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Preface: Climate extremes and biogeochemical cycles in the terrestrial biosphere: impacts and feedbacks across scales

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Climate projections suggest a significant increase in the frequency and severity of climate extremes (extreme weather or climate events), such as droughts, heatwaves, heavy precipitation events and storms (Seneviratne et al., 2012; Stocker et al., 2013). By impacting the biosphere and biogeochemical cycles, climate extremes may have profound implications for ecosystems, society and the climate system (Seneviratne et al., 2012; Reichstein et al., 2013). This special issue comprises a range of ecosystem-scale case studies, cross-system syntheses and continental-scale assessments of effects of climate extremes on biogeochemical cycles in the terrestrial biosphere. It has emerged from a global conference on the topic held in Seefeld, Austria, in 2013 (www.bgc-extremes2013.org; for major conclusions from the conference see Bahn et al., 2014, and Kayler et al., 2015) and related sessions at the American Geophysical Union Fall Meeting in 2013 and the European Geosciences Union General Assemblies in 2013 and 2014. The special issue complements another recent special issue of *Biogeosciences* entitled “Impacts of extreme climate events and disturbances on carbon dynamics“ (www.biogeosciences.net/special_issue124.html).

The ecosystem studies compiled here span from semi-arid and Mediterranean forests to temperate grasslands and the Arctic tundra. Several articles report on effects of drought and temperature anomalies on processes ranging from ecosystem CO_2 fluxes, productivity, carbon allocation and carbon use efficiency (Burri et al., 2014; Rambal et al., 2014; Ruehr et al., 2014; Zona et al. 2014) to plant water uptake (Hoekstra et al., 2014) and nitrogen cycling (Fuchslueger et al., 2014; Schuerings et al., 2014). A modelling study disentangles the role of physiological responses versus ecosystem properties and boundary layer feedbacks for explaining unexpectedly higher sensible heat fluxes over forest compared to grassland during heatwaves (van Heerwaarden and Teuling, 2014). Focussing on the effects of extreme rainfall events, Jung et al. (2014) analyse the export and reactivity of particulate and dissolved organic carbon in a headwater watershed under monsoon climate. While all these above papers report on direct concurrent effects of extreme events, some also point towards potential lagged effects (see Frank et al., 2015) of climate extremes on biogeochemical cycles, e.g. via carry-over effects from climate anomalies during previous years on tree growth (see combined model–data analysis by Rammig et al., 2015), differential responses of different species/functional types to climate extremes (Hoestra et al., 2014; Zona et al., 2014), implications of altered plant nitrogen uptake (Schuerings et al., 2014) for ecosystem carbon and nitrogen dynamics, or post-windthrow effects on microclimate and soil carbon turnover (Mayer et al., 2014). Two case studies highlight the consequences of indirect effects of climate extremes, which can facilitate the occurrence of fires or pest outbreaks. Fires have both immediate and slower follow-up effects on the terrestrial carbon balance (Li et al., 2014). A case study by Boot et al. (2015) shows that fire intensity may not necessarily affect the residence time of black carbon in litter. Another study on indirect effects of climate extremes analyses consequences of pine beetle outbreaks, whose impacts on growth and species composition can alter albedo and thus radiative forcing (Vanderhoof et al., 2013).

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Two synthesis studies explore effects of drought on important components of the carbon balance. Based on data synthesis and a modelling analysis across a range of biomes, Shi et al. (2014) conclude that responses of production and respiration differ in magnitude and are affected by different mechanisms which cause comparatively slower responses of respiration. Vicca et al. (2014) carried out a comprehensive synthesis of precipitation manipulation experiments, demonstrating that moisture responses of soil CO_2 efflux from current climatic conditions cannot be used for predicting this important carbon flux under altered precipitation regimes and highlighting the need for well-comparable experiments.

Several articles of this special issue provide regional- to continental-scale assessments based on remote sensing and model analyses. They recognize, that for assessing effects of climate extremes on biogeochemical cycles, an approach is required which explicitly links extreme weather conditions to anomalous ecosystem behaviour (Smith, 2011; Reichstein et al., 2013). A global analysis based on this concept identifies water scarcity as the key driver of extreme reductions in ecosystem carbon uptake across continents, while the importance of fires, temperature extremes and intense precipitation events differs between continents (Zscheischler et al., 2014). On continents where water scarcity is a widespread climatic constraint, rainfall variability is an important driver of the spatial–temporal variability in land surface phenology (Australia; Broich et al., 2014), and intra-seasonal rainfall variability and especially rainy season length can profoundly affect biome distribution and productivity (Africa; Guan et al., 2014). In Europe, increased drought severity is expected to increase future risks for the net primary productivity and carbon sequestration, especially in the Mediterranean area (Rolinski et al., 2015). The risks increase mainly because of greater drought probability; ecosystem vulnerability will increase to a lesser extent (Van Oijen et al., 2014). During heatwaves, drought and temperature may have combined or separate effects on carbon fluxes, and their effects on plant respiration in different land cover types may differ (Bastos et al., 2014). An analysis of the 2003 European heatwave indicates that vegetation height is a reliable predictor of vegetation response, possibly because of its association with rooting depth and canopy heat capacity (Bevan et al., 2014).

Several overarching conclusions can be drawn from the articles compiled in this special issue, including the following:

- Due to differential responses of species and biogeochemical processes, climate extremes have the potential to alter carbon and nutrient dynamics, the energy balance and finally the ecosystem structure. This may have consequences for carbon sequestration, radiative forcing and thus the regional and global climate, and can result in lagged effects of climate extremes on biogeochemical cycles and their responses to climate changes.

- Global changes such as climate warming and land-use change can alter ecosystem responses to climate extremes, leading to direct regional ecosystem-atmosphere feedbacks – for instance amplifying or moderating heatwaves. Thus future studies should make an effort to address their combined effects.

- The integration of experimental studies, long-term data sets, remote sensing and modelling is an important challenge and a promising avenue for achieving a more comprehensive understanding and improved projections of impacts and feedbacks of climate extremes on biogeochemical cycles across various temporal and spatial scales.

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