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Focus on Extreme Events and the Carbon Cycle

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Climate physics indicates that warming climate is a likely cause of extreme weather and more frequent and intense climate events. These extreme events can disrupt terrestrial carbon dynamics dramatically by triggering ecological disturbances and potentially forcing climate–carbon feedbacks. In this paper we synthesize the findings of 26 papers that focus on collecting evidence and developing knowledge of how extreme events disturb terrestrial carbon dynamics.

1. Introduction

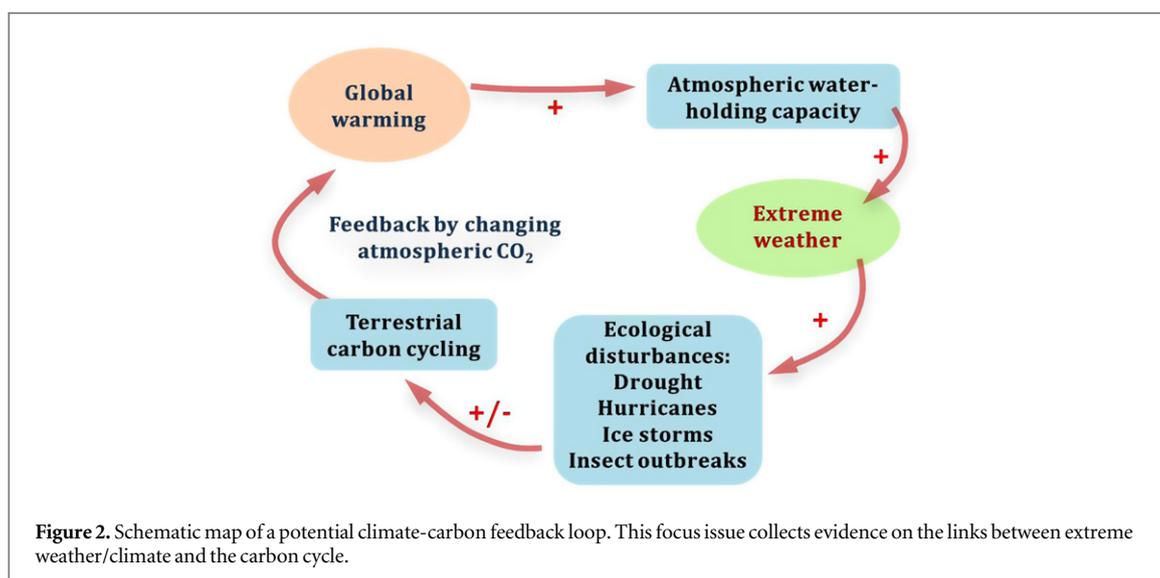
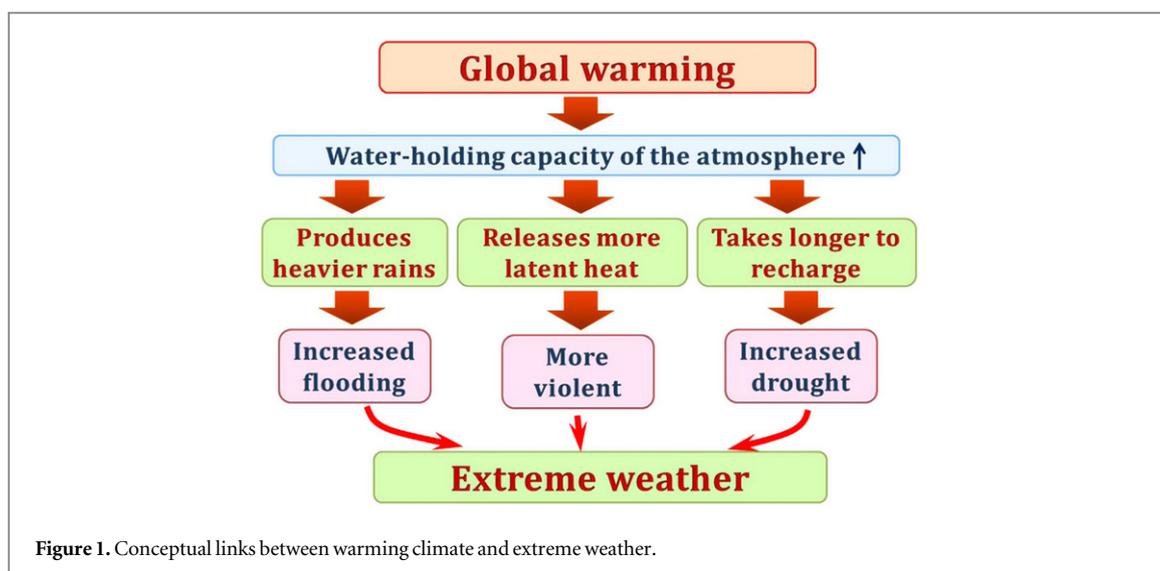
The World Meteorological Organization reported recently ‘that the world experienced unprecedented high-impact climate extremes during the 2001–2010 decade, which was the warmest since the start of modern measurements in 1850 and continued an extended period of pronounced global warming’ (World Meteorological Organization 2013). Even though since 2000, the warming rate is less than during the previous decade (the Hiatus period) extreme hot days have continued to increase in frequency and severity (Seneviratne *et al* 2014). Although global mean annual temperature is not increasing every year, global decadal mean temperature has increased every decade since 1970s. On the other hand, it is clearly evident that the frequency and intensity of extreme events of weather and climate have been increasing in this warming world (World Meteorological Organization 2011, Coumou and Rahmstorf 2012). Does global warming generate more extreme weather events? There has been no direct answer yet. However, the link between extreme weather and warming climate can be understood by the physics of climate. In principle, the ability of atmosphere to hold water is dictated by the Clausius–Clapeyron equation;

$$e_s(T) = 6.1094 \exp\left(\frac{17.625T}{T + 243.04}\right), \quad (1)$$

where, e_s is saturation vapor pressure in hPa, representing the maximum amount of water vapor that air

can hold at a given temperature T (°C) (Ahrens 2000). The Clausius–Clapeyron equation (1) is derived from the first and second law of thermodynamics and has been broadly verified under both laboratory and natural conditions. It predicts that the water-holding capacity of the atmosphere increases by about 7% for every 1 °C rise in temperature, which is close to satellite-based observations that recorded a rate of change in the atmospheric water vapor content 6% °C⁻¹ (Kininmonth 2010).

Figure 1 illustrates conceptual links between global warming and extreme weather. Warming air has higher saturation vapor pressure, i. e. larger size of the ‘room’ for water to evaporate from soils and water bodies and transpire from plants. In addition to increased saturation vapor pressure in the atmosphere, warming directly increases plant evapotranspiration demand, leading to more water emitted by vegetated surfaces to the atmosphere unless soil moisture gets too depleted. This is likely to cause extreme precipitation events as the probability of water molecules condensing increases. Meanwhile, weather systems accompanied with extreme precipitation events can become more violent as more latent heat is released. It will also take longer to recharge the atmosphere with moisture as its capacity to hold water increases. Thus, duration between rain events becomes longer and hence drought would increase. We cannot be certain that any particular extreme weather event is caused by global warming. However,

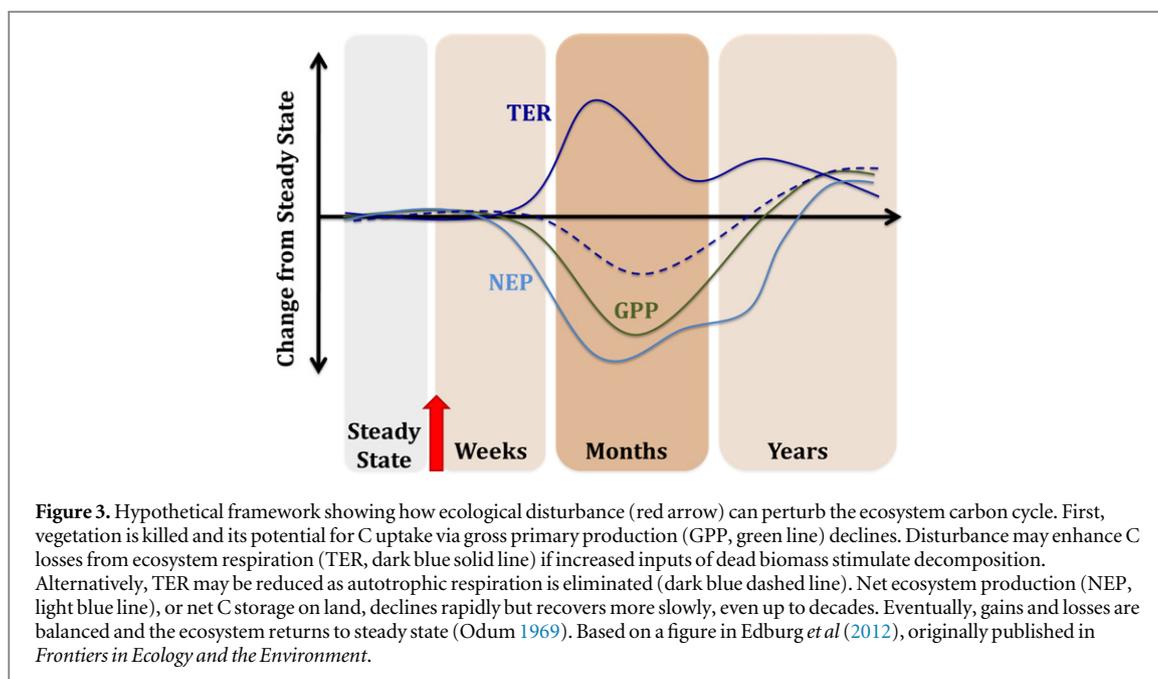


we are certain that global warming amplifies the risk factors for extreme weather events from the principle of thermodynamics—hot air can hold more water molecules. Global warming increases atmospheric evaporative demand, which is supported by observational data; about half of the land in warm regions (annual temperature $>16^{\circ}\text{C}$) has been drying with increasing temperature since the 1970s (Jung *et al* 2010, Yi *et al* 2014).

The high risk consequence of these warming-induced extreme events is that they often lead to ecological disturbances which can affect land–atmosphere exchanges of carbon and water dramatically, potentially contributing to climate–carbon feedback (Cox *et al* 2013), illustrated in figure 2. Most climate-related disturbance events have negative impacts on the health and carbon balance of ecosystems, especially in forests, because they kill trees, inducing a large carbon source to the atmosphere followed by a slow recovery sink (figure 3). Some ecosystems are more resistant to disturbance; for instance, deserts and grasslands are

adapted to water stress. However, mega-drought and heat-waves can cause damage to plants that results in mortality, and more frequent drought can in the long-term change ecosystem structure (Breshears *et al* 2005, Edburg *et al* 2012; figure 3).

In addition to altering the carbon balance, extreme events cause feedbacks to climate due to changed albedo and roughness, and because of altered sensible and latent heat emissions. Stand replacing fires in northern regions causes an increase in winter albedo due to higher snow cover over the short vegetation that covers the ground when the forest has burned. This has a net cooling climate effect (Randerson *et al* 2006). Extreme drought generally suppresses evapotranspiration and increases sensible heat (Teuling *et al* 2013), which acts to increase air temperature and decrease rain probability. This causes a positive feedback on heat and drought. Thus, the direction of feedback between ecological disturbance and global warming is challenging to predict, warranting the



investigations across a range of disturbance types and ecosystems presented in this focus issue.

The aim of this focus issue is not to verify the existence of feedbacks but to collect evidence on how these extreme events, such as heat waves, droughts, hurricanes and insect outbreaks change land–atmosphere exchanges, and to use quantitative approaches to identify these events and explore driving forces behind their ecological consequences.

2. Drought

Fourteen papers in this focus provide lines of evidence of how ongoing extreme droughts affect terrestrial ecosystem exchange of CO₂ with the atmosphere from tower-based flux measurements and satellite-based modeling. Net ecosystem–atmosphere exchange (NEE) of CO₂ is a small imbalance between two large CO₂ fluxes with opposite directions: uptake from the atmosphere by gross primary production (GPP) and release back to the atmosphere by terrestrial ecosystem respiration (TER). These papers demonstrate that impact of extreme droughts on these two components is different and also varies from season to season and from biome to biome.

2.1. Spring drought

Soil moisture availability in spring is usually higher than in summer because soil reservoirs have been recharged by winter precipitation, in many summer-dry northern regions. However, lower precipitation combined with warmer winter temperatures can lead to spring droughts. Based on eddy-flux data collected in Switzerland, Wolf *et al* (2013) found that grasslands and forests respond differently to spring droughts because these ecosystems exhibit different water use

strategies. The ratio of CO₂ uptake (GPP) to water loss (transpiration) is called water use efficiency (WUE), which can be optimized at the ecosystem level under water limited conditions as plants can regulate the size of stomatal openings (Claesson and Nycander 2013). The eddy-flux data indicate that forests increased their WUE during the spring drought, while grasslands' WUE did not change substantially during the spring drought (Wolf 2013).

The response of ecosystems to drought is different from biome to biome. For peatlands, drought conditions will not only reduce soil wetness (reducing GPP) but also lower the water table, increasing the depth of the aerobic respiration layer (increasing TER). The data collected in a south Swedish nutrient-poor peatland by eddy-flux measurements indicate that droughts can turn a temperate peatland from a carbon sink to a carbon source (Lund *et al* 2012). The effect of drought on the peatlands depends on drought duration. A prolonged drought in the early growing season resulted in reduced rates of GPP, while a short but severe drought in the middle of the growing season resulted in increased rates of TER (Lund *et al* 2012), demonstrating the contrasting effects of extreme climate events on components of the carbon cycle.

The 2010 spring drought in southwestern China was the most severe and long-lasting of the last half century. Satellite-based observations show that severe and extended spring droughts substantially reduced the enhanced vegetation index (EVI) and GPP and both did not recover from drought stress until August (Zhang *et al* 2012). This spring drought event also lowered the water levels of rivers, reservoirs and lakes, and even dried up some water bodies, which affected agricultural irrigation and hence crop production. Other satellite-based observations also show that spring drought induced by the El Niño/La Niña-Southern

Oscillation (ENSO) delayed vegetation onset time and reduced annual net primary production (NPP) in the subtropical island of Taiwan (Chang *et al* 2013).

2.2. Late-summer drought

Kolb *et al* (2013) found that impacts of extreme late-summer drought on net ecosystem production (NEP) of semi-arid forest in the southern west United State (SWUS) differed between disturbed and undisturbed ecosystems based on six-year eddy-covariance measurements. The late-summer drought shifted August NEP at the undisturbed site from a carbon sink to source because the reduction of GPP (70%) exceeded the reduction of TER (35%). At the burned site, late-summer drought shifted August NEP from a weak carbon source to neutral because the reduction of TER (40%) exceeded the reduction of GPP (20%). The results illustrate the sensitivity of semi-arid forest carbon sequestration to extreme drought and suggest that warming-associated drought may interact with disturbances such as fire, possibly weakening semi-arid forest carbon sinks.

The contrasting impact of drought on GPP and TER between grazed and ungrazed desert steppe was also evidenced by data collected with tower-based eddy covariance approach on the Mongolian Plateau (Shao *et al* 2013). This two-year dataset indicates that grazing can play a positive role in biophysical regulation of carbon fluxes in a desert steppe. The positive effects of grazing on the uptake of CO₂ in semiarid steppe were also reported by Kang *et al* (2013). Although both these examples were short, the analyses will be useful for grazing management. Nevertheless, additional long-term flux measurements are needed to understand the mechanisms underlying the interactions between extreme climate, ecological disturbance, and carbon cycling.

2.3. Long-term drought events

Babst *et al* (2012) did clustering analysis of tree-ring growth data at ~1000 sites across Europe that showed regionally consistent growth patterns driven by climate regimes and species-specific growth characteristics. Fifteen regional, synthetic chronologies that represent radial tree growth anomalies across Europe were reconstructed over the past ~500 years. The analysis revealed 18 extreme tree-growth events during the pre-instrumental and 2 events (1947/48 and 1976) in the instrumental period, which may be been caused by extreme late-summer drought conditions.

The complexity of interactions between drought and vegetation response is demonstrated in a 26-year study that analyzed vegetation growth based on Normalized Difference Vegetation Index (NDVI) in China (Xu *et al* 2012). Extreme events in temperature, precipitation and drought based on Palmer Drought Severity Index (PDSI) appear to have increased across China over the past three decades. Associated with the

increasing trend in heat waves and drought events, a decreasing trend in the extreme low NDVI events (low vegetation growth) was observed. However, different regions in China experienced contrasting temporal patterns. Although extreme drought events increased in the 2000s in both northern and southern China, extreme low NDVI events keep decreasing in southern China, while the decrease is stalled or even reversed in northern China. Apparently, drought does not impact vegetation productivity in a consistent fashion across continents; prior land use such as grazing may need to be considered to reveal detailed mechanisms.

3. Extreme weather

3.1. Hurricane

The impact of catastrophic hurricanes on life loss and property damage has received considerable attention, but environmental impacts are often neglected. Hurricanes create major ecological disturbances by killing hundreds of millions of trees and adding plant litter on the forest floor, and potentially increasing risk of forest fire conditions. The drastic ecological disturbance by hurricanes is expected to have significant impacts on regional forest carbon balances. In this focus issue, we report case-studies for hurricane impacts on carbon cycling in tropical savannas and temperate forest ecosystems (Hutley *et al* 2013, Vargas 2012, Fisk *et al* 2013).

3.1.1. Hurricane-savanna-fire interactions

Hutley *et al* (2013) estimated the ecological consequences of the mega-cyclone Monica that damaged or destroyed 140 million trees across the coastal and sub-coastal region of north Australia in 2006. They used the moderate resolution imaging spectroradiometer (MODIS) GPP (MOD17A2) to track spatial and temporal patterns between six years preceding and six years following the cyclone Monica. They found that there was a significant decline in the region's GPP (directly proportional to its capacity to sequester carbon) relative to the pre-cyclone rates, and this reduced productivity persisted for four years post-cyclone. The most important ecological consequences of hurricanes is that the hundreds of millions of trees killed or damaged will be converted into CO₂ and returned back to the atmosphere sooner by fire or later by decomposition. Hutley *et al* (2013) examined the impact that the massive increase in fuel load (vegetation debris) following Cyclone Monica would have on the region's fire regime. They found that fire frequency was extreme in the year following the cyclone, but fire frequency more or less returned to pre-cyclone conditions in the years that followed—an unexpected result.

3.1.2. Effect of hurricanes on the soil carbon flux

Vargas (2012) observed large pulses of soil CO₂ flux after hurricane Wilma in two-year time series of soil

carbon dioxide efflux measurements from two soil-sensor nodes. He reported that in the year following hurricane Wilma, annual soil carbon dioxide emissions were more than 3.9 kgC m^{-2} but decreased to 1.7 kgC m^{-2} for the second post-hurricane year. Vargas attributed the increase in the soil carbon flux post-Wilma to tree damage depositing nitrogen-rich, easily decomposable organic matter and higher basal soil CO_2 efflux rates. Moreover, GPP was not impacted immediately after the hurricane but during the drought period of the first year, a depletion of non-structural carbon reserves that likely were used for a 'rapid' recovery of canopy cover (e.g., leaf area index) during the first 2 months following the hurricane.

3.1.3. Carbon footprint of historical hurricanes in eastern US

The case studies conducted by Hutley *et al* (2013) and Vargas (2012) have demonstrated that a single hurricane event can exert a large disturbance in forest carbon balance, but forests have strong resilience to recover. In the short- to medium-term, hurricanes release carbon due to leaves and litters can be easily decomposed, while over the longer term, GPP will be increased from forest re-growth. Therefore, the recovery times of the two components, GPP and TER, of forest carbon balance from hurricane disturbances to approaching the normal rates are not the same (see figure 3). This imbalance between GPP and TER might affect the ability of forests to absorb carbon in a long-term perspective. Fisk *et al* (2013) investigated it by modeling the reconstructed maps of tree mortality from hurricanes impacting the eastern US from 1851 to 2000. They found how long it takes for the forest re-growth to recover the carbon loss depends on the type of forest. Small disturbances in fast-growing regions can recover quickly, but large disturbances or slower growth rates can result in recovery that takes more than a century. Fisk *et al* (2013) concluded that on average, tropical cyclones contribute a net carbon source over latter half of the 19th century due to high storm activity and the existence of larger forests during that period. However, throughout much of the 20th century a regional carbon sink is estimated resulting from periods of forest recovery exceeding damage.

3.2. Ice storms

Terrestrial ecosystems in temperate to subtropical regions are vulnerable to the invasion of extreme cold events like ice storms. These cold events are common in East Asia and can cause massive structural damage to forests and often define the northern boundaries of key tree species. Sun *et al* (2012) investigated the impact of the massive 2008 Chinese ice storm on forest ecosystems in southern China and found that while forest structures were substantially changed by the ice storm, forest greenness, as measured by satellite, recovered fairly quickly overall; however, moderately

damaged forests recovered the slowest as a consequence of salvage logging. These cold events can also interrupt ecosystem potential productivity dramatically. Huang *et al* (2013) observed the large reduction of GPP from Qianyanzhou Ecological Experimental Station in southern China as a result of ice storms in 2005 and 2008.

3.3. Extreme snow events

3.3.1. Extreme short snow season

Climate change is likely to shorten the duration of snow cover in mountainous regions such as the European Alps. In 2011, Europe experienced extremely warm spells in late winter. These events did not spare the Alps, and the Italian Aosta Valley region saw the earliest snowmelt for 65 years and the shortest snow season for 83 years. Galvagno *et al* (2013) examined how the short snow season modified the carbon balance of subalpine grassland in the region by eddy-covariance measurements. They observed that the extremely short snow season in the Alps led to a 100% increase in the annual net CO_2 uptake. They found, interestingly, this larger carbon sink was attributable to smaller carbon dioxide emissions by TER during the shorter winter, rather than to enhanced plant activity and GPP during the longer summer.

3.3.2. Summer drought worsens impacts of bitter winter in Mongolia Plateau

'Dzud' in the Mongolian Plateau refers to a winter with extreme cold, heavy snowfall, reduced availability of forage and widespread mortality of livestock (John *et al* 2013). Recently, the dzuds and droughts in the Mongolian Plateau have become more serious. Particularly when a dzud is preceded by a summer drought, the combined summer drought–dzud often leads to even higher mortality of livestock (Fernández-Giménez *et al* 2012). John *et al* (2013) identified such extreme events in the Mongolian Plateau during the period of 2000–2010 using precipitation and PDSI data, and examined the vegetation response to these extreme events using anomalies of vegetation indices. They concluded that the grassland biome on the plateau was more resilient to the extreme events than the desert biome.

4. Bark beetles

Global warming and drought are associated with expanding populations of forest insects and pathogens (Logan *et al* 2003), which cause widespread tree mortality and cascading ecosystem level disturbance impacts (Edburg *et al* 2012). Severe outbreaks of bark beetles may coincide with or follow extreme droughts (Breshears *et al* 2005), as stressed trees are unable to defend themselves from the attacking insects. Disruption to the carbon cycle by beetle-induced mortality

has been compared with the carbon losses by forest fires in Canada (Kurz *et al* 2008). In this focus issue, we provide four reports on climate-associated insect outbreaks and their impacts on carbon cycling in North America.

Over the last two decades, a widespread outbreak of bark beetles (*Dendroctonus* spp.) has affected tens of millions of hectares of conifer forests (Edburg *et al* 2012). In an Idaho pine forest, aboveground carbon stocks in trees were reduced by up to 50%, as shown by multispectral imaging and LIDAR (Bright *et al* 2012). Most of the area in this region was moderately affected by the beetles, although small areas experienced severe mortality. An inventory-based analysis over the western United States found that the amount of carbon in trees killed by beetles exceeded that lost to forest fires (Hicke *et al* 2013). These disturbances represent a loss of about 10% of the total carbon stock in Western US forests, comparable to the amount removed by logging activities. Although the impact of bark beetle-induced mortality is visually dramatic, their influence on carbon and water cycling may be less than anticipated. Using eddy covariance, Reed *et al* (2014) found that maximum carbon uptake by a Wyoming pine forest was not strongly altered despite the progression of mortality from 30% to nearly 80% in the tower footprint. They attributed the resilience of the ecosystem to enhanced light use efficiency by the surviving trees as the canopy opened.

The effects of defoliation on carbon cycling were evaluated using an ecosystem demography model that represents fine-scale canopy structure to scale up physiological processes (Medvigy *et al* 2012). The model indicated that net ecosystem production decreased linearly with increasing defoliation by gypsy moths, but that the carbon cycle responses interacted with drought impacts. Drought-induced tree mortality was lower in scenarios including defoliation disturbance (Medvigy *et al* 2012), possibly due to compensating processes such as enhanced water or nutrient availability at intermediate disturbance levels (Reed *et al* 2014).

5. Quantitative approaches

How to quantify relationships between the extreme events and their ecological consequences is a knowledge gap. In this focus issue, a few quantitative approaches have been demonstrated.

5.1. Tail Approach

The ecological consequences of extreme climate events can be mapped from remote sensing images with sharper changes in vegetation greenness and leaf area index, or can be identified by a large reduction in carbon uptake (GPP) with eddy-covariance measurements. Extreme events occur with small probability but with large amplitudes of changes in variables

characterizing the state of the terrestrial biosphere (Zscheischler *et al* 2014). These extreme events can be defined as the occurrence of certain values in the tails of the probability distribution of the anomalies of the variables, similar to extreme weather defined by IPCC (Seneviratne *et al* 2012). We call this method the 'tail approach'. The question is how long the tails can be cut to define extreme events.

Zscheischler *et al* (2014) applied this approach to the terrestrial carbon balance by defining extremes to be outside a certain threshold q , which is defined by a percentile (i.e. 1%, ..., 10%) on the absolute values of the anomalies. They then defined an extreme event by spatiotemporally contiguous points whose values are larger than q (positive extremes) and smaller than $-q$ (negative extremes), respectively. Zscheischler *et al* (2014) reanalyzed four global MODIS-based GPP datasets over the last 30 years and found that positive (extreme excess in carbon uptake) and negative (extreme reduction in photosynthetic carbon uptake) GPP extremes occurring on 7% of the spatiotemporal domain explained 78% of the global interannual variation in GPP. Most of the negative GPP extremes (larger than positive extremes) were attributed to droughts.

The tail approach depends on the shape of the probability distribution of the anomalies, and on their severity. The identification of extreme events requires that the shapes of probability distributions are similar so that comparison and analysis cross all sites can be made. However, it is impossible to have similar distribution of probability of the anomalies on a global scale due to heterogeneous properties of vegetation from region to region. Liu *et al* (2013) developed a new method of using the Box-Cox transformation (Box and Cox 1964) to convert non-normally distributed dataset into normally distributed dataset. They applied the new method to biweekly time series of global normalized difference vegetation index (NDVI) from 1982 to 2006 to investigate the extreme events on a global scale. They found that extreme NDVI events were aggregated in Amazonia and in the semi-arid and semi-humid regions in low and middle latitudes, while they seldom occurred in high latitudes. This NDVI data analysis indicates that precipitation was a major control on the NDVI extremes in low and middle latitudes, providing a consistent picture as by FLUXNET data synthetic analysis (Yi *et al* 2010, 2014).

5.2. Risk approach

Risk analysis is not a new method, but applying it to the understanding of interactions between extreme events and ecological resources is challenging. van Oijen *et al* (2013) introduced a simple probabilistic method that can be used to assess ecosystem risks imposed by extreme climatic events. In this approach, risk is quantified as the product of two components: the probability of hazardous conditions and the

vulnerability of ecosystems to those hazardous conditions. The challenge in this approach is to determine the threshold values of hazardous climate conditions, which varies between ecosystems and can also evolve with time. They have used their method to analyze the risk of drought in European forests under recent (1971–2000) and future (2071–2100) climate conditions. Vulnerability is defined as the mean difference in primary vegetation productivity between non-drought and drought years.

5.3. Perfect-deficit approach

A perfect-deficit approach developed by Yi *et al* (2012) is different from the widely used, traditional method of the tails approach (extreme fluctuations relative to mean values). The nature of the perfect-deficit approach is data-based. During observational period, a perfect growth (carbon uptake) curve can be constructed by the best growth of ecosystems across the years at the site. Thus, the growth curves of each year can be compared with the perfect growth curve. The difference between the perfect-growth curve and yearly growth curve is defined as deficit. Yi *et al* (2012) derived this approach based on GPP data measured from five grassland tower sites. They found strong links between GPP deficits and drought index. This approach can be applied to any continuous dataset of ecosystem–climate interactions. Therefore, the same extreme events can be cross-verified by different independent datasets.

Wei *et al* (2014) applied the perfect deficit approach to assess the effects of climate extremes on forest carbon assimilation capacity based on FLUXNET data and MODIS GPP datasets. They found a strong link between periods of drought and reduced capacity of trees to absorb carbon. In particular, broadleaf (evergreen and deciduous) trees were very sensitive, whereas coniferous trees were less affected. This is because most broadleaf trees are adapted to generally well watered and good nutrient conditions, whereas needles are a specific adaptation that evolved to maximize carbon uptake in water- and temperature-limited regions. Huang *et al* (2013) applied the perfect-deficit approach to explore how potential productivity of coniferous plantation forest was significantly reduced by extreme drought and ice storm. They found that temperature deficits rather than droughts were main drivers for the GPP deficits.

5.4. Climate mitigation

As illustrated in figure 1, more frequent extreme weather and drought events are likely to be associated with the warming climate. In this focus issue, we have collected evidence on how these warming-associated natural disturbances interrupted current terrestrial carbon dynamics. The disruption of the terrestrial carbon dynamics may trigger the potential climate–carbon feedbacks illustrated in figure 2. Le Page *et al*

(2013) used the Global Change Assessment Model (GCAM) to test what successful climate mitigation should be undertaken with the natural disturbances. They studied scenarios of stable, increasing and decreasing natural disturbance rates, with all model runs stabilizing atmospheric carbon dioxide at a level that is expected to keep global temperature increase within a certain range above pre-industrial levels by 2095. They found that in the case of increased disturbance rates, resulting terrestrial emissions would have to be balanced by further deployment of low-carbon technologies for society to achieve a given level of mitigation. Under a carbon market policy, this implies increased carbon prices and mitigation costs up to 2.5 times higher in the most extreme scenario (doubling disturbance rates). As a case study, Campbell *et al* (2012) examined the strategic effects of future mountaintop coal mining on the carbon budget of the southern Appalachian forest region by ecosystem modeling and field experiment data.

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