even at this stage it is clear that nearly all of the missing processes would add to the adverse carbon impacts of droughts and heat waves, reducing land carbon storage and intensifying the biospheric feedback to warming.

Put together, the declines in productivity seen with recent heat waves and droughts likely underestimate the impacts of such events in the future. The important contribution by Williams *et al* (2014) brings this perspective into sharp focus, shedding light on how terrestrial ecosystems respond to both trends and variability in the climate system, and lending credence to concerns about biospheric feedbacks that amplify global warming.

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