Ecosystem impacts of climate extremes crucially depend on the timing

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> The year 1540 was unprecedented in centuries. It was dreadful, bright, and hot. Bright weather and heat… lasted for 29 weeks, in which rain fell on not more than 6 days. … Meadows and forests were yellow from the heat, and the earth opened large cracks; at several locations, grapes and vine withered, many forests burned, fountains and springs dried out completely… (but) there was an abundance of corn and a lot of delicious wine.
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> Translated from German, a contemporary witness describing the contrasting impacts of a megaheat and drought event of 1540 in Europe (1).

The impacts of climate extremes have always been of crucial importance to human societies, but they also play a key role in affecting structure and functioning of ecosystems. Whether there are any impacts at all, and how these impacts manifest themselves, critically depends on the timing, magnitude, extent, and type of the climate anomaly. Although many studies have been undertaken to investigate the impacts of climate extremes on ecosystem functioning, attempts to build an overarching framework have had little success so far and many open questions remain (2). A study published in PNAS (3) provides new insights into the question of how impacts of climate extremes occurring during different periods of the year can interact and counteract each other.

Wolf et al. (3) investigated the year 2012 and its impacts on terrestrial carbon fluxes in the continental United States, an extreme year in which a record warm spring was followed by a severely dry and hot summer (4, 5). The authors analyzed three independent streams of observational data and data-driven models, and demonstrated that losses in net carbon uptake during summer were largely offset by unusual carbon gains in spring caused by its record-exceeding warmth and early arrival. In this way, the continental United States remained a carbon sink despite the exceptional drought that spanned most of the country.

This news is good and suggests that warmer springs can alleviate the devastating impacts of summer droughts (Fig. 1). The bad news, however, might follow suit: Because ecosystem fluxes of carbon and water are tightly coupled through plant stomata, higher spring carbon uptake might lead to an earlier depletion of soil water resources through increased evapotranspiration, thus amplifying extreme temperatures in the summer. Wolf et al. (3) hypothesize that this effect has exacerbated the 2012 summer drought and contributed to elevated surface heating, and thereby highlight the important role that land-atmosphere feedbacks could play during climate extremes. However, it cannot be excluded that a less warm spring would have depleted soil water resources less rapidly, rendering the impacts of the rainfall deficit in summer less severe. These important questions have not been answered definitely and deserve more detailed investigations. It is critical to disentangle the different counteracting feedbacks, not least because events such as the year 2012 in the United States might occur more often in the future.

The authors arrive at their synthesis by combining so-called "bottom-up" with "top-down" approaches. A network of local flux tower measurements of carbon and water exchange across the United States on land was complemented with photosynthetic carbon uptake derived from satellite remote sensing and an atmospheric inverse model that estimates net carbon uptake using atmospheric measurements of CO_2 concentrations. The study thus provides empirical evidence both at the ecosystem and continental scales that two different but prevalent types of climate extremes in temperate ecosystems can have compensatory impacts on the carbon cycle. The results complement previous analyses indicating that dry summers offset increases in vegetation carbon uptake driven by warmer springs in the Northern Hemisphere extratropics (6). Empirical insights into carbon and water cycle dynamics aside, however, the study highlights important scientific questions related to (*i*) disentangling the extent, magnitude, and relevant components that contributed to a compensation of climate extreme-related impacts and (*ii*) understanding and quantifying plant–soil–atmosphere feedbacks in a warmer world.

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See companion article on page 5880.

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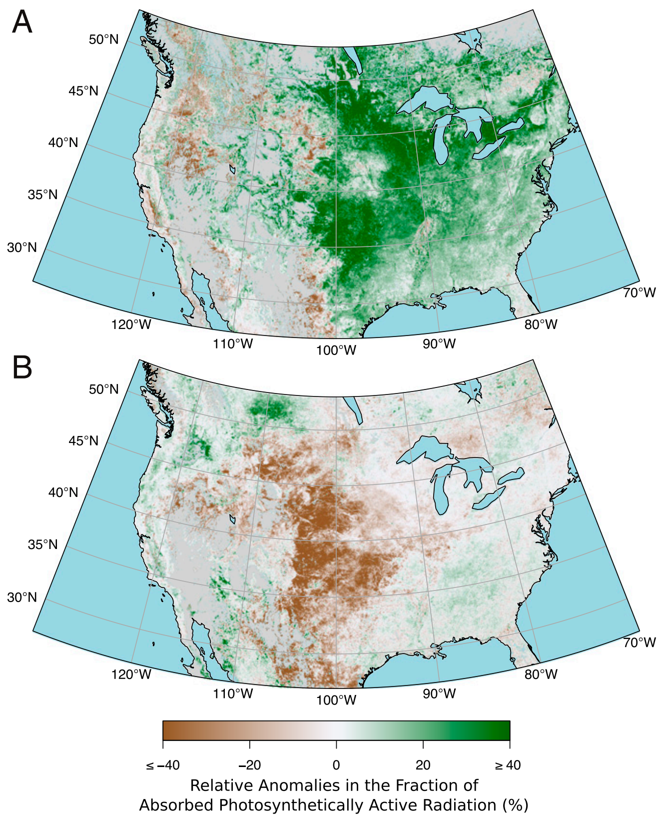


Fig. 1. Early spring gains (*A*, March–April) and late summer reductions (*B*, July–August) in the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR; %), an indicator for vegetation activity, in the year 2012 relative to 2001–2014. Grid cells with a long-term mean FAPAR below 10% are shown in gray. The JRC-TIP (Joint Research Centre Two-Stream Inversion Package) FAPAR dataset based on satellite broadband albedo observations (20) is provided by The Inversion Lab and the Joint Research Centre of the European Commission.

Identifying Carbon Cycle Components That Cancel Out

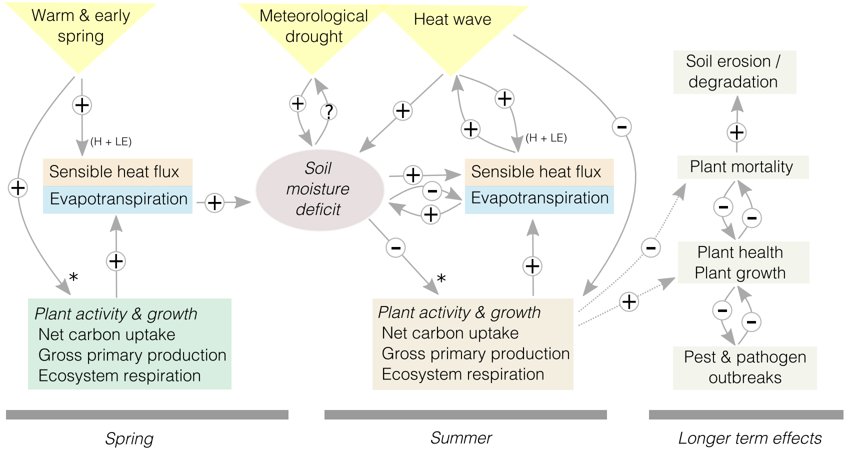
To advance our process understanding about impacts of events such as the extreme spring and summer in 2012 in the United States, it is important to understand which components of the carbon cycle contributed to the observed compensation. The net ecosystem carbon flux is the difference between the plant's photosynthetic carbon uptake and carbon losses through ecosystem respiration. During the summer of 2012, reductions in photosynthetic carbon uptake exceeded the reduction in respiratory carbon flux, consistent with previous observations during droughts (7). Despite the observed surplus in gross carbon uptake in spring, annual gross carbon uptake remained substantially below average across the continental United States. Surprisingly, annual net carbon uptake in the continental United States was still close to average, which highlights the role of ecosystem respiration in shaping the impacts of climate extremes on net carbon uptake. Ecosystem respiration increased in spring only moderately, whereas its decrease in summer was large. Grasping how individual carbon cycle components react to climate extremes and implementing these processes into mechanistic models may thereby lead to better constrained carbon projections (8). On a different note, Wolf et al. (3) find that high spring uptake, particularly in the eastern temperate forests, prevented the United States from shifting from a carbon sink to a carbon source. The spatially nonuniform signal demonstrates how the impacts of climate extremes differ between ecosystems and illustrates the challenge associated with finding general response patterns to climate extremes (2). What can be beneficial for one ecosystem might be devastating for another (9).

Global climate models indicate that warm spring temperatures similar to the temperatures in 2012 lie at the cooler end of the temperature distribution in the second half of the 21st century (3). In contrast, severe summer droughts will remain rare but impacts will likely be exacerbated by hotter temperatures (10). Over the past few decades, net carbon uptake in temperate forests has increased because of warmer spring temperatures that induce a lengthening of the growing season (11, 12). Overall warmer springs might thus offset some of the adverse impacts of hot summer droughts. However, to start leaf unfolding, temperate forests also require a sufficient degree of winter chilling, which implies that the observed warming-induced changes might not simply follow spring temperatures in the future (13, 14). Wolf et al. (3) have disentangled temporal and spatial components of ecosystem carbon impacts of the anomalous year 2012, but experimentalists and modelers will have to work together to figure out whether positive impacts of more favorable spring conditions or adverse impacts of dry and hot summers will prevail under future climate conditions.

The Role of Plant-Soil-Atmosphere Feedbacks in Enhancing Summer Heat

That land–atmosphere feedbacks can strongly influence the magnitude of extreme heatwaves and droughts has long been acknowledged (15). Dry soils can exacerbate extremely high temperatures, whereas wet soils impede the development of extreme heat waves through evaporative cooling (16). The role of plants in these feedback mechanisms is much less well understood. Warmer conditions, accompanied by higher radiation, generally lead to higher photosynthetic activity, particularly in the energy-limited areas that span most of the United States. More photosynthetic activity induces higher evapotranspiration rates, thereby depleting soil water. If photosynthesis is strongly enhanced in spring and soil water is not replenished through precipitation, in tandem with high summer temperatures (e.g., through a blocking event), the dry soils will enhance the summer heat because more of the incoming radiation is translated into sensible heat (15). Quantifying the different contributions of vegetation, lack of precipitation, and spring temperatures to the resulting concurrent drought and heatwave in summer is challenging (Fig. 2). To disentangle the impacts of enhanced photosynthesis in spring on summer drought and summer temperatures, one could conduct, for example, factorial model runs with and without vegetation.

Wolf et al. (3) show in their study that neither seasons (spring and summer) nor carbon, water, and energy fluxes should be interpreted separately when analyzing the impacts of climate extremes. On the one hand, the authors see depletion of soil moisture through early vegetation activity in a warm spring potentially amplifying summer heating, a typical lagged direct effect of an extremely warm spring (2). On the other hand, spring and summer, and photosynthesis and respiration, compensate each other with respect to the net annual effect on the carbon cycle, leading to a near-neutral same-year carbon balance. Can one thus speak of an overall reduced net carbon impact of the 2012 drought? The future will tell, because lagged and indirect effects can be important. Mechanisms for such effects include, for instance, depending on the ecosystem, plant mortality, pathogen dynamics, or soil erosion and degradation (17, 18). If 2012 conditions become more frequent in the future, in



* Climate effects on ecosystem carbon fluxes are shown only in qualitative terms. Individual fluxes might be affected differently by climate extremes (see text).

Fig. 2. Conceptual framework of potential plant-soil-atmosphere feedbacks and ecosystem impacts. Solid arrows indicate direct impacts (positive or negative), and dashed arrows show hypothesized longer term effects of summer drought. H, sensible heat; LE, latent heat or evapotranspiration.

concert with potential mitigation effects through elevated CO_2 (19), the competition between plant populations induced by vegetation dynamics may lead to either enhanced carbon storage (e.g., in woody vegetation) or depletion. Thus, for understanding the "true" integral effect of a year like 2012, it is important that we monitor and analyze subsequent years, which is possible thanks to long-term observations established by the respective research networks [e.g., AmeriFlux, Europe's Integrated Carbon Observation System (ICOS), and the National Ecological Observatory Network (NEON)]. In addition, even longer term archives (e.g., in tree rings or lake sediments) should provide complementary information in terms of the time scale and processes involved.

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