



**HAL**  
open science

## Effects of climate extremes on the terrestrial carbon cycle: concepts, processes and potential future impacts

Dorothea Frank, Markus Reichstein, Michael Bahn, Kirsten Thonicke, David Frank, Miguel D. Mahecha, Pete Smith, Marijn van Der Velde, Sara Vicca, Flurin Babst, et al.

### ► To cite this version:

Dorothea Frank, Markus Reichstein, Michael Bahn, Kirsten Thonicke, David Frank, et al.. Effects of climate extremes on the terrestrial carbon cycle: concepts, processes and potential future impacts. *Global Change Biology*, 2015, 21 (8), pp.2861–2880. 10.1111/gcb.12916 . hal-01444818

**HAL Id: hal-01444818**

**<https://hal.science/hal-01444818>**

Submitted on 12 Apr 2018

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Effects of climate extremes on the terrestrial carbon cycle: concepts,**  
2 **processes and potential future impacts**

3

4 *Frank, Dorothea<sup>1</sup>; Reichstein, Markus<sup>1</sup>; Bahn, Michael<sup>2</sup>; Frank, David<sup>3,17</sup>; Mahecha, Miguel*  
5 *D.<sup>1</sup>, Smith, Pete<sup>4</sup>, Thonicke, Kirsten<sup>5,22</sup>; van der Velde, Marijn<sup>6,21</sup>; Vicca, Sara<sup>7</sup>; Babst,*  
6 *Flurin<sup>3,18</sup>, Beer, Christian<sup>1,19</sup>; Buchmann, Nina<sup>8</sup>; Canadell, Josep G.<sup>9</sup>, Ciais, Philippe<sup>10</sup>,*  
7 *Cramer, Wolfgang<sup>11</sup>; Ibrom, Andreas<sup>12</sup>, Miglietta, Franco<sup>13,20</sup>, Poulter, Ben<sup>10</sup>, Rammig,*  
8 *Anja<sup>5,22</sup>; Seneviratne, Sonia I.<sup>8</sup>; Walz, Ariane<sup>14</sup>; Wattenbach; Martin<sup>15</sup>; Zavala, Miguel A.<sup>16</sup>;*  
9 *Zscheischler, Jakob<sup>1</sup>*

10 <sup>1</sup> Max Planck Institute for Biogeochemistry, 07745 Jena, Germany

11 <sup>2</sup> Institute of Ecology, University of Innsbruck, 6020 Innsbruck, Austria

12 <sup>3</sup> Swiss Federal Research Institute WSL, 8903 Birmensdorf, Switzerland

13 <sup>4</sup> University of Aberdeen, Institute of Biological and Environmental Sciences, 23 St Machar  
14 Drive, Aberdeen, AB24 3UU, UK

15 <sup>5</sup> Potsdam Institute for Climate Impact Research (PIK) e.V., 14773 Potsdam, Germany

16 <sup>6</sup> International Institute of Applied Systems Analysis (IIASA), Ecosystems Services and  
17 Management Program, A-2361 Laxenburg, Austria

18 <sup>7</sup> Research Group of Plant and Vegetation Ecology, Biology Department, University of  
19 Antwerp, Wilrijk, Belgium

20 <sup>8</sup> ETH Zurich, 8092 Zurich, Switzerland

21 <sup>9</sup> Global Carbon Project, CSIRO Oceans and Atmosphere Flagship, GPO Box  
22 3023, Canberra, ACT 2601, Australia

1 <sup>10</sup> IPSL – Laboratoire des Sciences du Climat et de l’Environnement CEA-CNRS-UVSQ,  
2 91191 Gif sur Yvette, France

3 <sup>11</sup> Institut Méditerranéen de Biodiversité et d’Ecologie marine et continentale (IMBE), Aix  
4 Marseille Université, CNRS, IRD, Avignon Université, Aix-en-Provence, France

5 <sup>12</sup> Department of chemical and biochemical Engineering, Technical University of Denmark,  
6 (DTU), Frederiksborgvej 399, 4000 Roskilde, Denmark

7 <sup>13</sup> IBIMET-CNR, Via Caproni, 8 50145 Firenze – Italy

8 <sup>14</sup> University of Potsdam, Institute of Earth and Environmental Science, 14476 Potsdam,  
9 Germany

10 <sup>15</sup> Helmholtz Centre Potsdam, GFZ German Research Centre For Geosciences, 14473  
11 Potsdam, Germany

12 <sup>16</sup> Forest Ecology and Restoration Group, Universidad de Alcalá, Alcalá de Henares, Madrid,  
13 Spain

14 <sup>17</sup> Oeschger Centre for Climate Change Research, University of Bern, CH-3012 Bern,  
15 Switzerland

16 <sup>18</sup> Laboratory of Tree-Ring Research, The University of Arizona, 1215 E Lowell St, Tucson,  
17 AZ 85721, USA

18 <sup>19</sup> Stockholm University, Department of Environmental Science and Analytical Chemistry  
19 (ACES), and the Bolin Centre for Climate Research, 10691 Stockholm, Sweden.

20 <sup>20</sup> FoxLab, Fondazione E.Mach, Via Mach 1 30158 San Michele a/Adige (Trento) - Italy

21 <sup>21</sup> currently at MARS Unit, Institute for Environment and Sustainability, Joint Research  
22 Centre, European Commission, Via E. Fermi 2749, I-21027 Ispra (VA), Italy

1 <sup>22</sup> Berlin-Brandenburg Institute of Advanced Biodiversity Research (BBIB), 14195 Berlin,  
2 Germany

3 Corresponding author: Dorothea Frank, Max Planck Institute for Biogeochemistry, Hans-  
4 Knöll-Strasse 10, 07745 Jena, Germany, e-mail: [dfrank@bgc-jena.mpg.de](mailto:dfrank@bgc-jena.mpg.de), phone: +49 3641  
5 576284, fax: +49 3641 577200

6 Keywords:

7 climate change, climate extremes, carbon cycle, climate variability, terrestrial ecosystems,  
8 disturbance

9

## 1 **Abstract**

2 Extreme droughts, heat waves, frosts, precipitation, wind storms and other climate extremes  
3 may impact the structure, composition, and functioning of terrestrial ecosystems, and thus  
4 carbon cycling and its feedbacks to the climate system. Yet, the interconnected avenues  
5 through which climate extremes drive ecological and physiological processes and alter the  
6 carbon balance are poorly understood. Here we review literature on carbon-cycle relevant  
7 responses of ecosystems to extreme climatic events. Given that impacts of climate extremes  
8 are considered disturbances, we assume the respective general disturbance-induced  
9 mechanisms and processes to also operate in an extreme context. The paucity of well-defined  
10 studies currently renders a quantitative meta-analysis impossible, but permits us to develop a  
11 deductive framework for identifying the main mechanisms (and coupling thereof) through  
12 which climate extremes may act on the carbon cycle. We find that ecosystem responses can  
13 exceed the duration of the climate impacts *via* lagged effects on the carbon cycle. The  
14 expected regional impacts of future climate extremes will depend on changes in the  
15 probability and severity of their occurrence, on the compound effects and timing of different  
16 climate extremes, and on the vulnerability of each land-cover type modulated by management.  
17 Though processes and sensitivities differ among biomes, based on expert opinion we expect  
18 forests to exhibit the largest net effect of extremes due to their large carbon pools and fluxes,  
19 potentially large indirect and lagged impacts, and long recovery time to re-gain previous  
20 stocks. At the global scale, we presume that droughts have the strongest and most widespread  
21 effects on terrestrial carbon cycling. Comparing impacts of climate extremes identified *via*  
22 remote sensing *vs.* ground-based observational case studies reveals that many regions in the  
23 (sub-)tropics are understudied. Hence, regional investigations are needed to allow a global  
24 upscaling of the impacts of climate extremes on global carbon-climate feedbacks.

## 1 **Introduction**

2 There is widespread recognition that climate change is having, and will continue to have,  
3 fundamental impacts on the natural environment and on human wellbeing (Parry *et al.*, 2007).  
4 Current projections, based upon contrasted emission scenarios, suggest somewhere between  
5 0.3 and 4.8°C warming by the end of this century (IPCC, 2013). The associated modification  
6 of the climate system strongly influences the carbon cycling of the terrestrial biosphere and  
7 thus land-atmosphere CO<sub>2</sub> fluxes (Fischlin *et al.*, 2007). An important observation is that  
8 climate change, and increasing concentrations of atmospheric greenhouse gases, not only lead  
9 to gradual mean global warming but may also change the frequency, the severity and even the  
10 nature of extreme events (IPCC, 2013). A relatively small change in the mean or variance of a  
11 climate variable, inherently leads to disproportionately large changes in the frequency of  
12 extremes, i.e. the infrequent events at the high and low end of the range of values of a  
13 particular variable (Nicholls & Alexander, 2007). Furthermore, climate change can  
14 fundamentally alter the inherent variability of temperature, precipitation and other weather  
15 phenomena (Seneviratne *et al.*, 2012). State-of-the-art climate models project global  
16 intensification of heavy precipitation events and heat extremes, and regions with stronger or  
17 longer-lasting droughts (Fischer & Knutti, 2014, IPCC, 2013).

18 Concerns about increasing variability of temperature and precipitation patterns and climate  
19 extremes were first articulated over two decades ago by Katz & Brown (1992), and became  
20 widely acknowledged after the second IPCC assessment of climate change in 1995 (Nicholls  
21 & Alexander, 2007). These concerns were raised because many biological systems (including  
22 human societies) are more sensitive to climate extremes than to gradual climate change, due  
23 to typically greater response strengths and shorter response times (Hanson *et al.*, 2006).

1 Key characteristics of the climate such as heat waves, seem to have already been modified  
2 beyond the natural variability within which society and its economic, social and political  
3 systems have developed (Schär *et al.*, 2004; Soussana *et al.*, 2010). Both the public media and  
4 the scientific community have recognized the widespread consequences of climate extremes  
5 such as e.g. the European heat wave in 2003 (Ciais *et al.*, 2005; Reichstein *et al.*, 2007;  
6 Bastos *et al.*, 2013a), the heat wave and associated forest fires in Greece in 2007 (Founda &  
7 Giannakopoulos, 2009), the dry spells in the Amazon basin in 2005 (Phillips *et al.*, 2009) and  
8 2010 (Lewis *et al.*, 2011), in the U.S.A. 2000-2004 (Breshears *et al.*, 2005; Schwalm *et al.*,  
9 2012), the forest fires in Russia in 2010 (Barriopedo *et al.*, 2011; Konovalov *et al.*, 2011;  
10 Coumou & Rahmstorf, 2012; Bastos *et al.*, 2013a), the Pakistan Floods in 2010 (Hong *et al.*,  
11 2011; Houze *et al.*, 2011; Trenberth & Fasullo, 2012), the storm Lothar in Europe in 1999  
12 (Lindroth *et al.*, 2009), hurricane Katrina in the U.S. in 2005 (Chambers *et al.*, 2007), or the  
13 ice-storm in southern and central China in 2008 (Stone 2008, Sun *et al.*, 2012), and the 2010-  
14 2011 La Nina rains over Australia (Boening *et al.*, 2012; Poulter *et al.*, 2014). These  
15 documented recent events demonstrate the massive impacts climate extremes can have on  
16 harvests, economies and human health, as well as on the carbon balance of terrestrial  
17 ecosystems (IPCC, 2012; Reichstein *et al.*, 2013).

18 Alterations of the biosphere's carbon balance through changes in the strength of carbon  
19 uptake or losses in turn affect the climate system (Friedlingstein *et al.*, 2006; Frank *et al.*,  
20 2010). In addition, extreme drought will often reduce evapotranspiration and its cooling effect  
21 and thereby causes a positive local feedback on warming (e.g. Seneviratne *et al.*, 2010;  
22 Teuling *et al.*, 2010; Mueller & Seneviratne, 2012; Peng *et al.*, 2014). Regional assessments  
23 clearly indicate the relevance of climate extremes on the carbon cycle and potential climate  
24 feedbacks (e.g. for drought extreme in Europe, Ciais *et al.*, 2005; Reichstein *et al.*, 2007; and  
25 for western North America, Schwalm *et al.*, 2012). Yet a synthesis of the direct and indirect

1 impacts of climate extremes on the carbon cycle and the underlying mechanisms, is still  
2 lacking. In a recent broad perspective, Reichstein *et al.* (2013) highlighted the possibility that  
3 climate extremes and their impacts on the global carbon cycle may lead to an amplification of  
4 positive climate-carbon cycle feedbacks. However, the underlying mechanisms, and how they  
5 likely apply to current and future response patterns observed in different biomes and  
6 ecosystem types, have not yet been synthesized in detail, especially with respect to possible  
7 differences in response time (concurrent / lagged) and direction of impacts (direct / indirect).  
8 Such detailed information is needed, given the complexity of carbon-cycle responses to  
9 climate extremes, and their dependence on background climate and ecosystem conditions  
10 (Knapp *et al.*, 2008).

11 In this review we aim to, 1) develop a coherent conceptual framework based on logically  
12 deductive reasoning for integrating direct and indirect effects climate extremes could have on  
13 the carbon cycle and to identify the main mechanisms underlying these effects, 2) synthesize  
14 how different types of ecosystems are affected by climate extremes based on available well  
15 documented case studies, and 3) provide an overview of likely responses of the terrestrial  
16 carbon cycle in relation to likely future climate extremes, and the specific role of lagged  
17 impacts.

18 At the outset, we acknowledge that the lack of systematically collected data and the highly  
19 non-linear responses of ecosystems to extreme events makes a quantitative meta-analysis of  
20 effects of climate extremes on the carbon cycle across the range of observational and  
21 experimental studies virtually impossible (cf. also Vicca *et al.*, 2014). While there is ample  
22 information in the literature on specific effects of extreme climatic conditions (experimentally  
23 induced or naturally occurring) on specific ecosystems, the severity of these extreme  
24 conditions and their consequences has often not been systematically evaluated. This is not



1 only due to a lack of common metrics reported across the various studies (e.g. Vicca *et al.*,  
2 2012), but also complicated by the fact that climate extremes are by definition rare and their  
3 effects are highly context-dependent, typically threshold-based and highly non-linear (e.g.  
4 Knapp *et al.*, 2008, Smith *et al.*, 2011, Bahn *et al.*, 2014). Thus, in our review, we rely on a  
5 qualitative, logically deductive reasoning, supported by multiple case studies, combined with  
6 remote sensing based global analysis to derive hypotheses on potential effects of climate  
7 extremes on the terrestrial carbon cycle.

8

## 1 **Definitions**

### 2 **Climate extremes and impacts**

3 Terms, such as ‘climate extremes’, ‘weather extremes’ or ‘extreme weather events’, are used  
4 in various ways in the scientific literature. Thus, for clarity we provide and briefly justify the  
5 definitions we use in this review:

6 An ‘*extreme*’, as stated in Seneviratne *et al.* (2012) is “the occurrence of a value of a weather  
7 or climate variable above (or below) a threshold value near the upper (or lower) ends of the  
8 range of observed values of the variable” within a defined climate reference period (e.g. 1981-  
9 2010). Thus, ‘*climate extreme*’ is an aggregate term encompassing both ‘extreme weather’  
10 and ‘extreme climate’ events. The distinction of weather events and climate events is related  
11 to the time scale. An extreme climate event occurs on longer time-scales than an extreme  
12 weather event, and can be the accumulation of extreme weather events. This definition  
13 follows the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to  
14 Advance Climate Change Adaptation (Seneviratne *et al.*, 2012).

15 However, the above definitions reflecting climatological considerations do not consider  
16 potential consequences for the biosphere and the carbon cycle. Smith (2011) suggested that  
17 one has to specifically address events where both climate is anomalous and the biosphere  
18 experiences a pronounced impact outside the bounds of what is considered normal variability.  
19 Along these lines we use the term ‘*extreme impact*’ to describe, from a functional perspective,  
20 when a resilience threshold (‘extreme response threshold’, *sensu* Smith 2011) is passed,  
21 placing the ecosystem and associated carbon cycling into an unusual or rare state. Thresholds  
22 are typically exceeded when stressor dose (i.e., cumulative amount defined by stress intensity  
23 multiplied by stress duration) reaches a critical level (e.g., during flooding, drought and / or  
24 extended periods of exceptionally high or low temperatures), or when the intensity of an

1 extreme climatic event is critically high (e.g., during a storm). Thresholds can be passed at  
2 organ, plant or community level, and lead to emergent carbon cycle impacts at ecosystem  
3 level. We note that the definition of “extreme impact” may partly overlap with the concept of  
4 “disturbance” as it is commonly used in ecology (White & Jentsch 2001). Here, we consider  
5 every climate extreme which has an impact on the ecosystem carbon cycle a “disturbance”,  
6 but note that not every disturbance is caused by climate extremes. A typical example is fire,  
7 which can be part of a system intrinsic disturbance cycle. But in this study, we consider those  
8 fires which are of rare magnitude or even are unprecedented, and likely facilitated by extreme  
9 climate conditions. Given that impacts caused by “climate extremes” can be considered  
10 “disturbances”, we assume that respective general mechanisms and processes induced by  
11 “disturbances” also operate in this specific “extreme” context.

12 In order to specifically address extreme impacts with repercussions to the carbon cycle,  
13 denoted as “carbon cycle extreme”, and to entail anomalies in biosphere-atmosphere carbon  
14 fluxes or extreme changes in ecosystem carbon pools, it is useful to distinguish ‘*concurrent*’  
15 versus ‘*lagged*’ and ‘*direct*’ versus ‘*indirect*’ impacts (Fig. 1). These four categories of  
16 impacts indicate how they are related to the stressor. Concurrent impacts begin to occur  
17 during the climate extreme, while lagged impacts occur sometime thereafter. Direct impacts  
18 are only caused by the climate extreme (either concurrently or lagged) if, and only if, a  
19 threshold of the climatic stress dose (dashed line in Fig. 1A) is passed. Indirect impacts are  
20 facilitated by the climate extreme by increasing the susceptibility of the ecosystem, but  
21 directly initiated by another (not necessarily extreme *per se*) external trigger. Hence, here the  
22 likelihood (P) of an extreme system response is a function of both the susceptibility and the  
23 characteristics of the external trigger (cf. Fig 1B and D).

24 Examples for these four categories of impacts are:

- 1 1. Direct, concurrent impact: wind-throw caused by storm; ice breakage; reduced  
2 productivity or increased mortality during drought, thermal stress or flooding (cf.  
3 Figure 1A)
- 4 2. Indirect, concurrent impact: loss of biomass or soil organic matter due to fire caused by  
5 lightning or human ignition, facilitated by an ongoing extreme dry and/or warm event  
6 (cf. Figure 1B)
- 7 3. Direct, lagged impact: reduced productivity / growth in the year(s) following the year of  
8 an extreme drought, caused e.g. by carbohydrate depletion / reduced bud development  
9 / partial mortality during a drought in the previous year (cf. Figure 1C)
- 10 4. Indirect, lagged impact: increased pest- or pathogen-caused mortality following a climate  
11 extreme; loss of biomass or soil organic matter due to fire facilitated through  
12 deadwood accumulation after a wind-throw; loss of soil carbon due to erosion during  
13 heavy precipitation or permafrost thawing and carbon losses as indirectly facilitated  
14 by reduced vegetation cover and / or changes in soil hydrophobicity following  
15 overgrazing, drought or fire (cf. Figure 1D)

16 Any effect, which can be attributed to a previous climate extreme, is termed here a “legacy  
17 effect” and hence per definition time-lagged compared to the “climate extreme” (please note  
18 that we prefer this terminology compared to the sometimes synonymously used  
19 anthropomorphic term “memory effect” (Walter *et al.*, 2013)). Legacy effects can include  
20 both changes in ecosystem states or process rates after the termination of a climate extreme,  
21 as well as altered ecosystem responses to environmental conditions, including subsequent  
22 extremes, and are often related to changes in species composition and their functional  
23 attributes (e.g. Smith 2011, Sala *et al.*, 2012).

1 It should be noted that is essential to define the time-scale under scrutiny when quantifying  
2 the overall effect of a 'climate extreme' on the carbon cycle (Fig. 2). It is the time-scale  
3 determining the degree to which concurrent and lagged effects alter the carbon balance of an  
4 ecosystem. Negative concurrent effects, often related to the resistance of an ecosystem to an  
5 extreme event, may in the long run be balanced by enhanced regrowth during recovery (Fig.  
6 2), depending on the resilience of the system. Lagged effects may impair the ability of an  
7 ecosystem to recover from an extreme event and may thereby alter the ecosystem carbon  
8 balance over a given period (Fig. 2).

9

## 1 **Impacts of climate extremes on the terrestrial carbon cycle: Mechanisms** 2 **and processes**

3 Climate extremes can impact the structure, composition, and functioning of terrestrial  
4 ecosystems and can thereby severely affect the regional carbon cycle, with the potential of  
5 causing a shift from a carbon sink towards a carbon source. During the “European 2003 heat  
6 wave”, which was an extreme drought event, Western European ecosystems were estimated to  
7 have lost an amount of CO<sub>2</sub> comparable to that which had been absorbed from the atmosphere  
8 during the previous three to five years under normal weather conditions (Ciais *et al.*, 2005;  
9 Reichstein *et al.*, 2007; Vetter *et al.*, 2008). Likewise, during the 2000-2004 drought, the  
10 strength of the western North American carbon sink declined substantially, with reductions  
11 ranging between 30 and 298 Tg C yr<sup>-1</sup> (Schwalm *et al.*, 2012). In 2004, heavy precipitation  
12 associated with Typhoon Mindulle led to a particulate organic carbon flux of 0.5 Mt over a 96  
13 hour period, with subsequent rapid burial of the terrestrial carbon in the ocean (Goldsmith *et*  
14 *al.*, 2008). Also, extreme wind storms and cyclones can severely impact the regional carbon  
15 balance: In 1999 storm Lothar reduced the European C sink by 16 Mt C, which corresponds  
16 to 30% of Europe’s net biome production (Lindroth *et al.*, 2009) and, hurricane Katrina in  
17 2005 destroyed an amount equivalent to 50 - 140% of the net annual U.S. C sink in forest  
18 trees (Chambers *et al.*, 2007). Fires, pest and pathogen outbreaks are obviously not climate  
19 extremes, but can be facilitated by climate extremes. Extreme fire events release large  
20 quantities of carbon to the atmosphere. For example, in Indonesia, people had drained and  
21 deforested tropical wetlands which they then ignited to burn the debris awaiting the rain  
22 season to extinguish the fires, which failed due to the onset of the strong El-Niño Southern  
23 Oscillation in 1997/98, which instead burnt the duff layers and vegetation releasing between  
24 0.81 and 2.57 Gt C (Page *et al.*, 2002). This amount was equivalent to the estimated annual  
25 release (van der Werf *et al.*, 2010) and, together with the extreme fire events occurring in

1 Siberia, produced a signal detected by atmospheric CO<sub>2</sub> and CH<sub>4</sub> monitoring stations  
2 (Simpson *et al.*, 2006). Pest and pathogen outbreaks can have large impacts on forest carbon  
3 stocks and fluxes, and may impact the regional carbon cycle (Hicke *et al.*, 2012), as was the  
4 case in a mountain pine beetle outbreak in British Columbia of unprecedented extent and  
5 severity, which converted the forest from a small net carbon sink to a large net carbon source  
6 (during and immediately after the outbreak) with an estimated cumulative regional impact of  
7 270 Mt C for 2000–2020 (Kurz *et al.*, 2008b).

8 To be able to generalize and project presumable impacts of climate extremes on the carbon  
9 cycle, an understanding of the likely mechanisms and processes involved in extreme impacts  
10 is crucial. In this section, we review the primary environmental-biological processes  
11 according to their hypothesized relevance to different ecosystems, and the cascade of  
12 associated consequences. The complex pathways of how climate extremes may act on the  
13 major processes and components of the terrestrial CO<sub>2</sub> balance are illustrated in Figure 3. We  
14 then provide a schematic overview of possible concurrent, lagged, direct and indirect impacts  
15 of climate extremes on processes underlying ecosystem carbon dynamics highlighting the  
16 importance of lagged impacts (Fig. 4).

## 17 **Direct impacts**

18 **Temperature extremes** can directly and concurrently impact photosynthesis and respiration  
19 (cf. Fig.3a, b). Effects differ between species, ecosystem types and biomes, and may change  
20 seasonally and even diurnally through hardening responses (Larcher 2003). Concurrent direct  
21 impacts of extremely high temperatures range from disruptions in enzyme activity affecting  
22 photosynthesis and respiration, to changes in growth and development (Larcher, 2003;  
23 Schulze *et al.*, 2005; Lobell *et al.*, 2012; Niu *et al.*, 2014). Likewise, extremely low  
24 temperatures impact physiological functions and developmental processes. Frost damage is

1 perhaps the most important direct concurrent impact of cold climate extremes. In this context,  
2 timing is a crucial factor: in temperate ecosystems risk of plant damage is particularly high in  
3 spring when temperatures drop below freezing after an early warming event (Bokhorst *et al.*,  
4 2009; Migliavacca *et al.*, 2009), or during cold outbreaks when autumn hardening is  
5 insufficient, or when a protective snow cover is absent during extreme frost. In addition to  
6 frost damage of needles, xylem embolism in response to freeze-thaw cycles frequently adds to  
7 the factors decreasing plant vitality (Fig. 3a) (Sperry & Sullivan, 1992; Mayr *et al.*, 2003,  
8 2007).

9 Unusual warming events at the end of the winter season in temperate and boreal climates can  
10 induce plant activity too early, a phenomenon that has been called “false spring” (e.g. Marino  
11 *et al.*, 2011). Extreme warm late winters together with the general trend of average warming  
12 may lead to earlier onset of the seasonal plant development, unfulfilled chilling requirements,  
13 i.e. the exposure to cool temperatures that is required before dormancy can be broken. A  
14 general trend of earlier onset of greening has been observed at local scales, from phenological  
15 gardens across Europe and globally from remote sensing NDVI data (Myneni *et al.*, 1997;  
16 Menzel *et al.*, 2006; Pilegaard *et al.*, 2011). If plants switch from dormancy to physiological  
17 activity earlier, they may become more susceptible to frost events with strong negative  
18 consequences, such as tissue mortality (Polle *et al.*, 1996), increased tree crown transparency  
19 (Dittmar & Elling, 2007), and reduced tree growth (Dittmar *et al.*, 2006) and plant  
20 performance (Kreyling, 2010).

21 **Drought extremes** may have manifold impacts on the carbon cycle *via* direct concurrent  
22 impacts (e.g. on plant physiology and soil microbial activity), direct lagged impacts (e.g. on  
23 the phenology of plants, reduced growth in the following year due to lower carbohydrate  
24 storage in the year of the drought, altered composition of plant species, soil microbial



1 community structure and activity), as well as indirect lagged impacts, e.g. by drought-  
2 facilitated pest and pathogen outbreaks or fire ignition and spread (see Figures 3 and 4).  
3 Effects of drought on gross ecosystem productivity are typically larger than for ecosystem  
4 respiration (Schwalm *et al.*, 2010; cf. Fig. 3b).

5 Drought stress occurs if the water potential of an organism / tissue drops below a critical  
6 threshold. For example, in temperate and Mediterranean forest ecosystems, decreased  
7 transpiration, gross photosynthesis and respiration were observed when relative root  
8 extractable soil water dropped below 40% (Granier *et al.*, 2007). High temperatures and low  
9 relative humidity (often expressed at the vapour pressure deficit) serve to increase evaporative  
10 demand, and drought stress of plants occurs when soil water supply can no longer meet the  
11 plant evaporative demand (e.g., Sperry, 2000). Plant available water is influenced by soil type  
12 and local surface and subsurface characteristics, such as the depth to the groundwater level or  
13 bedrock. The amount of water actually available to a plant depends strongly on the  
14 distribution of soil water across the profile in relation to root depth and type (Schachtschabel  
15 *et al.*, 1992; Tolck, 2003; White, 2006; Vicca *et al.*, 2012).

16 Droughts and extreme high temperatures (heat waves), both to be considered climate  
17 extremes in their own right, cannot be seen as independent phenomena since in many  
18 (transitional climate) regions droughts additionally are connected with high temperature  
19 extremes (Mueller & Seneviratne, 2012) (Fig. 3b). The combination of high temperatures and  
20 droughts initiate a positive regional feedback mechanism (e.g. Durre *et al.*, 2000; Seneviratne  
21 *et al.*, 2006; Fischer *et al.*, 2007; Vautard *et al.*, 2007; Zampieri *et al.*, 2009; Diffenbaugh &  
22 Ashfaq, 2010; Hirschi *et al.*, 2011): the precipitation deficits and enhanced evaporative  
23 demand generally associated with warm spells (e.g. atmospheric blockings) triggers soil  
24 moisture deficit, thus suppressing evaporative cooling (Teuling *et al.*, 2010) and leading to

1 hotter and drier conditions if soil moisture becomes limiting for evapotranspiration  
2 (Seneviratne *et al.*, 2010). Warmer temperatures additionally increase vapour pressure deficit,  
3 even without a concurrent reduction in rainfall, and this process alone causes extra drought  
4 stress (Williams *et al.*, 2012). In addition, there are likely also non-local feedbacks between  
5 drought conditions and heat waves, for instance through the advection of dry air or the  
6 modification of regional-scale circulation patterns (e.g. Vautard *et al.*, 2007; Haarsma *et al.*,  
7 2009).

8 Plants may respond to drought stress by structural or physiological adjustments such as  
9 decreased leaf area index, changes in the root-shoot ratio, or changes in osmolyte  
10 concentration (Larcher, 2003; Breda *et al.*, 2006). The ability of plants to extract water from  
11 deeper layers under soil moisture stress, up to some limit, has been reported (e.g., Nepstad *et al.*,  
12 1994; Canadell *et al.*, 1996; Wan *et al.*, 2002; Teuling *et al.*, 2006). Drought decreases  
13 CO<sub>2</sub> assimilation rates (according to our definitions, a direct concurrent impact) by reducing  
14 stomatal and mesophyll conductance, the activity and concentrations of photosynthetic  
15 enzymes (Lawlor, 1995; Chaves *et al.*, 2009; Keenan *et al.*, 2010) and reducing sink strength  
16 (Palacio *et al.*, 2014). Generally, direct concurrent drought impacts are larger for plant  
17 photosynthesis than for respiration of plants (Atkin & Macherel, 2009) and ecosystems  
18 (Schwalm *et al.*, 2010; Shi *et al.*, 2014) (Fig. 3b).

19 In addition to direct concurrent drought impacts like decreased carbon (and nutrient)  
20 assimilation (Fig. 3b), drought may have lagged impacts on the carbon cycle *via* the re-  
21 allocation of existing stored reserves for repair, maintenance (including that of hydraulic  
22 integrity), growth and defence, as well as indirect lagged impacts (Fig. 4) by increasing the  
23 ecosystems' vulnerability to additional stressors such as pests and pathogens, or subsequent

1 drought events (Breda *et al.*, 2006; Desprez-Lousteau *et al.*, 2006; McDowell *et al.*, 2011;  
2 Sala *et al.*, 2012; Keith *et al.*, 2012).

3 Water stress has a direct, concurrent impact on microbial activity, which depends on the  
4 presence of water films for substrate diffusion and exo-enzyme activity (Davidson &  
5 Janssens, 2006), whereas indirect and lagged drought impacts on microbial activity may be  
6 initiated by various mechanisms such as a decreased input of labile carbon into the soil due to  
7 reduced plant productivity (Araus *et al.*, 2002; Reddy *et al.*, 2004), and altered soil nutrient  
8 retention and availability (Muhr *et al.*, 2010; Bloor & Bardgett, 2012). Drought may also alter  
9 microbial community structure (Sheik *et al.*, 2011) with consequences for carbon cycling  
10 (Fig.4; direct concurrent and (in-)direct lagged impact via changes in species composition)  
11 (Fuchslueger *et al.*, 2014). In Mediterranean ecosystems, for example, fungi were less  
12 affected by drought than bacteria and controlled soil organic matter decomposition (Curiel-  
13 Yuste *et al.*, 2011). While soil and ecosystem respiration are reduced by drought, rewetting by  
14 rainfall following drought can strongly stimulate soil CO<sub>2</sub> emissions to levels substantially  
15 exceeding pre-drought (or control) rates, with immediate consequences for the carbon cycle  
16 (Fig. 2, Jarvis *et al.*, 2007; see also reviews by Borken & Matzner 2009; Kim *et al.*, 2012,  
17 Vicca *et al.*, 2014). Different mechanisms act when drying-rewetting cycles become more  
18 pronounced. Among others, physical disruption of aggregates (Borken & Matzner, 2009),  
19 increased soil water repellency (Goebel *et al.*, 2011) and altered nutrient retention (Borken &  
20 Matzner, 2009; Bloor & Bardgett, 2012) can be responsible for legacy effects on microbial  
21 activity and respiration, by modifying substrate and nutrient availability (indirect and lagged  
22 impact).

23 The magnitude of the impact on key ecosystem processes from an altered quantity, frequency  
24 or intensity of precipitation critically depends on the ecosystems' (seasonally varying)

1 baseline water limitation (Gerten *et al.*, 2008). In addition to intensity and duration, the timing  
2 of droughts is a crucial factor due to the pronounced seasonal cycle of many ecosystems and  
3 land uses (Allard *et al.*, 2008; Unger *et al.*, 2009; Misson *et al.*, 2010, 2011; De Boeck *et al.*,  
4 2011).

5 **Extreme precipitation events** may alter soil CO<sub>2</sub> fluxes and CO<sub>2</sub> uptake by plants during  
6 water logging phases (direct concurrent impacts on the carbon cycle), may lead to flooding-  
7 related tree mortality (Kramer *et al.*, 2007) and may cause topsoil erosion (Fig. 3c; see also  
8 below and Figure 4) with losses of particulate and dissolved organic carbon from terrestrial to  
9 riverine ecosystems (Hilton *et al.*, 2008; Dinsmore *et al.*, 2013). In more water-limited  
10 systems, longer intervals between rainfall events may increase the duration and severity of  
11 soil drought stress. In contrast, longer intervals between heavy rainfall events may reduce  
12 periods of anoxia and be favourable to plant growth in more hydric ecosystems (see also  
13 Knapp *et al.*, 2008). The impacts of extreme precipitation events are often exacerbated by  
14 their association, in most climatic regions, with extreme wind storms/ cyclones.

15 **Ice-storms** are a form of extreme precipitation that occurs when liquid precipitation (often in  
16 a supercooled state) freezes shortly after contact with the terrestrial surface. The growing  
17 layer of ice can add substantial weight to vegetation and therefore result in the loss of  
18 branches, limbs, or uproot entire trees (Bragg *et al.*, 2003; McCarthy *et al.*, 2006; Sun *et al.*,  
19 2012).

20 **Extreme wind storms and tropical cyclones** are often associated with extreme precipitation  
21 events (see above), but have the additional potential to cause, depending upon their intensity  
22 severe damage and direct concurrent impacts on the carbon cycle (Fig. 3d) *via* defoliation,  
23 damage to branches, and wind throw or flooding by (e.g., saltwater) storm surges related tree  
24 mortality (Conner & Inabinette, 2003; MCPFE, 2007; Chambers *et al.*, 2007; Imbert and

1 Portecop, 2008; Zeng *et al.*, 2009; Negrón-Juárez *et al.*, 2010a) and lodging in  
2 agroecosystems (when crop stems are broken and crops are flattened). In addition, in forests,  
3 wind throw can cause long-term indirect lagged impacts on the carbon balance *via* tree  
4 mortality and dry dead wood accumulation that may facilitate lagged insect outbreaks or  
5 massive fires (Fig. 3d; see also below). Individual extreme storms and cyclones can severely  
6 impact the regional carbon balance (e.g. Lindroth *et al.*, (2009) for Europe or Chambers *et al.*  
7 (2007) for the U.S.). For example, in October 2005, Hurricane Wilma made landfall over the  
8 Yucatán peninsula with particularly intense winds. Immediate reductions in leaf area and  
9 productivity were observed, while in the year following the hurricane, increased carbon  
10 emissions from soils were observed that were attributable to the addition of nitrogen-rich  
11 organic matter (Vargas 2012). Depending on the spatial and temporal scale considered, the  
12 frequency and intensity of the storm/cyclone, the characteristics of the impact and the  
13 recovery processes involved, the overall carbon balance can vary between a source and a sink  
14 (Fig. 2; see e.g., Fisk *et al.*, 2012).

15 Soil erosion can be caused by the extreme precipitation events and extreme wind storms (or a  
16 combination of both) and is co-determined by topography, soil characteristics, vegetation  
17 cover and human activities (e.g. Lal *et al.*, 2013) with significant on- and off-site impacts.  
18 Extreme weather events can result in direct, rapid and substantial local soil carbon losses  
19 (Hilton *et al.*, 2008; Jung *et al.*, 2012), and subsequent transport/redistribution and deposition  
20 (Goldsmith *et al.*, 2008). Soils are especially susceptible to erosion if vegetation cover is low,  
21 e.g. crop ecosystems at fallow stages or grasslands after drought periods. Soil carbon loss due  
22 to erosion can therefore be a direct concurrent as well as an indirect lagged climate extreme  
23 impact (see Figure 4). In addition, soil erosion leads to losses of soil nutrient and water  
24 retention capacity, and to a generally lower productivity on eroded soils (Lal & Pimentel,  
25 2008), inducing further (indirect) lagged impacts on the ecosystems carbon cycle. Eroded soil

1 and mobilized soil organic matter is often redeposited within the same ecosystem at short-  
2 time scales, but soil organic carbon can also be laterally exported from a particular ecosystem  
3 (VandenBygaart *et al.*, 2012; Behre & Kleber, 2013). The deposition and subsequent  
4 residence time of carbon removed with eroded soil determines the contribution of soil organic  
5 carbon erosion to CO<sub>2</sub> fluxes (van Oost *et al.*, 2007; Lal & Pimentel, 2008). Soil erosion  
6 processes can also increase the terrestrial carbon sink if eroded carbon is not transformed to  
7 CO<sub>2</sub>, but trapped in deposits with longer residence times than the original soil (van Oost *et al.*,  
8 2007; Hilton *et al.*, 2008). Hence erosion and subsequent sedimentation affects the overall  
9 land carbon budget, but the net effect of erosion on the carbon cycle remains controversial  
10 (Lal, 2009) and improved, scientifically-rigorous terminology may be needed to describe  
11 landscape soil carbon turnover (Behre & Kleber, 2013).

## 12 **Indirect Impacts**

13 While extreme droughts, heat waves, frosts, precipitation and wind storms are climate  
14 extremes, soil erosion can be a direct concurrent impact of extreme precipitation and/ or wind  
15 storms and, additionally, may be amplified by indirect lagged climate extreme impacts (cf.  
16 Fig.4); fires and pest and pathogen outbreaks are impacts facilitated by climate extremes (cf.  
17 Fig.4), but initiated by another trigger (not necessarily an extreme event *per se*) (cf. Fig. 1B,  
18 1D).

19 **Fire** related losses of biomass or soil organic matter generally occur as an indirect, and often  
20 lagged, impact of climate extremes (cf. Fig. 3b, 3d; Fig.4) and are caused by the interaction  
21 between biotic (e.g., fuel load) and abiotic factors (e.g. dry weather, wind velocity, fuel  
22 continuity, slope of terrain and landscape fragmentation,) and human ignition (Moriondo *et*  
23 *al.*, 2006; Bowman *et al.*, 2009; Aldersley *et al.*, 2001; Pausas & Paula 2012). Fire frequency  
24 and intensity is highly sensitive to climate extremes because fire behaviour responds

1 immediately to fuel moisture, which is affected by the combination of precipitation, relative  
2 humidity, air temperature and wind speed (Moriondo *et al.*, 2006). Fires release carbon stored  
3 in biomass and organic soils to the atmosphere in form of CO<sub>2</sub>, CO, CH<sub>4</sub> and other climate  
4 relevant trace gases and aerosols, but can also serve to prevent land-atmosphere CO<sub>2</sub> fluxes  
5 when burned organic matter (i.e., charcoal) is formed during the combustion process.  
6 Charcoal is typically more resistant to decomposition and is thought to contribute to long term  
7 carbon sequestration in soils (Preston & Schmidt, 2006; Schmidt *et al.*, 2011), although recent  
8 advances point to a much faster decomposition rate which depends on thermal conditions  
9 during formation and soil conditions afterwards, than previously thought (Major *et al.*, 2010;  
10 Singh *et al.*, 2012; Kasin *et al.*, 2013).

11 Extreme fire events release large quantities of carbon to the atmosphere (Page *et al.*, 2002)  
12 and may have long-lasting consequences on vegetation composition (Bond *et al.*, 2005), soil  
13 structure, hydrophobicity and nutrient availability (Certini, 2005) with presumable multiple  
14 indirect and lagged impacts on the terrestrial carbon cycle (cf. Figs. 3b, 4). Carbon stored in  
15 litter, and organic soils such as peat, is burned during high-intensity but slow-spreading fires,  
16 and can be irreversibly destroyed, particularly during peat fires where carbon accumulated  
17 over very long time-scales is immediately released, but can be additionally accelerated by  
18 another trigger (Page *et al.*, 2002; Turetsky *et al.*, 2011a). Note, however, that not all climate-  
19 induced fires are carbon cycle extremes, but are within the range of the particular disturbance  
20 regime. For instance, frequent and low intensity savannah fires (Archibald *et al.*, 2012) may  
21 release over a year as much CO<sub>2</sub> as would have been decomposed otherwise by microbes (Li  
22 *et al.*, 2013).

23 The occurrence, frequency and magnitude of **insect and pathogen outbreaks** are often  
24 related to natural cycles in population size, driven by predictor-prey type dynamics (Jepsen *et*

1 *al.*, 2009; Kausrud *et al.*, 2012). But there is consensus - despite many uncertainties – that  
2 climate conditions influence strength and timing of insect/pathogen outbreaks *via* changes in  
3 dispersal, reproduction, development of host plants, and mortality and distributional range  
4 changes of insect herbivores (Netherer & Schopf 2010; Cornelissen 2011). Different types of  
5 climate extremes may therefore catalyse insect and pathogen outbreaks leading as we  
6 hypothesize towards indirect lagged impacts on the carbon cycle (see Figures 3 and 4). Warm  
7 temperatures appear to favour radical increases in insect populations as a result of reduced  
8 mortality during the cold season, accelerated insect development rates, and earlier flight  
9 periods (Virtanen *et al.*, 1998; Stahl *et al.*, 2006; Robinet and Roques 2010; Johnson *et al.*,  
10 2010). We regard these patterns as an indirect lagged impact of fewer cold temperature  
11 extremes (cf. Figs. 3a, 4). Mechanisms, associated with indirect lagged impacts of extreme  
12 heat and drought (cf. Figures 3b, 4), were observed during the European 2003 heat wave. Soil  
13 water deficits appeared to lower tree resistance to pest attacks, i.e. a positive drought - disease  
14 association, and defoliators additionally benefitted from increased nitrogen in plant tissues  
15 linked to moderate or intermittent drought stress (Desprez-Lousteau *et al.*, 2006; Rouault *et*  
16 *al.*, 2006). Multiple examples of how primary productivity and carbon stocks are reduced by  
17 insects and pathogens, and changes in carbon sink strength, are given in Hicke *et al.* (2012).

## 18 **Impacts of extreme events on different ecosystem types**

19 Ecosystems react differently to climate extremes: therefore we deduce that a climate extreme  
20 of a given magnitude will not have the same impact in a forest, grassland, peatland or  
21 cropland. With both large aboveground carbon stocks (standing biomass) and carbon uptake  
22 being affected by climate extremes, we expect the largest net effects on the terrestrial carbon  
23 balance in forests compared to other ecosystems. Forest carbon stocks may be lost or reduced  
24 as CO<sub>2</sub> rapidly by fire (as an indirect concurrent or lagged effect due to drought and heat



1 extremes; Fig.4), or more slowly during the decomposition of dead wood after extreme wind  
2 and ice-storms or forest dieback after an extreme drought, which lead to lagged carbon  
3 emissions for a presumable long period after the climate extreme has occurred.

4 There are notable differences in how individual tree species respond to intra-annual climatic  
5 extremes including the timing of maximum sensitivity (Babst *et al.*, 2012), and the  
6 complexity of forest ecosystem dynamics makes prediction of the impacts of extreme events  
7 on carbon cycling challenging (Rammig *et al.*, 2014). At the same time, we hypothesize the  
8 complexity of forest ecosystems contributes to their resilience to climate extreme related  
9 impacts as e.g., heterogeneous forests are known to be less susceptible to wind-throw  
10 (Lindroth *et al.*, 2009), insect outbreaks (Drever *et al.*, 2006), and mass movements (Bebi *et*  
11 *al.*, 2009) (see S1, section A. for biome-specific extremes and related impacts). Forests  
12 generally have better access to deeper ground water than grasslands, and are reported to be  
13 likely less strongly affected by drought and heat waves (Teuling *et al.*, 2010). However, once  
14 their mortality thresholds are passed, we suppose forests to be less resilient to extreme events  
15 than grasslands, which have evolved to recover rapidly from disturbances. Natural grasslands  
16 prevail in regions where climatic constraints limit the occurrence of woody life forms (Suttie  
17 *et al.*, 2005). Grasslands are typically characterized by comparatively higher turnover rates  
18 compared to woody vegetation and we therefore assume grasslands to be more resilient to  
19 climate extremes than forests (see S1, section B. for more details). In this context, amongst  
20 the climate extremes, drought is expected to have the largest effect on the carbon cycle of  
21 grasslands (Zavalloni *et al.*, 2008; Gilgen and Buchmann, 2009; van der Molen *et al.*, 2011),  
22 while other extremes (e.g. wind storms) play a smaller if not negligible role (Reichstein *et al.*,  
23 2013). However, degradation feedbacks, as triggered by e.g. grazing pressure (Albertson *et*  
24 *al.*, 1957), erosion (Breshears *et al.*, 2003) or fire combined with extreme precipitation events,  
25 may amplify effects of extreme drought and lead to substantial soil carbon losses. In

1 comparison to forests, when normalizing for the per cent of bare soil, potential post-fire  
2 erosion tends to be lower in grassland (Johansen *et al.*, 2001).

3 Peatlands have characteristics in common with both forests and grasslands, namely large  
4 organic carbon stocks and a clear dominance of belowground carbon stocks, respectively. The  
5 large carbon stocks stored in peatlands are mainly protected by decomposition-limiting low  
6 temperatures and/or high water levels (Freeman *et al.*, 2001). Peatland carbon stocks are  
7 highly susceptible to immediate oxidation by fire (van der Werf *et al.*, 2008, 2010; Turetsky  
8 *et al.*, 2011a, b) and drought- or drainage- induced processes of microbial decomposition of  
9 organic carbon (Jungkunst & Fiedler, 2007; Couwenberg *et al.*, 2010; Froelking *et al.*, 2011).  
10 Therefore we hypothesize peatlands to be highly susceptibility to drought extremes and fire  
11 events caused by climate extremes (see S1, section C for more details).

12 Croplands are distinct from forests, grasslands, and peatlands, in that most crops are planted  
13 and harvested on an annual basis. The response of croplands is strongly coupled to the timing  
14 of the climate extreme, i.e. the sensitivity of the growth stage of the impacted crop (e.g. van  
15 der Velde *et al.*, 2012) and the management actions taken (e.g., Porter & Semenov, 2005;  
16 Ramankutty *et al.*, 2008; van der Velde *et al.*, 2010; Lobell *et al.*, 2012). In croplands, many  
17 climate extreme impacts can (theoretically) be mitigated through management, either within  
18 the same year (e.g. irrigation, replanting of a failed crop), or through longer term adaptation  
19 (e.g. changed rotations, drought and/or heat resistant cultivars). Lagged impacts of more than  
20 one year are of minor importance in croplands compared with the other ecosystem types.

21 A quantitative and systematic assessment of the impacts from different types of extreme  
22 events is currently limited by the number of observed case studies, a general lack of  
23 systematic data, and a lack of common metrics across experimental and impact studies (see  
24 introduction). It is therefore currently only possible to provide a detailed literature survey

- 1 about how drought, wind storms, temperature and precipitation extremes, may possibly act on
- 2 carbon cycle processes in forests, grasslands, peatlands and croplands (see S1).
- 3

## 1 **Future climate extremes and their impact on the carbon cycle**

2 There are inherently few data available to make robust assessments regarding changes in the  
3 frequency or intensity of carbon cycle extremes. First of all, climate extremes are hard to  
4 predict, as many predictions of climate extremes are either not sufficiently well resolved (e.g.  
5 heavy precipitation) or associated with high uncertainties (e.g. drought) in current climate  
6 models (Seneviratne *et al.*, 2012). Even in leading sectorial (e.g. agriculture) models, the  
7 effects of high temperatures, increased climate variability and several other growth-limiting  
8 factors such as soil nutrients, pests and weeds are not yet fully understood, and thus not  
9 implemented (Soussana *et al.*, 2010). Hence, it is very difficult to anticipate future impacts of  
10 climate extremes on the global carbon cycle. Thus, we here only hypothesize the most  
11 important current and future risks of the terrestrial carbon cycle in the face of climate  
12 extremes given the available literature.

13 In those parts of the boreal zone where litter and soil moisture will likely decrease e.g. *via*  
14 rising temperatures and decreasing precipitation (Seneviratne *et al.*, 2012) and earlier  
15 snowmelt (Grippa *et al.*, 2005), we hypothesize an increased risk that extreme dryness and  
16 tree mortality will increase the susceptibility to triggers such as lightning and human ignition,  
17 causing fires as an indirect concurrent or lagged effect (c.f. Fig. 1D, Figure 4; Michaelian *et*  
18 *al.*, 2011).

19 On the other hand, according to current climate projections, large areas in the boreal zone will  
20 likely become wetter (IPCC, 2013). More extreme snow fall has the potential to lead to  
21 stronger insulation of the soil in the winter. The higher soil temperatures may favour the  
22 thawing of permafrost (Zhang *et al.*, 2001; Gouttevin *et al.*, 2012), but also increase  
23 mineralization and growing season productivity (Monson *et al.*, 2006). Assessment of the  
24 magnitude and timing of these two opposing effects will require further research. As host-

1 pathogen interactions are strongly influenced by weather and climate, we further hypothesize  
2 that decreased frost occurrence and fewer cold extremes will facilitate pest and pathogen  
3 outbreaks (e.g., Virtanen *et al.*, 1998, Hicke *et al.*, 2011; Samaraju *et al.*, 2012; Price *et al.*,  
4 2013) with supposed important indirect and lagged impacts on the carbon cycle.

5 Temperate regions, being situated between cold boreal and warm, summer-dry Mediterranean  
6 regions are susceptible to temperature and precipitation extremes, droughts and storms, and  
7 impacts facilitated by them. Storms are considered to be the most important natural  
8 disturbance agent in temperate European forests, and even a small increase in storm frequency  
9 could potentially lead to a long-term reduction of the carbon stock (Fuhrer *et al.*, 2006;  
10 Lindroth *et al.*, 2009). Yet, current predictions of changes in storm intensity and frequency are  
11 not very robust (IPCC, 2013), such that no speculation on future impacts of storms on  
12 ecosystem is possible.

13 In contrast, we conjecture that in dry temperate regions there will be a sizeable negative effect  
14 on the carbon cycle through drought extremes, because towards the drier border of temperate  
15 regions there is consensus among climate models that, for example, the number of  
16 consecutive dry days will increase (Seneviratne *et al.*, 2012). Droughts, often occurring in  
17 concert with heat waves, can extend spatially across sub-continental domains and have a  
18 pronounced effect on forests, grasslands and croplands (Reichstein *et al.*, 2007; Schwalm *et*  
19 *al.*, 2010). Yet, the potentially mitigating effect of increased plant water use efficiency  
20 through increased CO<sub>2</sub> concentrations needs to be scrutinized in future research (e.g. Morgan  
21 *et al.*, 2011, Zscheischler *et al.*, 2014c).

22 Mediterranean and sub-tropical ecosystems are already shaped by strong seasonality of water  
23 availability. Changes in precipitation patterns with longer dry spells and more intense  
24 precipitation events are very likely (Seneviratne *et al.*, 2012). We suggest that in forests these

1 changing patterns will contribute to higher tree mortality rates, increased fire activity in  
2 forests, and thus more sparse vegetation, and therefore as an indirect lagged effect (cf. Fig. 1D,  
3 Fig. 4) enhanced soil erosion, with expected negative consequences for ecosystem  
4 productivity (e.g. Allen *et al.*, 2010; Williams *et al.*, 2012). We further hypothesize that such  
5 positive feedback loops within the ecosystem triggered and enforced by alternating dry spells  
6 and subsequent heavy precipitation are even more likely and rapidly to occur in grasslands  
7 and cropland (e.g. with lower thresholds) because the non-woody vegetation with shorter  
8 turnover is likely to respond faster.

9 In the tropics, susceptibility of the carbon cycle to climate extremes will strongly depend on  
10 the interaction with human drivers. For example, fire risk is low in undisturbed Amazonian  
11 rainforests, and almost all fires are a consequence of land-use related burning activities  
12 (Aragão & Shimabukuro, 2010). Once burnt, forests are more susceptible to repeated burning,  
13 creating a positive feedback, which has the potential to transform large parts of rainforests  
14 into degraded forests or even savannah (Barlow *et al.*, 2008; Brando *et al.*, 2012; Brando *et*  
15 *al.*, 2014; Morton *et al.*, 2013). Changes in precipitation patterns with longer dry spells might  
16 additionally increase fire risk with decreasing canopy closure. While tropical forests and  
17 cropping systems are susceptible to long-term droughts, heavy precipitation and wind storms,  
18 future projections of these climatic extremes are particularly uncertain. The effect of high  
19 temperatures on photosynthesis is the second crucial mechanism that can directly impact  
20 tropical forests, where the most intensive CO<sub>2</sub>-emission scenarios yield temperatures  
21 sufficient to damage photosynthesis and growth (Doughty & Goulden, 2008). But the long-  
22 term acclimation, and adaptation potential of tropical forest ecosystems (e.g. shift to heat-  
23 tolerant species) is not well known (Corlett, 2011; Smith & Dukes, 2013). We expect also the  
24 susceptibility of tropical peatlands to climate extremes to be strongly dependent on the  
25 interaction with human drivers, as peatland carbon stocks are highly susceptible to fires and

1 drought- or drainage- induced microbial decomposition processes of their organic carbon  
2 stocks (see section above). Thus, we hypothesize that climate extremes will affect the tropical  
3 rainforest and peatland carbon cycle substantially, but the magnitude will strongly depend on  
4 the local human influence on these carbon stocks.

5

## 1 **Outlook: On improving detection and prediction of global carbon cycle**

### 2 **extremes**

3 From a mechanistic and process perspective it is clear that climate extremes can have a  
4 profound impact on the carbon cycle, and case studies have reported such impacts (Figure 5).

5 However, great challenges remain for both a rigorous global quantification of carbon cycle  
6 extremes and estimation of the future impacts on terrestrial-atmosphere CO<sub>2</sub> fluxes, and hence  
7 carbon-cycle climate feedbacks.

8 Remote sensing of the biosphere from space with a short return interval to identical locations  
9 and nearly global coverage offers promising perspectives to detect extreme anomalies in the  
10 biosphere in a consistent way (but see below). Land-surface states can be estimated by  
11 analysing the interaction of electromagnetic radiation (from visible to microwave) with the  
12 vegetation or upper centimetres of the soil *via* relatively well-evaluated radiation transfer  
13 models and their inversion. Thus, vegetation states (e.g. leaf area index, biomass) and  
14 radiative properties (e.g. fractions of absorbed radiation) can be monitored, albeit they require  
15 improvements to correct retrieved signals affected by noise and biases related to atmospheric  
16 conditions. Direct methods exist for use on the ground (Pan *et al.*, 2011; Baldocchi *et al.*,  
17 2012; Babst *et al.*, 2014) and can be combined with remote sensing and modelling approaches  
18 to infer carbon cycling at the global scale (Jung *et al.*, 2011).

19 Zscheischler *et al.* (2013) have taken a first approach to detect extreme changes in fAPAR  
20 (fraction of absorbed photosynthetically active radiation) and GPP (Zscheischler *et al.* 2014a)  
21 associated with climate anomalies that occurred during the last three decades and their  
22 association with climate anomalies. They presented four major findings: 1) The total effect of  
23 negative carbon cycle GPP extremes is of a similar magnitude as the mean terrestrial carbon  
24 sink, 2) The spatial distribution of extremes is highly uneven with 'hotspot' regions in many



1 semiarid monsoon-affected regions, 3) The distribution of extreme carbon impacts follows a  
2 power law, and 4) The detected carbon cycle extremes are statistically mostly strongly  
3 associated with droughts. The background map in Figure 5 shows the spatial distribution of  
4 carbon cycle extremes detected in the Zscheischler *et al.* studies. Many regions, where case  
5 studies have reported carbon cycle extremes, are also detected by the global remote sensing-  
6 based approach, but not all. In particular, Amazonian extreme anomalies in the carbon cycle  
7 suggested by Phillips *et al.* (2009) or Negrón-Juárez *et al.* (2010b) are not evident in the  
8 remote sensing-supported analysis of Zscheischler *et al.* (2013), and are only seen in one  
9 model in the analysis of negative extremes in four different data-driven and modelled GPP  
10 estimates (Zscheischler *et al.* 2014a). One reason for this might be the lack of sensitivity of  
11 fAPAR in dense evergreen vegetation (data-driven estimates of GPP often rely strongly on  
12 fAPAR). Evergreen vegetation often changes its physiology without strong alterations in the  
13 leaf or canopy reflective properties. This effect has also been observed outside tropical  
14 regions, for instance, during the extreme heat and drought in Europe 2003 (Reichstein *et al.*,  
15 2007). Currently, more direct observations of photosynthetic processes *via* fluorescence offer  
16 the potential to overcome this problem (Frankenberg *et al.*, 2011; Guanter *et al.*, 2014), as  
17 well as combined observations of greenness indices and land surface temperature (Mildrexler  
18 *et al.*, 2009). However, one striking feature of Figure 5 is the lack of presumably reported  
19 extreme impacts on the carbon cycle in some hotspot areas seen by the satellite data analysis.  
20 These include North East Brazil, the Indian subcontinent, East Asia, and particularly sub-  
21 Saharan Africa. To our understanding, without observations and experiments in those tropical  
22 hotspot areas, it will be hard to fully understand carbon climate cycle feedbacks and the role  
23 of carbon cycle extremes therein at a global scale.

24 According to our understanding, not all climate extremes cause extreme impacts in  
25 ecosystems, but they can have in-/direct and/or immediate/lagged effects. Lagged effects can

1 either slow down the carbon cycle, when reduced vegetation productivity and/or wide-spread  
2 mortality after an extreme drought are not compensated by regeneration, but they can also  
3 accelerate the carbon cycle, when, e.g., productive tree and shrub seedlings cause rapid  
4 regrowth after windthrow or fire. Likewise, not all terrestrial carbon cycle extremes are  
5 propagated immediately into the atmosphere. For example, an extreme mortality event  
6 increases coarse woody debris, which is then slowly decomposed during the following years.  
7 Terrestrial carbon cycle extremes leading to structural changes without immediate fluxes to  
8 the atmosphere are currently globally undetectable due to lack of observation capabilities.  
9 LiDAR or Radar satellite missions with sufficient spatial and temporal resolution should be  
10 encouraged to increase such capabilities in the future. Detection systems need to resolve  
11 processes that cause immediate or lagged effects at different spatial and temporal scales, as  
12 the resilience of the respective ecosystem differ by ecosystem type.

13 This review also showed the lack of quantitative and consistent experimental data on the  
14 impact of climate extremes on the terrestrial carbon cycle, such that our conclusions are  
15 largely based on expert knowledge, scattered case studies and logical reasoning. Future  
16 experimental and observational designs should have a clear definition of the extreme  
17 conditions at the onset (e.g. by return interval), a consistent classification of resulting  
18 (extreme) impacts and should consider testing hypotheses around the conceptual framework  
19 presented in Fig. 1. In particular, indirect effects (Fig. 1B, D) need to receive increased  
20 attention in our opinion, given the complexity of the mechanisms involved and the paucity of  
21 current studies.

22 Future experiments should not only strive towards increasing comparability of treatments  
23 across case-studies, as suggested above; they should also account for increasing severity of  
24 future climate extremes and test more explicitly for threshold effects and mortality and

1 recovery responses after extreme events, including those related to changing shifts of  
2 ecosystem states (Smith *et al.*, 2011, Beier *et al.*, 2012, Bahn *et al.*, 2014). Gradient studies  
3 that contain at least one very extreme (and possibly unrealistic) treatment would be  
4 particularly useful for this (Kreyling *et al.*, 2014). Future experiments should address lagged  
5 and legacy effects more consistently, as well as ecosystem responses to multiple subsequent  
6 climate extremes, with the aim of elaborating mechanisms, as e.g. related to stress physiology,  
7 mortality and community assembly, as well as plant-soil interactions and soil processes at  
8 large (Backhaus *et al.*, 2014; Kopittke *et al.* 2014; Vicca *et al.*, 2014). Only through holistic  
9 approaches will we be able to fully understand the impacts of climate extremes on ecosystem  
10 carbon cycling; information needed to obtain realistic predictions of future carbon cycling and  
11 climate feedbacks. For more details and best-practice guidance in climate change experiments  
12 that aim to improve our understanding of the impacts of climate extremes, we refer to Beier *et*  
13 *al.*, 2012; Vicca *et al.*, 2012, 2014; Kreyling *et al.*, 2014.

14 For ecosystems dominated by long-lived species such as forests, a better integration of  
15 experimental and modelling studies is needed, with experiments targeting critical hypotheses  
16 underlying model assumptions or specific mechanisms (e.g. processes linked to ecosystem  
17 transitions). State-of-the-art coupled climate-carbon cycle models (CMIP5) indicate a stronger  
18 negative effect of carbon cycle extremes than the above-mentioned observation driven  
19 estimates (Reichstein *et al.*, 2013), and an increasing absolute effect in the future. However, a  
20 reliable projection of the future impact of climate extremes on the terrestrial carbon cycle  
21 must rely on improved earth-system modelling, as well as improved description of the  
22 biospheric responses. Higher spatial (both horizontal and vertical) resolution and better  
23 representation of convective processes and clouds are pre-requisites for the simulation of  
24 climate extremes, and particularly hydro-meteorological extremes. On the biosphere  
25 modelling side, all processes leading to direct/indirect, as well as concurrent/lagged impacts

1 (Figure 4), need to receive attention. In particular, vegetation mortality in response to climate  
2 extremes (e.g. drought) and its mechanisms are increasingly well documented. Effort needs to  
3 be taken now to include this knowledge into global biosphere models. Including pest and  
4 pathogens, their reaction to climate extremes such as cold extremes and their effect on the  
5 carbon-cycle within an integrated modelling system at global scale is likely still too ambitious  
6 and needs landscape-modelling approaches, where lateral interactions are considered.  
7 Promising local- to regional-scale approaches do exist here and need to be further developed  
8 (Seidl *et al.*, 2011). Representation of these impacts into carbon cycle models will likely  
9 increase projected effects of climate extremes on the carbon cycle. On the other hand, we  
10 have to note that fundamental adaptive processes, such as acclimation, plasticity, migration,  
11 selection and evolution have the potential to mitigate effects of climate extremes. Modelling  
12 approaches accounting for these adaptations urgently need to be underpinned with more  
13 observational data and further developed (Scheiter *et al.*, 2013).

14 This study underlines the demand for better structured impacts studies of climate extremes on  
15 terrestrial ecosystems and the carbon cycle which follow a standardized protocol and  
16 definitions and allow for intercomparison studies. It has also shown the varying depth of  
17 analysis for different types of climate extremes, as well as identifying critically understudied  
18 regions. The findings underline the importance of biospheric processes in modulating impacts  
19 of climate extremes to assess the feedback to the global carbon cycle. In other words,  
20 biospheric processes are likely to determine the reaction of the global carbon cycle to climate  
21 extremes under global change.

22

## 1 **Acknowledgements**

2 This work emerged from the CARBO-Extreme project, funded by the European Community's  
3 7<sup>th</sup> framework programme under grant agreement (FP7-ENV-2008-1-226701). We are  
4 grateful to the Reviewers and the Subject Editor for helpful guidance. We thank to Silvana  
5 Schott for graphic support. Mirco Miglivacca provided helpful comments on the manuscript.  
6 Michael Bahn acknowledges support from the Austrian Science Fund (FWF; P22214-B17).  
7 Sara Vicca is a postdoctoral research associate of the Fund for Scientific Research – Flanders.  
8 Wolfgang Cramer contributes to the Labex OT-Med (n° ANR-11-LABX-0061) funded by the  
9 French government through the A\*MIDEX project (n° ANR-11-IDEX-0001-02). Flurin Babst  
10 acknowledges support from the Swiss National Science Foundation (P300P2\_154543).

11

## 1 **References**

- 2 Adams HD, Guardiola-Claramonte M, Barron-Gafford GA *et al.* (2009) Temperature  
3 sensitivity of drought-induced tree mortality portends increased regional die-off under global-  
4 change-type drought. *Proceedings of the National Academy of Sciences of the United States of*  
5 *America*, **106**, 7063-7066.
- 6 Albertson FW, Tomanek GW, Andrew Riegel A (1957) Ecology of Drought Cycles and  
7 Grazing Intensity on Grasslands of Central Great Plains. *Ecological Monographs*, **27**, 27-44.
- 8 Allard V, Ourcival J-M, Rambal S, Joffre R, Rocheteau A (2008) Seasonal and annual  
9 variation of carbon exchange in an evergreen Mediterranean forest in southern France. *Global*  
10 *Change Biology*, **14**, 714-725.
- 11 Aldersley A, Murray SJ, Cornell SE (2011) Global and regional analysis of climate and  
12 human drivers of wildfire. *Science of the Total Environment*, **409**, 3472–3481.
- 13 Allen CD, Macalady AK, Chenchouni H *et al.* (2010) A global overview of drought and heat-  
14 induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and*  
15 *Management*, **259**, 660-684.
- 16 Aragão LEOC, Shimabukuro YE (2010) The incidence of fire in Amazonian forests with  
17 implications for REDD. *Science*, **328**, 1275-1278.
- 18 Araus JL, Slafer GA, Reynolds MP, Royo C (2002) Plant breeding and drought in C<sub>3</sub> cereals:  
19 What should we breed for? *Annals of Botany*, **89**, 925-940.
- 20 Archibald S, Lehman CER, Gomez-Dans JL, Bradstock RA (2012) Defining pyromes and  
21 global syndromes of fire regimes. *Proceedings of the National Academy of Sciences of the*  
22 *United States of America*, **110** (16), 6442–6447.
- 23 Atkin OK, Macherel D (2009) The crucial role of plant mitochondria in orchestrating drought  
24 tolerance. *Annals of Botany*, **103**, 581-597.
- 25 Babst F, Carrer M, Poulter B, Urbinati C, Neuwirth B, Frank D (2012) 500 years of regional

- 1 forest growth variability and links to climatic extreme events in Europe. *Environmental*  
2 *Research Letters*, **7**, 045705 (045711 pp.).
- 3 Babst F, Bouriaud O, Papale D *et al.* (2014) Aboveground woody carbon sequestration  
4 measured from tree rings is coherent with net ecosystem productivity at five eddy covariance  
5 sites. *New Phytologist*, **201** (4), 1289-1303.
- 6 Backhaus S, Kreyling J, Grant K, Beierkuhnlein C, Walter J, Jentsch A (2014) Recurrent mild  
7 drought events increase resistance toward extreme drought stress. *Ecosystems* (in press),  
8 doi:10.1007/s10021-014-9781-5
- 9 Bahn M, Reichstein M, Dukes JS, Smith MD, McDowell NG (2014) Climate-biosphere  
10 interactions in a more extreme world. *New Phytologist*, **202**, 356-359.
- 11 Baldocchi D, Reichstein M, Papale D, Koteen L, Vargas R, Agarwal D, Cook R (2012) The  
12 role of trace gas flux networks in the biogeosciences. *Eos, Transactions, AGU*, **93**, 217-224.
- 13 Barber VA, Juday GP, Finney BP (2000) Reduced growth of Alaskan white spruce in the  
14 twentieth century from temperature-induced drought stress. *Nature*, **405**, 668-673.
- 15 Barriopedro D, Fischer EM, Luterbacher J, Trigo RM, García-Herrera R (2011) The hot  
16 summer of 2010: redrawing the temperature record map of Europe. *Science*, **332**, 220-224.
- 17 Barlow J, Peres CA (2008) Fire-mediated dieback and compositional cascade in an  
18 Amazonian forest. *Philosophical Transactions of the Royal Society B-Biological Sciences*,  
19 **363**, 1787-1794.
- 20 Bastos A, Gouveia CM, Trigo RM, Running SW (2013a) Comparing the impacts of 2003 and  
21 2010 heatwaves in NPP over Europe. *Biogeosciences Discussions*, **10**, 15879-15911.
- 22 Bastos A, Running SW, Gouveia C *et al.* (2013b) The global NPP dependence on ENSO: La  
23 Nina and the extraordinary year of 2011. *Journal of Geophysical Research-Biogeosciences*  
24 **118**, 1247-1255.
- 25 Bebi P, Kulakowski D, Rixen C (2009) Snow avalanche disturbances in forest ecosystems -

- 1 state of research and implications for management. *Forest Ecology and Management*, **257**,  
2 1883-1892.
- 3 Beier C, Beierkuhnlein C, Wohlgemuth T, Penuelas J *et al.* (2012) Precipitation manipulation  
4 experiments--challenges and recommendations for the future. *Ecol. Lett.*, **15**, 899-911.
- 5 Berhe AA, Kleber M (2013) Erosion, deposition, and the persistence of soil organic matter:  
6 mechanistic considerations and problems with terminology. *Earth Surf. Process. Landforms*,  
7 **38**, 908–912.
- 8 Berry PM, Sterling M, Baker CJ, Spink J, Sparkes DL (2003) A calibrated model of wheat  
9 lodging compared with field measurements. *Agricultural and Forest Meteorology*, **119**, 167–  
10 180.
- 11 Bloor JMG, Bardgett RD (2012) Stability of above-ground and below-ground processes to  
12 extreme drought in model grassland ecosystems: Interactions with plant species diversity and  
13 soil nitrogen availability. *Perspectives in Plant Ecology Evolution and Systematics*, **14**, 193-  
14 204.
- 15 Bokhorst SF, Bjerke JW, Tømmervik H, Callaghan TV, Phoenix GK (2009) Winter warming  
16 events damage sub-Arctic vegetation: consistent evidence from an experimental manipulation  
17 and a natural event. *Journal of Ecology*, **97**, 1408-1415.
- 18 Boening C, Willis J K, Landerer F W, Nerem R S, Fasullo J (2012) The 2011 La Niña: So  
19 strong, the oceans fell. *Geophysical Research Letters* 39, doi: 10.1029/2012GL053055.
- 20 Bond WJ, Woodward FI, Midgley GF (2005) The global distribution of ecosystems in a world  
21 without fire. *New Phytologist*, **165**, 525-538.
- 22 Borken W, Matzner E (2009) Reappraisal of drying and wetting effects on C and N  
23 mineralization and fluxes in soils. *Global Change Biology*, **15**, 808-824.
- 24 Bowman DMJS, Balch JK, Artaxo P, Bond WJ *et al.* (2009) Fire in the Earth System. *Science*,  
25 **324**, 481-484.



- 1 Brando P M, Nepstad DC, Balch JK, Bolker B, Christman MC, Coe M, Putz FE (2012) Fire-  
2 induced tree mortality in a neotropical forest: the roles of bark traits, tree size, wood density  
3 and fire behavior. *Global Change Biology*, **18**, 630-641.
- 4 Bragg DC, Shelton MG, Zeide B (2003) Impacts and management implications of ice storms  
5 on forests in the southern United States. *Forest Ecology and Management* **186**, 99–123
- 6 Brando P M, Balch J K, Nepstad D C et al. (2014) Abrupt increases in Amazonian tree  
7 mortality due to drought-fire interactions. *Proceedings of the National Academy of Sciences*  
8 *of the United States of America*, **111**(17), 6347-6352.
- 9 Bréda N, Huc R, Granier A, Dreyer E (2006) Temperate forest trees and stands under severe  
10 drought: a review of ecophysiological responses, adaptation processes and long-term  
11 consequences. *Annals of Forest Science*, **63**, 625-644.
- 12 Brémond P, Grelot F, Agenais A-L (2013) Review Article: Economic evaluation of flood  
13 damage to agriculture - review and analysis of existing methods. *Natural Hazards and Earth*  
14 *System Sciences*, **13**, 2493-2512.
- 15 Breshears DD, Whicker JJ, Johansen MP, Pinder JE (2003) Wind and water erosion and  
16 transport in semi-arid shrubland, grassland and forest ecosystems: quantifying dominance of  
17 horizontal wind-driven transport. *Earth Surf. Process. Landforms*, **28**, 1189–1209.
- 18 Breshears DD, Cobb NS, Rich PM *et al.* (2005) Regional vegetation die-off in response to  
19 global-change-type drought. *Proceedings of the National Academy of Sciences of the United*  
20 *States of America*, **102**, 15144-15148.
- 21 Canadell J, Jackson RB, Ehleringer JR, Mooney HA, Sala OE, Schulze ED (1996) Maximum  
22 rooting depth of vegetation types at the global scale. *Oecologia*, **108**, 583-595.
- 23 Certini G (2005) Effects of fire on properties of forest soils: a review. *Oecologia*, **143**, 1-10.
- 24 Chambers JQ, Fisher JI, Zeng HC, Chapman EL, Baker DB, Hurtt GC (2007) Hurricane  
25 Katrina's carbon footprint on U.S. Gulf Coast forests. *Science*, **318**, p. 1107.

- 1 Changnon SA (2003) Characteristics of ice storms in the United States. *Journal of Applied*  
2 *Meteorology*, **42**, 630-639.
- 3 Chaves MM, Flexas J, Pinheiro C (2009) Photosynthesis under drought and salt stress:  
4 regulation mechanisms from whole plant to cell. *Annals of Botany*, **103**, 551-560.
- 5 Ciais P, Reichstein M, Viovy N *et al.* (2005) Europe-wide reduction in primary productivity  
6 caused by the heat and drought in 2003. *Nature*, **437**, 529-533.
- 7 Conner WH, Inabinette LW (2003) Tree growth in three South Carolina (USA) swamps after  
8 Hurricane Hugo: 1991–2001. *Forest Ecology and Management* 182, 371–380.
- 9 Corlett RT (2011) Impacts of warming on tropical lowland rainforests. *Trends in Ecology and*  
10 *Evolution*, **26**, 606-613.
- 11 Cornelissen T (2011) Climate change and its effects on terrestrial insects and herbivory  
12 patterns. *Neotropical Entomology*, **40**, 155-163.
- 13 Coumou D, Rahmstorf S (2012) A decade of weather extremes. *Nature Climate Change*, **2**,  
14 491-496.
- 15 Couwenberg J, Dommain R, Joosten H (2010). Greenhouse gas fluxes from tropical peatlands  
16 in south-east Asia. *Global Change Biology*, **16**, 1715-1732.
- 17 Curiel-Yuste J, Peñuelas J, Estiarte M, Garcia-Mas J, Ogaya R, Pujol M, Sardans J (2011)  
18 Drought-resistant fungi control soil organic matter decomposition and its response to  
19 temperature. *Global Change Biology*, **17**, 1475-1486.
- 20 Dakos V, Carpenter SR, Brock WA *et al.* (2012) Methods for detecting early warnings of  
21 critical transitions in time series illustrated using simulated ecological data. *Plos One*, **7**, Art.  
22 e41010.
- 23 Davidson EA, Janssens IA (2006) Temperature sensitivity of soil carbon decomposition and  
24 feedbacks to climate change. *Nature*, **440**, 165-173.
- 25 De Boeck HJ, Dreesen FE, Janssens IA, Nijs I (2011) Whole-system responses of

- 1 experimental plant communities to climate extremes imposed in different seasons. *New*  
2 *Phytologist*, **189**, 806-817.
- 3 Desprez-Loustau M-L, Marçais B, Nageleisen L-M, Piou D, Vannini A (2006) Interactive  
4 effects of drought and pathogens in forest trees. *Annals of Forest Science*, **63**, 597-612.
- 5 Diez JM, D'antonio CM, Dukes JS *et al.* (2012) Will extreme climatic events facilitate  
6 biological invasions? *Frontiers in Ecology and the Environment*, **10**, 249-257.
- 7 Diffenbaugh NS, Ashfaq M (2010) Intensification of hot extremes in the United States.  
8 *Geophysical Research Letters*, **37**, doi:10.1029/2010GL043888.
- 9 Dinsmore KJ, Billett MF, Dyson KE (2013) Temperature and precipitation drive temporal  
10 variability in aquatic carbon and GHG concentrations and fluxes in a peatland catchment.  
11 *Global Change Biology*, **19**, 2133-2148.
- 12 Dittmar C, Elling W (2007) Dendroecological investigation of the vitality of Common Beech  
13 (*Fagus sylvatica* L.) in mixed mountain forests of the Northern Alps (South Bavaria).  
14 *Dendrochronologia*, **25**, 37-56.
- 15 Dittmar C, Fricke W, Elling W (2006) Impact of late frost events on radial growth of common  
16 beech (*Fagus sylvatica* L.) in Southern Germany. *European Journal of Forest Research*, **125**,  
17 249-259.
- 18 Doughty CE, Goulden ML (2008) Are tropical forests near a high temperature threshold?  
19 *Journal of Geophysical Research - Biogeosciences*, **113**, G00B07,  
20 doi:10.1029/2007JG000632.
- 21 Drake JM, Griffen BD (2010) Early warning signals of extinction in deteriorating  
22 environments. *Nature*, **467**, 456-459.
- 23 Drever C, Messier C, Bergeron Y, Flannigan M (2006) Can forest management based on  
24 natural disturbances maintain ecological resilience? *Canadian Journal of Forest Research*, **36**,  
25 2285-2299.

- 1 Durre I, Wallace JM, Lettenmaier DP (2000) Dependence of extreme daily maximum  
2 temperatures on antecedent soil moisture in the contiguous United States during summer.  
3 *Journal of Climate*, **13**, 2641-2651.
- 4 Eamus D, Boulain N, Cleverly J, Breshears DD (2013) Global change-type drought-induced  
5 tree mortality: vapor pressure deficit is more important than temperature per se in causing  
6 decline in tree health. *Ecology and Evolution*, **3**, 2711-2729.
- 7 Eilmann B, Zweifel R, Buchmann N, Pannatier EG, Rigling A (2011) Drought alters timing,  
8 quantity, and quality of wood formation in Scots pine. *Journal of Experimental Botany*, **62**,  
9 2763-2771.
- 10 Fisher EM, Knutti R (2014) Detection of spatially aggregated changes in temperature and  
11 precipitation extremes, *Geophys. Res. Lett.*, 10.1002/2013GL058499
- 12 Fischer EM, Seneviratne SI, Lüthi D, Schär C (2007) Contribution of land-atmosphere  
13 coupling to recent European summer heat waves. *Geophysical Research Letters*, **34**,  
14 doi:10.1029/2006GL029068.
- 15 Fischlin A, Midgley GF, Price JT *et al.* (2007) Ecosystems, their properties, goods, and  
16 services. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of*  
17 *Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on*  
18 *Climate Change*. (eds Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE),  
19 pp. 211-272, Cambridge, Cambridge University Press.
- 20 Fisk JP, Hurtt GC, Chambers JQ, Zeng H, Dolan KA, Negrón-Juárez RI (2013) The impacts  
21 of tropical cyclones on the net carbon balance of eastern US forests (1851–2000). *Environ.*  
22 *Res. Lett.* **8**, 045017 (6pp).
- 23 Founda D, Giannakopoulos C (2009) The exceptionally hot summer of 2007 in Athens,  
24 Greece — A typical summer in the future climate? *Global and Planetary Change* **67**,227–236.
- 25 Frankenberg C, Fisher JB, Worden J *et al.* (2011) New global observations of the terrestrial

- 1 carbon cycle from GOSAT: Patterns of plant fluorescence with gross primary productivity.  
2 *Geophysical Research Letters*, **38**, L17706, doi:10.11029/2011GL048738.
- 3 Freeman C, Ostle N, Kang H (2001) An enzymic 'latch' on a global carbon store. *Nature*, **409**,  
4 149-150.
- 5 Frolking S, Talbot J, Jones MC, Treat CC, Kauffman JB, Tuittila ES, Roulet N (2011)  
6 Peatlands in the Earth's 21st century climate system. *Environmental Reviews*, **19**, 371-396.
- 7 Fuchslueger L, Bahn M, Fritz K, Hasibeder R, Richter A (2014) Experimental drought  
8 reduces the transfer of recently fixed plant carbon to soil microbes and alters the bacterial  
9 community composition in a mountain meadow. *New Phytologist*, **201**, 916-927.
- 10 Fuhrer J, Beniston M, Fischlin A, Frei C, Goyette S, Jasper K, Pfister C (2006) Climate risks  
11 and their impact on agriculture and forests in Switzerland. *Climatic Change*, **79**, 79-102.
- 12 Ganteaume A, Camia A, Jappiot M, San-Miguel-Ayanz J, Long-Fournel M, Lampin C (2013)  
13 A Review of the Main Driving Factors of Forest Fire Ignition Over Europe. *Environmental*  
14 *Management*, **51**, 651-662.
- 15 García-Ruiz JM, Nadal-Romero E, Lana-Renault N, Beguería S (2013) Erosion in  
16 Mediterranean landscapes: Changes and future challenges. *Geomorphology*, **198**, 20-36.
- 17 Gerten D, Luo Y, Le Maire G *et al.* (2008) Modelled effects of precipitation on ecosystem  
18 carbon and water dynamics in different climatic zones. *Global Change Biology*, **14**, 2365-  
19 2379.
- 20 Gilgen AK, Buchmann N (2009) Response of temperate grasslands at different altitudes to  
21 simulated summer drought differed but scaled with annual precipitation. *Biogeosciences*, **6**,  
22 2525-2539.
- 23 Goebel M-O, Bachmann J, Reichstein M, Janssens IA, Guggenberger G (2011) Review: Soil  
24 water repellency and its implications for organic matter decomposition - is there a link to  
25 extreme climatic events? *Global Change Biology*, **17**, 2640-2656.

- 1 Goldsmith ST, Carey AE, Lyons BW, Kao S-J, Lee T-Y, Chen J (2008) Extreme storm events,  
2 landscape denudation, and carbon sequestration: Typhoon Mindulle, Choshui River, Taiwan.  
3 *Geology*, **36** (6), 483-486.
- 4 Gorham E (1991) Northern peatlands: role in the carbon cycle and probable responses to  
5 climatic warming. *Ecological Applications*, **1**, 182-195.
- 6 Gouttevin I, Menegoz M, Domine F *et al.* (2012) How the insulating properties of snow affect  
7 soil carbon distribution in the continental pan-Arctic area. *Journal of Geophysical Research -*  
8 *Biogeosciences*, **117**, G02020, doi:02010.01029/02011JG001916.
- 9 Granda E, Camarero JJ, Gimeno TE, Martínez-Fernández J, Valladares F (2013) Intensity and  
10 timing of warming and drought differentially affect growth patterns of co-occurring  
11 Mediterranean tree species. *European Journal of Forest Research*, **132**, 469-480.
- 12 Granier A, Reichstein M, Bréda N *et al.* (2007) Evidence for soil water control on carbon and  
13 water dynamics in European forests during the extremely dry year: 2003. *Agricultural and*  
14 *Forest Meteorology*, **143**, 123–145.
- 15 Grimm V, Wissel C (1997) Babel, or the ecological stability discussions: An inventory and  
16 analysis of terminology and a guide for avoiding confusion. *Oecologia*, **109**, 323-334.
- 17 Grippa M, Kergoat L, Toan TL, Mognard NM, Delbart N, L'Hermitte J, Vicente-Settano SM  
18 (2005) The impact of snow depth and snowmelt on the vegetation variability over central  
19 Siberia. *Geophysical Research Letters*, **32**, L21412, doi:10.1029/2005GL024286
- 20 Guanter L, Zhang Y, Jung M *et al.* (2014) Accurate, global and time-resolved monitoring of  
21 crop photosynthesis with chlorophyll fluorescence. *Proceedings of the National Academy of*  
22 *Sciences of the United States of America*, (revised Jan. 14)
- 23 Haarsma RJ, Selten F, Hurk BV, Hazeleger W, Wang XL (2009) Drier Mediterranean soils  
24 due to greenhouse warming bring easterly winds over summertime central Europe.  
25 *Geophysical Research Letters*, **36**, doi:10.1029/2008GL036617.

- 1 Hanson CE, Palutikof JP, Dlugolecki A, Giannakopoulos C (2006) Bridging the gap between  
2 science and the stakeholder: the case of climate change research. *Climate Research*, **31**, 121-  
3 133.
- 4 Hao ZX, Zheng JY, Ge QS, Wang W-C (2011) Historical analogues of the 2008 extreme  
5 snow event over Central and Southern China. *Climate Research*, **50**, 161-170.
- 6 Haverd V, Raupach MR, Briggs PR *et al.* (2013) The Australian terrestrial carbon budget.  
7 *Biogeosciences*, **10**, 851-869.
- 8 Hicke JA., Allen CD, Desai AR *et al.* (2012) Effects of biotic disturbances on forest carbon  
9 cycling in the United States and Canada. *Global Change Biology*, 18(1), 7-34.
- 10 Hilton RG, Galy A, Hovius N, Chen M-C, Horng M-J, Chen H (2008) Tropical-cyclone-  
11 driven erosion of the terrestrial biosphere from mountains. *Nature Geoscience*, **1**, 759-762.
- 12 Hirschi M, Seneviratne SI, Alexandrov V *et al.* (2011) Observational evidence for soil-  
13 moisture impact on hot extremes in southeastern Europe. *Nature Geoscience*, **4**, 17-21.
- 14 Holling CS (1973) Resilience and stability of ecological systems. *Annual Review of Ecology*  
15 *and Systematics*, **4**, 1-23.
- 16 Hong C-C, Hsu H-H, Lin N-H, Chiu H (2011) Roles of European blocking and tropical -  
17 extratropical interaction in the 2010 Pakistan flooding, *Geophys. Res. Lett.*, **38**, L13806.
- 18 Houze RA, Rasmussen KL, Medina S, Brodzik SR, Romatschke U (2011) Anomalous  
19 Atmospheric Events Leading to the Summer 2010 Floods in Pakistan. *Bull. Am. Soc.*, **92** (3),  
20 291-298.
- 21 Imbert D, Portecop J (2008) Hurricane disturbance and forest resilience: Assessing structural  
22 vs. functional changes in a Caribbean dry forest. *Forest Ecology and Management* **255**, 3494-  
23 3501.
- 24 IPCC (2012) Summary for Policymakers. In: *Managing the Risks of Extreme Events and*  
25 *Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and*

- 1 *II of the Intergovernmental Panel on Climate Change*. (eds Field CB, Barros V, Stocker TF *et*  
2 *al.*), pp. 1-19. Cambridge (UK), New York (USA), Cambridge University Press.
- 3 IPCC (2013) Summary for Policymakers. In: *Climate Change 2013: The Physical Science*  
4 *Basis. Contribution of Working Group I to the Fifth Assessment Report of the*  
5 *Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M.  
6 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)].  
7 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- 8 Irland LC (2000) Ice storms and forest impacts. *Science of the Total Environment*, **262**, 231-  
9 242.
- 10 Jactel H, Petit J, Desprez-Loustau M-L, Delzon S, Piou D, Battisti A, Koricheva J (2012)  
11 Drought effects on damage by forest insects and pathogens: a meta-analysis. *Global Change*  
12 *Biology*, **18**, 267-276.
- 13 Jarvis P, Rey A, Petsikos C *et al.* (2007) Drying and wetting of Mediterranean soils stimulates  
14 decomposition and carbon dioxide emission: the "Birch effect". *Tree Physiology*, **27**, 929-940.
- 15 Jentsch A, Kreyling J, Boettcher-Treschkow J, Beierkuhnlein C (2009) Beyond gradual  
16 warming: extreme weather events alter flower phenology of European grassland and heath  
17 species. *Global Change Biology*, **15**, 837-849.
- 18 Jepsen J, Hagen S, Hogda K, Ims R, Karlsen S, Tommervik H, Yoccoz N (2009) Monitoring  
19 the spatio-temporal dynamics of geometrid moth outbreaks in birch forest using MODIS-  
20 NDVI data. *Remote Sensing of Environment*, **113**, 1939-1947.
- 21 Johansen MP, Hakonson TE, Breshears DD (2001) Post-fire runoff and erosion from rainfall  
22 simulation: contrasting forests with shrublands and grasslands. *Hydrological Processes* **15**,  
23 2953-2965.
- 24 Johnson DM, Büntgen U, Frank DC *et al.* (2010) Climatic warming disrupts recurrent Alpine  
25 insect outbreaks. *Proceedings of the National Academy of Sciences of the United States of*



- 1 *America*, **107**, 20576-20581.
- 2 Jung M, Reichstein M, Margolis HA *et al.* (2011) Global patterns of land-atmosphere fluxes  
3 of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and  
4 meteorological observations. *Journal of Geophysical Research - Biogeosciences*, **116**, G00J07,  
5 doi:10.1029/2010JG001566.
- 6 Jung B-J, Lee H-J, Jeong J-J, Owen J, Kim B, Measburger K, Alewel, C, Gebauer G, Shope C,  
7 Park J-H. (2012) Storm pulses and varying sources of hydrologic carbon export from a  
8 mountainous watershed. *Journal of Hydrology*, **440-441**, 90-101.
- 9 Jungkunst HF, Fiedler S (2007) Latitudinal differentiated water table control of carbon  
10 dioxide, methane and nitrous oxide fluxes from hydromorphic soils: feedbacks to climate  
11 change. *Global Change Biology*, **13**, 2668-2683.
- 12 Kasin I, Ohlson M (2013). An experimental study of charcoal degradation in a boreal forest.  
13 *Soil Biology & Biochemistry*, **65**, 39-49.
- 14 Katz RW, Brown BG (1992) Extreme events in a changing climate: Variability is more  
15 important than averages. *Climatic Change*, **21**, 289-302.
- 16 Kausrud K, Okland B, Skarpaas O (2012) Population dynamics in changing environments: the  
17 case of an eruptive forest pest species. *Biological Reviews*, **87**, 34-51.
- 18 Keenan T, Sabate S, Gracia C (2010) The importance of mesophyll conductance in regulating  
19 forest ecosystem productivity during drought periods. *Global Change Biology*, **16**, 1019-1034.
- 20 Keith H, van Gorsel E, Jacobsen KL, Cleugh HA (2012) Dynamics of carbon exchange in a  
21 *Eucalyptus* forest in response to interacting disturbance factors. *Agricultural and Forest*  
22 *Meteorology*, **153**, 67-81.
- 23 Kim D-G, Vargas R, Bond-Lamberty B, Turetsky MR (2012) Effects of soil rewetting and  
24 thawing on soil gas fluxes: a review of current literature and suggestions for future research.  
25 *Biogeosciences*, **9**, 2459-2483.

- 1 Knapp AK, Beier C, Briske DD *et al.* (2008) Consequences of more extreme precipitation  
2 regimes for terrestrial ecosystems. *Bioscience*, **58**, 811-821.
- 3 Komonen A, Schroeder LM, Weslien J (2011) Ips typographus population development after  
4 a severe storm in a nature reserve in southern Sweden. *Journal of Applied Entomology*, **135**,  
5 132-141.
- 6 Konovalov IB, Beekmann M, Kuznetsova IN, Yurova A, Zvyagintsev AM (2011)  
7 Atmospheric impacts of the 2010 Russian wildfires: integrating modelling and measurements  
8 of an extreme air pollution episode in the Moscow region. *Atmospheric Chemistry and*  
9 *Physics*, **11**, 10031-10056.
- 10 Kopittke GR, Tietema A, van Loon EE, Assheman D (2014) Fourteen Annually Repeated  
11 Droughts Suppressed Autotrophic Soil Respiration and Resulted in an Ecosystem Change.  
12 *Ecosystems*, **17**, 242–257.
- 13 Körner C (2003) Slow in, rapid out - carbon flux studies and Kyoto targets. *Science*, **300**,  
14 1242-1243.
- 15 Kramer K, Vreugdenhil S J, van der Werf DC (2007) Effects of flooding on the recruitment,  
16 damage and mortality of riparian tree species: A field and simulation study on the Rhine  
17 floodplain. *Forest Ecology and Management* **255**, 3893–3903.
- 18 Kramer K, Leinonen I, Loustau D (2000) The importance of phenology for the evaluation of  
19 impact of climate change on growth of boreal, temperate and Mediterranean forests  
20 ecosystems: an overview. *International Journal of Biometeorology*, **44**, 67-75.
- 21 Kranner I, Minibayeva FV, Beckett RP, Seal CE (2010) What is stress? Concepts, definitions  
22 and applications in seed science. *New Phytologist*, **188**, 655-673.
- 23 Kreuzwieser J, Papadopoulou E, Rennenberg H (2004) Interaction of flooding with carbon  
24 metabolism of forest trees. *Plant Biology*, **6**, 299-306.
- 25 Kreyling J (2010) Winter climate change: a critical factor for temperate vegetation

- 1 performance. *Ecology*, **91**, 1939-1948.
- 2 Kreyling J, Jentsch A, Beierkuhnlein C (2011) Stochastic trajectories of succession initiated  
3 by extreme climatic events. *Ecology Letters*, **14**, 758-764.
- 4 Kreyling J, Jentsch A, Beier C (2014) Beyond realism in climate change experiments:  
5 gradient approaches identify thresholds and tipping points. *Ecology Letters* **17**, 125-e1.
- 6 Kurz WA, Stinson G, Rampley G (2008a) Could increased boreal forest ecosystem  
7 productivity offset carbon losses from increased disturbances? *Philosophical Transactions of*  
8 *the Royal Society B-Biological Sciences* **363**(1501) 2261-2269.
- 9 Kurz WA, Dymond CC, Stinson G *et al.* (2008b) Mountain pine beetle and forest carbon  
10 feedback to climate change. *Nature*, **452**, 987-990.
- 11 Lal R (2009) Challenges and opportunities in soil organic matter research. *European Journal*  
12 *of Soil Science*, **60**, 158-169.
- 13 Lal R, Pimentel D (2008) Soil erosion: A carbon sink or source? *Science*, **319**, 1040-1042.
- 14 Lal R, Lorenz K, Hüttl, RF, Schneider BU, von Braun J (eds.) (2013) Ecosystem Services and  
15 Carbon Sequestration in the Biosphere. Springer, Dodrecht, Heidelberg, New York, London.
- 16 Larcher W (2003) *Physiological Plant Ecology*, Berlin, Springer.
- 17 Lawlor DW (1995) The effects of water deficit on photosynthesis. In: *Environment And Plant*  
18 *Metabolism - Flexibility and Acclimation* (ed Smirnoff N), 129-160 pp. Oxford, Bios  
19 Scientific Publishers.
- 20 Lenton TM (2011) Early warning of climate tipping points. *Nature Climate Change*, **1**, 201-  
21 209.
- 22 Lenton TM, Held H, Kriegler E, Hall JW, Lucht W, Rahmstorf S, Schellnhuber HJ (2008)  
23 Tipping elements in the Earth's climate system. *Proceedings of the National Academy of*  
24 *Sciences of the United States of America*, **105**, 1786-1793.
- 25 Lewis SL, Brando PM, Phillips OL, Van Der Heijden GMF, Nepstad D (2011) The 2010

- 1 Amazon drought. *Science*, **331**, p. 554.
- 2 Li F, Bond-Lamberty B, Levis S (2013) Quantifying the role of fire in the Earth system – Part  
3 2: Impact on the net carbon balance of global terrestrial ecosystems for the 20<sup>th</sup> century.  
4 *Biogeosciences Discuss.*, **10**, 17309–17350.
- 5 Lindroth A, Lagergren F, Grelle A, Klemedtsson L, Langvall O, Weslien P, Tuulik J (2009)  
6 Storms can cause Europe-wide reduction in forest carbon sink. *Global Change Biology*, **15**,  
7 346-355.
- 8 Lobell DB, Sibley A, Ortiz-Monasterio JI (2012) Extreme heat effects on wheat senescence in  
9 India. *Nature Climate Change*, **2**, 1-4.
- 10 Lorenz R, Davin EL, Lawrence DM, Stöckli R, Seneviratne SI (2013) How important is  
11 vegetation phenology for European climate and heat waves? *Journal of Climate*, **26**, 10077-  
12 10100.
- 13 Luo Y, Weng E (2011) Dynamic disequilibrium of the terrestrial carbon cycle under global  
14 change. *Trends in Ecology and Evolution*, **26**, 96-104.
- 15 Major J, Lehmann J, Rondon M, Goodale C (2010) Fate of soil-applied black carbon:  
16 downward migration, leaching and soil respiration. *Global Change Biology*, **16**(4), 1366-  
17 1379.
- 18 Malhi Y, Roberts JT, Betts RA, Killeen TJ, Li W, Nobre CA (2008) Climate change,  
19 deforestation, and the fate of the Amazon. *Science*, **319**, 169-172.
- 20 Marino GP, Kaiser DP, Gu L, Ricciuto DM (2011) Reconstruction of false spring occurrences  
21 over the southeastern United States, 1901-2007: an increasing risk of spring freeze damage?  
22 *Environmental Research Letters*, **6**, Art. 024015.
- 23 Mayr S, Cochard H, Améglio T, Kikuta SB (2007) Embolism formation during freezing in the  
24 wood of *Picea abies*. *Plant Physiology*, **143**, 60-67.
- 25 Mayr S, Gruber A, Bauer H (2003) Repeated freeze-thaw cycles induce embolism in drought

- 1 stressed conifers (Norway spruce, stone pine). *Planta*, **217**, 436-441.
- 2 McDowell N, Pockman WT, Allen CD *et al.* (2008) Mechanisms of plant survival and  
3 mortality during drought: why do some plants survive while others succumb to drought? *New*  
4 *Phytologist*, **178**, 719-739.
- 5 McCarthy H R, Oren R, Kim H S, Johnsen K H, Maier C, Pritchard S G, Davis M A (2006)  
6 Interaction of ice storms and management practices on current carbon sequestration in forests  
7 with potential mitigation under future CO<sub>2</sub> atmosphere. *Journal of Geophysical Research:*  
8 *Atmospheres* **111**, DOI:10.1029/2005JD006428.
- 9 McDowell NG, Beerling DJ, Breshears DD, Fisher RA, Raffa KF, Stitt M (2011) The  
10 interdependence of mechanisms underlying climate-driven vegetation mortality. *Trends in*  
11 *Ecology and Evolution*, **26**, 523-532.
- 12 McDowell NG, Fisher RA, Xu C *et al.* (2013) Evaluating theories of drought-induced  
13 vegetation mortality using a multimodel-experiment framework. *New Phytologist*, **200**, 304-  
14 321.
- 15 MCPFE (2007) State of Europe's Forests 2007. The MCPFE Report on Sustainable Forest  
16 Management in Europe. Ministerial Conference on the Protection of Forests in Europe  
17 (MCPFE) Liaison Unit Warsaw. 247 pp. MCPFE, United Nations Economic Commission for  
18 Europe (UNECE), Food and Agricultural Organization of the United Nations (FAO).
- 19 Meehl GA, Karl T, Easterling DR *et al.* (2000) An introduction to trends in extreme weather  
20 and climate events: Observations, socioeconomic impacts, terrestrial ecological impacts, and  
21 model projections. *Bulletin of the American Meteorological Society*, **81**, 413-416.
- 22 Menzel A, Sparks TH, Estrella N *et al.* (2006) European phenological response to climate  
23 change matches the warming pattern. *Global Change Biology*, **12**, 1969-1976.
- 24 Michaelian M, Hogg EH, Hall RJ, Arsenault E (2011) Massive mortality of aspen following  
25 severe drought along the southern edge of the Canadian boreal forest. *Global Change Biology*,

- 1 17, 2084-2094.
- 2 Migliavacca M, Meroni M, Manca G, Matteucci G, Montagnani L, Grassi G, Zenone T,  
3 Teobaldelli M, Godec I, Colombo R, Seufert G (2009) Seasonal and interannual patterns of  
4 carbon and water fluxes of a poplar plantation under peculiar eco-climatic conditions.  
5 *Agricultural and Forest Meteorology*, **149** (9), 1460-1476.
- 6 Misson L, Limousin J-M, Rodriguez R, Letts MG (2010) Leaf physiological responses to  
7 extreme droughts in Mediterranean *Quercus ilex* forest. *Plant, Cell and Environment*, **33**,  
8 1898-1910.
- 9 Misson L, Degueldre D, Collin C, Rodriguez R, Rocheteau A, Ourcival J-M, Rambal S (2011)  
10 Phenological responses to extreme droughts in a Mediterranean forest. *Global Change*  
11 *Biology*, **17**, 1036-1048.
- 12 Monson RK, Lipson DL, Burns SP, Turnipseed AA, Delany AC, Williams MW, Schmidt SK  
13 (2006) Winter forest soil respiration controlled by climate and microbial community  
14 composition. *Nature*, **439**, 711-714.
- 15 Morgan JA, LeCain DR, Pendall E *et al.* (2011) C4 grasses prosper as carbon dioxide  
16 eliminates desiccation in warmed semi-arid grassland. *Nature*, **476**, 202-205.
- 17 Moriondo M, Good P, Durao R, Bindi M, Giannakopoulos C, Corte-Real J (2006) Potential  
18 impact of climate change on fire risk in the Mediterranean area. *Climate Research*, **31**, 85-95.
- 19 Morton DC, Le Page Y, DeFries R, Collatz GJ, Hurtt GC (2013) Understorey fire frequency  
20 and the fate of burned forests in southern Amazonia. *Philosophical Transactions of the Royal*  
21 *Society B-Biological Sciences*, **368**, 20120163.
- 22 Mueller B, Seneviratne SI (2012) Hot days induced by precipitation deficits at the global scale.  
23 *Proceedings of the National Academy of Sciences of the United States of America*, **109**,  
24 12398-12403.
- 25 Muhr J, Franke J, Borken W (2010) Drying-rewetting events reduce C and N losses from a

- 1 Norway spruce forest floor. *Soil Biology & Biochemistry*, **42**, 1303-1312.
- 2 Myneni RB, Keeling CD, Tucker CJ, Asrar G, Nemani RR (1997) Increased plant growth in  
3 the northern high latitudes from 1981 to 1991. *Nature*, **386**, 698-702.
- 4 Nagy L, Kreyling J, Gellesch E, Beierkuhnlein C, Jentsch A (2013) Recurring weather  
5 extremes alter the flowering phenology of two common temperate shrubs. *International*  
6 *Journal of Biometeorology*, **57**, 579-588.
- 7 Negrón-Juárez R, Baker DB, Zeng H, Henkel TK, Chambers JQ (2010a) Assessing hurricane-  
8 induced tree mortality in U.S. Gulf Coast forest ecosystems. *Journal of Geophysical Research*  
9 *- Biogeosciences*, **115**, doi:10.1029/2009JG001221.
- 10 Negrón-Juárez RI, Chambers JQ, Guimaraes G *et al.* (2010b) Widespread Amazon forest tree  
11 mortality from a single cross-basin squall line event. *Geophysical Research Letters*, **37**,  
12 doi:10.1029/2010GL043733.
- 13 Nepstad DC, Decarvalho CR, Davidson EA *et al.* (1994) The role of deep roots in the  
14 hydrological and carbon cycles of Amazonian forests and pastures. *Nature*, **372**, 666-669.
- 15 Netherer S, Schopf A (2010) Potential effects of climate change on insect herbivores in  
16 European forests - General aspects and the pine processionary moth as specific example.  
17 *Forest Ecology and Management*, **259**, 831-838.
- 18 Nicholls N, Alexander L (2007) Has the climate become more variable or extreme? Progress  
19 1992-2006. *Progress in Physical Geography*, **31**, 77-87.
- 20 Niu S, Luo Y, Li D, Cao S, Xia J, Li J, Smith MD (2014) Plant growth and mortality under  
21 climatic extremes: An overview. *Environment and Experimental Botany*, **98**, 13-19.
- 22 Nykänen M-L, Peltola H, Quine CP, Kellomäki S, Broadgate M (1997) Factors affecting  
23 snow damage of trees with particular reference to European conditions. *Silva Fennica*, **31**,  
24 193-213.
- 25 Øygarden L (2003) Rill and gully development during an extreme winter runoff event in

- 1 Norway. *Catena*, **50**, 217-242.
- 2 Page SE, Siegert F, Rieley JO, Boehm HDV, Jaya A, Limin S (2002) The amount of carbon  
3 released from peat and forest fires in Indonesia during 1997. *Nature*, **420**, 61-65.
- 4 Palacio S, Hoch G, Sala A, Körner C, Millard P (2014) Does carbon storage limit tree growth?  
5 *New Phytologist*, **201**(4), 1096-1100.
- 6 Pan Y, Birdsey RA, Fang J *et al.* (2011) A large and persistent carbon sink in the world's  
7 forests. *Science*, **333**, 988-993.
- 8 Parry ML, Canziani OF, Palutikof JP, Co-Authors (2007) Technical Summary. In: *Climate*  
9 *Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to*  
10 *the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (eds Parry  
11 ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE), 23-78 pp. Cambridge, UK,  
12 Cambridge University Press.
- 13 Pausas JG and Paula S (2012) Fuel shapes the fire-climate relationship: Evidence from  
14 Mediterranean ecosystems, *Global Ecol. Biogeogr.*, **21**(11), 1074–1082.
- 15 Peng SS, Piao S, Zeng Z, Ciais P, Zhou L, Li LZ, Myeni RB, Yin Y, Zeng H (2014)  
16 Afforestation in China cools local land surface temperature. *Proceedings of the National*  
17 *Academy of Sciences of the United States of America*,  
18 <http://www.pnas.org/content/early/2014/02/04/1315126111>
- 19 Peñuelas J, Sardans J, Estiarte M *et al.* (2013) Evidence of current impact of climate change  
20 on life: a walk from genes to the biosphere. *Global Change Biology*, **19**, 2303-2338.
- 21 Pereira JS, Mateus JA, Aires LM *et al.* (2007) Net ecosystem carbon exchange in three  
22 contrasting Mediterranean ecosystems - the effect of drought. *Biogeosciences*, **4**, 791-802.
- 23 Phillips OL, Aragão LEOC, Lewis SL *et al.* (2009) Drought sensitivity of the Amazon  
24 rainforest. *Science*, **323**, 1344-1347.
- 25 Pilegaard K, Ibrom A, Courtney MS, Hummelshøj P, Jensen NO (2011) Increasing net CO<sub>2</sub>



- 1 uptake by a Danish beech forest during the period from 1996 to 2009. *Agricultural and Forest*  
2 *Meteorology*, **151**, 934-946.
- 3 Polle A, Kröniger W, Rennenberg H (1996) Seasonal fluctuations of ascorbate-related  
4 enzymes: Acute and delayed effects of late frost in spring on antioxidative systems in needles  
5 of Norway spruce (*Picea abies* L.). *Plant and Cell Physiology*, **37**, 717-725.
- 6 Porter JR, Semenov MA (2005) Crop responses to climatic variation. *Philosophical*  
7 *Transactions of the Royal Society B - Biological Sciences*, **360**, 2021-2035.
- 8 Posthumus H, Morris J, Hess TM, Neville D, Phillips E, Baylis A (2009) Impacts of the  
9 summer 2007 floods on agriculture in England. *Journal of Flood Risk Management*, **2**, 182-  
10 189.
- 11 Poulter B, Frank D, Ciais P, Myneni R B, Andela N, Bi J, Broquet G, Canadell J G,  
12 Chevallier F, Liu Y Y, Running S W, Sitch S, van der Werf G R (2014) Contribution of semi-  
13 arid ecosystems to interannual variability of the global carbon cycle. *Nature*, **509**, 600-603.
- 14 Preston CM, Schmidt MWI (2006) Black (pyrogenic) carbon: a synthesis of current  
15 knowledge and uncertainties with special consideration of boreal regions. *Biogeosciences*, **3**,  
16 397-420.
- 17 Price DT, Alfaro RI, Brown KJ, Flannigan MD *et al.* (2013) Anticipating the consequences of  
18 climate change for Canada's boreal forest ecosystems. *Environ. Rev.* **21**, 322-365.
- 19 Ramankutty N, Evan AT, Monfreda C, Foley JA (2008) Farming the planet: 1. Geographic  
20 distribution of global agricultural lands in the year 2000. *Global Biogeochemical Cycles*, **22**,  
21 doi:10.1029/2007GB002952.
- 22 Rammig A, Wiedermann M, Donges J, Babst F *et al.* (2014) Tree-ring responses to extreme  
23 climate events as benchmarks for terrestrial dynamic vegetation models. *Biogeosciences*  
24 *Discuss.*, **11**, 2537-2568.
- 25 Reddy AR, Chaitanya KV, Vivekanandan M (2004) Drought-induced responses of

- 1 photosynthesis and antioxidant metabolism in higher plants. *Journal of Plant Physiology*, **161**,  
2 1189-1202.
- 3 Reichstein M, Ciais P, Papale D *et al.* (2007) Reduction of ecosystem productivity and  
4 respiration during the European summer 2003 climate anomaly: a joint flux tower, remote  
5 sensing and modelling analysis. *Global Change Biology*, **13**, 634–651.
- 6 Reichstein M, Bahn M, Ciais P *et al.* (2013) Climate extremes and the carbon cycle. *Nature*,  
7 **500**, 287-295.
- 8 Reyer CPO, Leuzinger S, Rammig A *et al.* (2012) A plant's perspective of extremes:  
9 terrestrial plant responses to changing climatic variability. *Global Change Biology*, **19**, 75-89.
- 10 Robinet C, Roques A (2010) Direct impacts of recent climate warming on insect populations.  
11 *Integrative Zoology*, **5**, 132-142.
- 12 Rosenzweig CE, Tubiello F, Goldberg R, Mills E, Bloomfield J (2002) Increased crop  
13 damage in the U.S. from excess precipitation under climate change. *Global Environ. Change*  
14 *A*, **12**, 197-202.
- 15 Rouault G, Candau J-N, Lieutier F, Nageleisen L-M, Martin J-C, Warzee N (2006) Effects of  
16 drought and heat on forest insect populations in relation to the 2003 drought in Western  
17 Europe. *Annals of Forest Science*, **63**, 613-624.
- 18 Sala A, Woodruff DR, Meinzer FC (2012) Carbon dynamics in trees: feast or famine? *Tree*  
19 *Physiology*, **32**, 764-775.
- 20 Sambaraju K R, Carroll A L, Jhu J, Stahl K, Moore R D, Aukema B H (2012) Climate change  
21 could alter the distribution of mountain pine beetle outbreaks in western Canada. *Ecography*  
22 **35**(3), 211-223.
- 23 Schachtschabel P, Blume H-P, Brümmer G, Hartge K-H, Schwertmann U (1992) *Lehrbuch*  
24 *der Bodenkunde*, Stuttgart.
- 25 Schär C, Vidale PL, Lüthi D, Frei C, Häberli C, Liniger MA, Appenzeller C (2004) The role

- 1 of increasing temperature variability in European summer heatwaves. *Nature*, **427**, 332-336.
- 2 Scheiter S, Langgan L, Higgins SI (2013) Next-generation dynamic global vegetation models:  
3 learning from community ecology. *New Phytologist*, **198**, 957—969.
- 4 Scheffer M, Carpenter S, Foley JA, Folke C, Walker B (2001) Catastrophic shifts in  
5 ecosystems. *Nature*, **413**, 591-596.
- 6 Schimel D, Baker D (2002) The wildfire factor. *Nature*, **420**, 29-30.
- 7 Schlyter P, Stjernquist I, Barring L, Jönsson AM, Nilsson C (2006) Assessment of the impacts  
8 of climate change and weather extremes on boreal forests in northern Europe, focusing on  
9 Norway spruce. *Climate Research*, **31**, 75-84.
- 10 Schmidt MWI, Torn MS, Abiven S *et al.* (2011) Persistence of soil organic matter as an  
11 ecosystem property. *Nature*, **478**, 49-56.
- 12 Schulze E-D, Beck E, Müller-Hohenstein K (2005) *Plant Ecology*, Heidelberg, Springer  
13 Verlag.
- 14 Schwalm CR, Williams CA, Schaefer K *et al.* (2010) Assimilation exceeds respiration  
15 sensitivity to drought: A FLUXNET synthesis. *Global Change Biology*, **16**, 657-670.
- 16 Schwalm CR, Williams CA, Schaefer K *et al.* (2012) Reduction in carbon uptake during turn  
17 of the century drought in western North America. *Nature Geoscience*, **5**, 551-556.
- 18 Seidl R, Fernandes PM, Fonseca TF *et al.* (2011) Modelling natural disturbances in forest  
19 ecosystems: a review. *Ecological Modelling*, **222**, 903-924.
- 20 Seneviratne SI, Lüthi D, Litschi M, Schär C (2006) Land-atmosphere coupling and climate  
21 change in Europe. *Nature*, **443**, 205-209.
- 22 Seneviratne SI, Corti T, Davin EL *et al.* (2010) Investigating soil moisture-climate  
23 interactions in a changing climate: A review. *Earth-Science Reviews*, **99**, 125-161.
- 24 Seneviratne SI, Nicholls N, Easterling D *et al.* (2012) Changes in climate extremes and their  
25 impacts on the natural physical environment. In: *Managing the Risks of Extreme Events and*

- 1 *Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and*  
2 *II of the Intergovernmental Panel on Climate Change (IPCC SREX Report).* (eds Field CB,  
3 Barros V, Stocker TF *et al.*), 109-230 pp. Cambridge (UK), New York (USA), Cambridge  
4 University Press.
- 5 Sheik CS, Beasley WH, Elshahed MS, Zhou X, Luo Y, Krumholz LR (2011) Effect of  
6 warming and drought on grassland microbial communities. *The ISME Journal -*  
7 *Multidisciplinary Journal of Microbial Ecology*, **5**, 1692-1700.
- 8 Shi Z, Thomey ML, Mowll W *et al.* (2014) Differential effects of extreme drought on  
9 production and respiration: synthesis and modeling analysis. *Biogeosciences*, **11**, 621–633.
- 10 Shinoda M, Gillies JA, Mikami M, Shao Y (2011) Temperate grasslands as a dust source:  
11 Knowledge, uncertainties, and challenges. *Aeolian Research*, **3**, 271-293.
- 12 Simpson IJ, Rowland FS, Meinardi S, Blake DR (2006) Influence of biomass burning during  
13 recent fluctuations in the slow growth of global tropospheric methane. *Geophysical Research*  
14 *Letters*, **33**, doi:10.1029/2006GL027330.
- 15 Singh N, Abiven S, Torn MS, Schmidt MWI (2012) Fire-derived organic carbon in soil turns  
16 over on a centennial scale. *Biogeosciences*, **9**, 2847-2857.
- 17 Smith MD (2011) An ecological perspective on extreme climatic events: a synthetic definition  
18 and framework to guide future research. *Journal of Ecology*, **99**, 656-663.
- 19 Smith NG, Dukes JS (2013) Plant respiration and photosynthesis in global-scale models:  
20 incorporating acclimation to temperature and CO<sub>2</sub>. *Global Change Biology*, **19**, 45-63.
- 21 Soja AJ, Tchepakova NM, French NHF *et al.* (2007) Climate-induced boreal forest change:  
22 Predictions versus current observations. *Global and Planetary Change*, **56**, 274-296.
- 23 Soussana J-F, Graux AI, Tubiello F-N (2010) Improving the use of modelling for projections  
24 of climate change impacts on crops and pastures. *Journal of Experimental Botany*, **61**, 2217-  
25 2228.

- 1 Sowerby A, Emmett BA, Tietema A, Beier C (2008) Contrasting effects of repeated summer  
2 drought on soil carbon efflux in hydric and mesic heathland soils. *Global Change Biology*, **14**,  
3 2388-2404.
- 4 Sperry JS (2000) Hydraulic constraints on plant gas exchange. *Agricultural and Forest*  
5 *Meteorology* **104**, 13–23.
- 6 Sullivan JEM (1992) Xylem embolism in response to freeze-thaw cycles and water-stress in  
7 ring-porous, diffuse-porous, and conifer species. *Plant Physiology*, **100**, 605-613.
- 8 Stahl K, Moore RD, Mckendry IG (2006) Climatology of winter cold spells in relation to  
9 mountain pine beetle mortality in British Columbia, Canada. *Climate Research*, **32**, 13-23.
- 10 Stone R (2008) Ecologists report huge storm losses in China's forests. *Science*, **319**, 1318-  
11 1319.
- 12 Suarez ML, Kitzberger T (2008) Recruitment patterns following a severe drought: long-term  
13 compositional shifts in Patagonian forests. *Canadian Journal of Forest Research*, **38**, 3002-  
14 3010.
- 15 Sun Y, Gu LH, Dickinson RE, Zhou BZ (2012) Forest greenness after the massive 2008  
16 Chinese ice storm: integrated effects of natural processes and human intervention.  
17 *Environmental Research Letters*, **7**, Art. 035702.
- 18 Suttie JM, Reynolds SG, Batello C eds. (2005) Grasslands of the World. *Plant Production*  
19 *and Protection Series*, **34**. FAO, Rome.
- 20 Tarnocai C, Canadell JG, Schuur EaG, Kuhry P, Mazhitova G, Zimov S (2009) Soil organic  
21 carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles*,  
22 **23**, GB2023, doi:2010.1029/2008GB003327.
- 23 Teuling AJ, Seneviratne SI, Stöckli R *et al.* (2010) Contrasting response of European forest  
24 and grassland energy exchange to heatwaves. *Nature Geoscience*, **3**, 722-727.
- 25 Teuling AJ, Uijlenhoet R, Hupet F, Troch PA (2006) Impact of plant water uptake strategy on

- 1 soil moisture and evapotranspiration dynamics during drydown. *Geophysical Research*  
2 *Letters*, **33**, doi:10.1029/2005GL025019.
- 3 Thothong W, Huon S, Janeau JL *et al.* (2011) Impact of land use change and rainfall on  
4 sediment and carbon accumulation in a water reservoir of North Thailand. *Agriculture,*  
5 *Ecosystems and Environment*, **140**, 521-533.
- 6 Tian H, Melillo JM, Kicklighter DW, McGiure AD, Helfrich III J, Moore III B, Vörösmarty  
7 CJ (1998) Effect of interannual climate variability on carbon storage in Amazonian  
8 ecosystems. *Nature*, **396**, 664-667.
- 9 Tolk JA (2003) Plant available soil water. In: Stewart BA, Howell TA, eds. Encyclopedia of  
10 water science. New York, NY, USA: Marcel-Dekker, Inc, 669–672.
- 11 Trenberth, K. E., Fasullo J. T. (2012), Climate extremes and climate change: The Russian heat  
12 wave and other climate extremes of 2010, *J. Geophys. Res.*, **117**, D17103.
- 13 Trigo RM, Pereira JMC, Pereira MRG *et al.* (2006) Atmospheric conditions associated with  
14 the exceptional fire season of 2003 in Portugal. *International Journal of Climatology* **26**,  
15 1741-1757.
- 16 Turetsky M, Wieder K, Halsey L, Vitt D (2002) Current disturbance and the diminishing  
17 peatland carbon sink. *Geophysical Research Letters*, **29**, 1526, doi:1510.1029/2001GL014000.
- 18 Turetsky MR, Donahue WF, Benscoter BW (2011a) Experimental drying intensifies burning  
19 and carbon losses in a northern peatland. *Nature Communications*, **2**, Art. 514.
- 20 Turetsky MR, Kane ES, Harden JW, Ottmar RD, Manies KL, Hoy E, Kasischke ES (2011b)  
21 Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands.  
22 *Nature Geoscience*, **4**, 27-31.
- 23 Unger S, Máguas C, Pereira JS, Aires LM, David TS, Werner C (2009) Partitioning carbon  
24 fluxes in a Mediterranean oak forest to disentangle changes in ecosystem sink strength during  
25 drought. *Agricultural and Forest Meteorology*, **149**, 949-961.

- 1 Valentin C, Agus F, Alamban R *et al.* (2008) Runoff and sediment losses from 27 upland  
2 catchments in Southeast Asia: Impact of rapid land use changes and conservation practices.  
3 *Agriculture, Ecosystem and Environment*, **128**, 225-238.
- 4 VandenBygaart AJ, Kroetsch D, Gregorich EG, Lobb DA (2012) Soil C erosion and burial in  
5 cropland. *Global Change Biology*, **18**, 1441–1452.
- 6 van der Molen MK, Dolman AJ, Ciais P *et al.* (2011) Drought and ecosystem carbon cycling.  
7 *Agricultural and Forest Meteorology*, **151**, 765-773.
- 8 van der Velde M, Tubiello FN, Vrieling A, Bouraoui F (2012) Impacts of extreme weather on  
9 wheat and maize in France: evaluating regional crop simulations against observed data.  
10 *Climatic Change*, **113**, 751-765.
- 11 van der Velde M, Wriedt G, Bouraoui F (2010) Estimating irrigation use and effects on maize  
12 yield during the 2003 heatwave in France. *Agriculture, Ecosystems and Environment*, **135**,  
13 90-97.
- 14 van der Werf GR, Dempewolf J, Trigg SN *et al.* (2008) Climate regulation of fire emissions  
15 and deforestation in equatorial Asia. *Proceedings of the National Academy of Sciences of the*  
16 *United States of America*, **105**, 20350-20355.
- 17 van der Werf GR, Randerson JT, Giglio L *et al.* (2010) Global fire emissions and the  
18 contribution of deforestation, savanna, forest, agricultural, and peat fires (1997-2009).  
19 *Atmospheric Chemistry and Physics*, **10**, 11707-11735.
- 20 van Oost K, Quine TA, Govers G *et al.* (2007) The impact of agricultural soil erosion on the  
21 global carbon cycle. *Science*, **318**, 626-629.
- 22 Vargas R (2012) How a hurricane disturbance influences extreme CO<sub>2</sub> fluxes and variance in  
23 a tropical forest. *Environ. Res. Lett.* **7** 035704. doi:10.1088/1748-9326/7/3/035704
- 24 Vautard R, Yiou P, D'andrea F *et al.* (2007) Summertime European heat and drought waves  
25 induced by wintertime Mediterranean rainfall deficit. *Geophysical Research Letters*, **34**,

- 1 doi:10.1029/2006GL028001.
- 2 Vervuren PJA, Blom CWPM, De Kroon H (2003) Extreme flooding events on the Rhine and  
3 the survival and distribution of riparian plant species. *Journal of Ecology*, **91**, 135-146.
- 4 Vetter M, Churkina G, Jung M *et al.* (2008) Analyzing the causes and spatial pattern of the  
5 European 2003 carbon flux anomaly using seven models. *Biogeosciences*, **5**, 561-583.
- 6 Vicca S, Gilgen A K, Camino Serrano M, Dreesen FE *et al.* (2012) Urgent need for a  
7 common metric to make precipitation manipulation experiments comparable. *New Phytologist*,  
8 **195**, 518-522.
- 9 Vicca S, Bahn M, Estiarte M *et al.* (2014) Can current moisture responses predict soil CO<sub>2</sub>  
10 efflux under altered precipitation regimes? A synthesis of manipulation experiments.  
11 *Biogeosciences* **11**, 2991-3013.
- 12 Virtanen T, Neuvonen S, Nikula A (1998) Modelling topoclimatic patterns of egg mortality of  
13 *Epirrita autumnata* (Lepidoptera: Geometridae) with a Geographical Information System:  
14 predictions for current climate and warmer climate scenarios. *Journal of Applied Ecology*, **35**,  
15 311-322.
- 16 Walter J, Nagy L, Hein R, Rascher U, Beierkuhnlein C, Willner E, Jentsch A (2011) Do plants  
17 remember drought? Hints towards a drought-memory in grasses. *Environmental and*  
18 *Experimental Botany*, **71**, 34-40.
- 19 Walter J, Hein R, Auge H *et al.* (2012) How do extreme drought and plant community  
20 composition affect host plant metabolites and herbivore performance? *Arthropod-Plant*  
21 *Interactions*, **6**, 15-25.
- 22 Walter J, Jentsch A, Beierkuhnlein C, Kreyling J (2013) Ecological stress memory and cross  
23 stress tolerance in plants in the face of climate extremes. *Environmental and Experimental*  
24 *Botany*, **94**, 3-8.
- 25 Wan CG, Yilmaz I, Sosebee RE (2002) Seasonal soil-water availability influences snakeweed



- 1 root dynamics. *Journal of Arid Environments*, **51**, 255-264.
- 2 Wang XB, Enema O, Hoogmed WB, Perdok UD, Cai DX (2006) Dust storm erosion and its  
3 impact on soil carbon and nitrogen losses in northern China. *Catena*, **66**, 221-227.
- 4 Wendler G, Conner J, Moor B, Shulski M, Stuefer M (2011) Climatology of Alaskan  
5 wildfires with special emphasis on the extreme year of 2004. *Theoretical and Applied*  
6 *Climatology* **104**, 459-472.
- 7 White PS, Jentsch A (2001) The Search for Generality in Studies of Disturbance and  
8 Ecosystem Dynamics, *Progress in Botany*, **62**, 399-450.
- 9 White RE (2006) Hydrology, soil water and temperature. In: White RE, ed. Principles and  
10 practice of soil science, 4th edn. Malden, MA, USA, Oxford, UK, Victoria, Australia:  
11 Blackwell Publishing, 103–132.
- 12 Williams AP, Allen CD, Macalady AK *et al.* (2012) Temperature as a potent driver of  
13 regional forest drought stress and tree mortality. *Nature Climate Change*, **3**, 292-297.
- 14 Wolf S, Eugster W, Ammann C, Häni M, Zielis S, Hiller R, Stieger J, Imer D, Merbold L,  
15 Buchmann N (2013) Contrasting response of grassland *versus* forest carbon and water fluxes  
16 to spring drought in Switzerland. *Environmental Research Letters* **8**, 035007.
- 17 Wu Z, Dijkstra P, Koch GW, Peñuelas J, Hungate BA (2011) Responses of terrestrial  
18 ecosystems to temperature and precipitation change: a meta-analysis of experimental  
19 manipulation. *Global Change Biology*, **17**, 927-942.
- 20 Zampieri M, D'Andrea F, Vautard R, Ciais P, de Noblet-Ducoudre N, Yiou P (2009) Hot  
21 European Summers and the Role of Soil Moisture in the Propagation of Mediterranean.  
22 *Journal of Climate* **22**, 4747-4758.
- 23 Zavalloni C, Gielen B, Lemmens CMHM *et al.* (2008) Does a warmer climate with frequent  
24 mild water shortages protect grassland communities against a prolonged drought? *Plant and*  
25 *Soil*, **308**, 119-130.

- 1 Zeng HC, Chambers JQ, Negrón-Juárez RI, Hurtt GC, Baker DB, Powell MD (2009) Impacts  
2 of tropical cyclones on U.S. forest tree mortality and carbon flux from 1851 to 2000.  
3 *Proceedings of the National Academy of Sciences of the United States of America*, **106**, 7888-  
4 7892.
- 5 Zhang T, Barry RG, Haeberli W (2001) Numerical simulations of the influence of the  
6 seasonal snow cover on the occurrence of permafrost at high latitudes. *Norsk Geografisk*  
7 *Tidsskrift*, **55**, 261-266.
- 8 Zscheischler J, Mahecha MD, Harmeling S, Reichstein M (2013) Detection and attribution of  
9 large spatiotemporal extreme events in Earth observation data. *Ecological Informatics*, **15**, 66-  
10 73.
- 11 Zscheischler J, Mahecha MD, von Buttlar J, Harmeling S, Jung M, Rammig A, Randerson JT,  
12 Schölkopf B, Seneviratne SI, Tomelleri E, Zaehle S, Reichstein M (2014a) A few extreme  
13 events dominate interannual variability in gross primary production. *Environmental Research*  
14 *Letters* **9**, 035001.
- 15 Zscheischler J, Reichstein M, Harmeling S, Rammig A, Tomelleri E, Mahecha MD (2014b)  
16 Extreme events in gross primary production: a characterization across continents.  
17 *Biogeosciences* **11**, 2909-2924.
- 18 Zscheischler J, Reichstein M, von Buttlar J, Mu M, Randerson JT, Mahecha MD (2014c)  
19 Carbon cycle extremes during the 21st century in CMIP5 models: Future evolution and  
20 attribution to climatic drivers. *Geophysical Research Letters* **41**, 8853-8861.  
21  
22

1 **Supporting Information legend**

2 S1

3 Supporting information S1 provides a detailed literature survey about how climate extremes  
4 act on forests, grasslands, peatlands and croplands.

5

## 1 **Figure legends**

2 Figure 1: Schematic diagram illustrating direct concurrent and lagged (A, B) and indirect  
3 concurrent and lagged (C, D) impacts of climate extremes and corresponding extreme  
4 ecosystem responses. In the direct case the extreme impact occurs if (and only if) a threshold  
5 is reached, i.e. a critical dose (blue line) is passed. In the indirect case, the climate extreme  
6 increases the susceptibility (red line) to an external trigger (climatic or non-climatic, extreme  
7 or not extreme). The likelihood as a function of the trigger and the susceptibility is indicated  
8 with the symbol “P” in the circle. Concurrent responses start during the climate extreme, but  
9 may last longer for indefinite time (dashed extensions of green boxes). Lagged responses only  
10 happen after the climate extreme. The responses can be of different non-linear shapes as  
11 indicated in Fig. 2.

12  
13

14 Figure 2: Hypothesized temporal dynamics of direct and indirect concurrent and lagged  
15 effects of climate extremes (examples: drought / heat wave; storm) and of ecosystem recovery  
16 on the ecosystem carbon balance. (Note that for simplicity regrowth after fire and pest  
17 outbreak are not shown in this figure). Line colours correspond to the colour of the climate  
18 extreme in the figure.

19

20 Figure 3: Processes and mechanisms underlying impacts of climate extremes on the carbon  
21 cycle. Positive/ enhancing impacts with a “+” and negative/reducing impacts with a “-“ sign;  
22 predominant (in-)direct impacts (dashed) arrows (for further details please see text);  
23 importance of impact/relationship is shown by arrow width (high=thick, low=thin) (modified  
24 after Reichstein *et al.*, 2013).

25

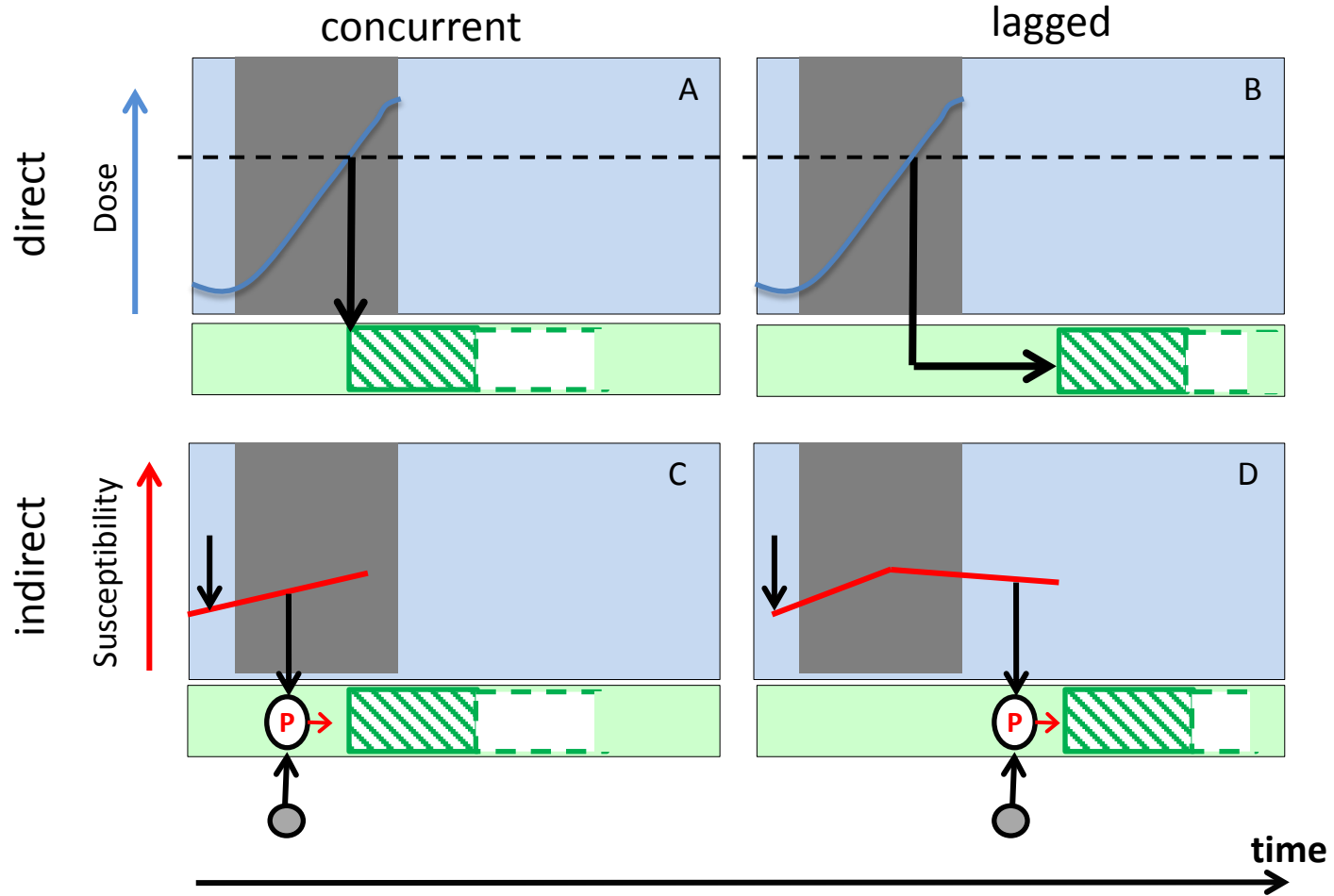
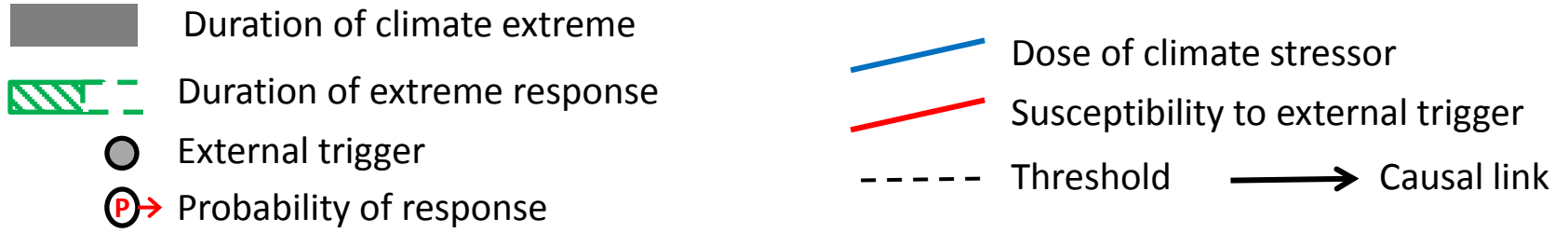
1 Figure 4: Schematic overview of concurrent, lagged, direct and indirect impacts of climate  
2 extremes on processes underlying ecosystem carbon dynamics. Respective references  
3 (selection of examples) are indicated as followed: **1** [Larcher, 2003; Mayr *et al.*, 2007]; **2**  
4 [Larcher, 2003; Schulze *et al.*, 2005; Lobell *et al.*, 2012; Porter & Semenov, 2005; Niu *et al.*,  
5 2014]; **3** [Larcher, 2003; Breda *et al.*, 2006; Keenan *et al.*, 2010; Reichstein *et al.*, 2007;  
6 Mission *et al.*, 2010; Schwalm *et al.*, 2010; Eamus *et al.*, 2013]; **4** [Rosenzweig *et al.*, 2002;  
7 Vervuren *et al.*, 2003; Kreuzwieser *et al.*, 2004; van der Velde *et al.*, 2012]; **5** [Nykänen *et*  
8 *al.*, 1997; Irland 2000; Chagnon 2000; Hao *et al.*, 2011; Sun *et al.*, 2012]; **6** [Berry *et al.*,  
9 2003; Fuhrer *et al.*, 2006; MCPFE, 2007; Lindroth *et al.*, 2009; Zeng *et al.*, 2009; Negrón-  
10 Juárez *et al.*, 2010b]; **7** [Larcher 2003; Schulze *et al.*, 2005; Dittmar *et al.*, 2007; Bokhorst *et*  
11 *al.*, 2009]; **8** [Larcher, 2003; Porter & Semenov, 2005; Breda *et al.*, 2006; Lobell *et al.*, 2012];  
12 **9** [Barber *et al.*, 2000; Eilmann *et al.*, 2011; Fuhrer *et al.*, 2006; Phillips *et al.*, 2009;  
13 Michaelian *et al.*, 2010; McDowell *et al.*, 2013; Peñuelas *et al.*, 2013)]; **10** [Vervuren *et al.*,  
14 2003; Posthumus *et al.*, 2009]; **11** [MCPFE, 2007; Chambers *et al.*, 2007; Zeng *et al.*, 2009;  
15 Negrón-Juárez *et al.*, 2010a, b]; **12** [Fuhrer *et al.*, 2006; Hilton *et al.*, 2008; García-Ruiz *et*  
16 *al.*, 2013]; **13** [Wang *et al.*, 2006; Shinoda *et al.*, 2011]; **14** [Jentsch *et al.*, 2011; Fuchslueger  
17 *et al.*, 2014]; **15** [Moriondo *et al.*, 2006; Ganteaume *et al.*, 2013]; **16** [Porter & Semenov,  
18 2005; Jentsch *et al.*, 2009; Mission *et al.*, 2011; Nagy *et al.*, 2013), Peñuelas *et al.*, 2013]; **17**  
19 [Breda *et al.*, 2006; McDowell *et al.*, 2008, 2011, 2013; Walter *et al.*, 2012]; **18** [Breda *et al.*,  
20 2006; Adams *et al.*, 2009; Allen *et al.*, 2010; Michaelian *et al.*, 2010; McDowell *et al.*, 2008,  
21 2011; Granda *et al.*, 2013]; **19** [Kreyling *et al.*, 2011; Suarez & Kitzberger, 2008; Diez *et al.*,  
22 2012]; **20** [Larcher, 2003; Walter *et al.*, 2013]; **21** [Virtanen *et al.*, 1998; Stahl *et al.*, 2006;  
23 Robinet and Roques 2010; Kausrud *et al.*, 2012]; **22** [Breda *et al.*, 2006; Desprez-Lousteau *et*  
24 *al.*, 2006; Rouault *et al.*, 2006; MCPFE, 2007; McDowell *et al.*, 2008, 2011; Jactel *et al.*,  
25 2012; Keith *et al.*, 2012; Kausrud *et al.*, 2012; Walter *et al.*, 2012]; **23** [Schlyter *et al.*, 2006,

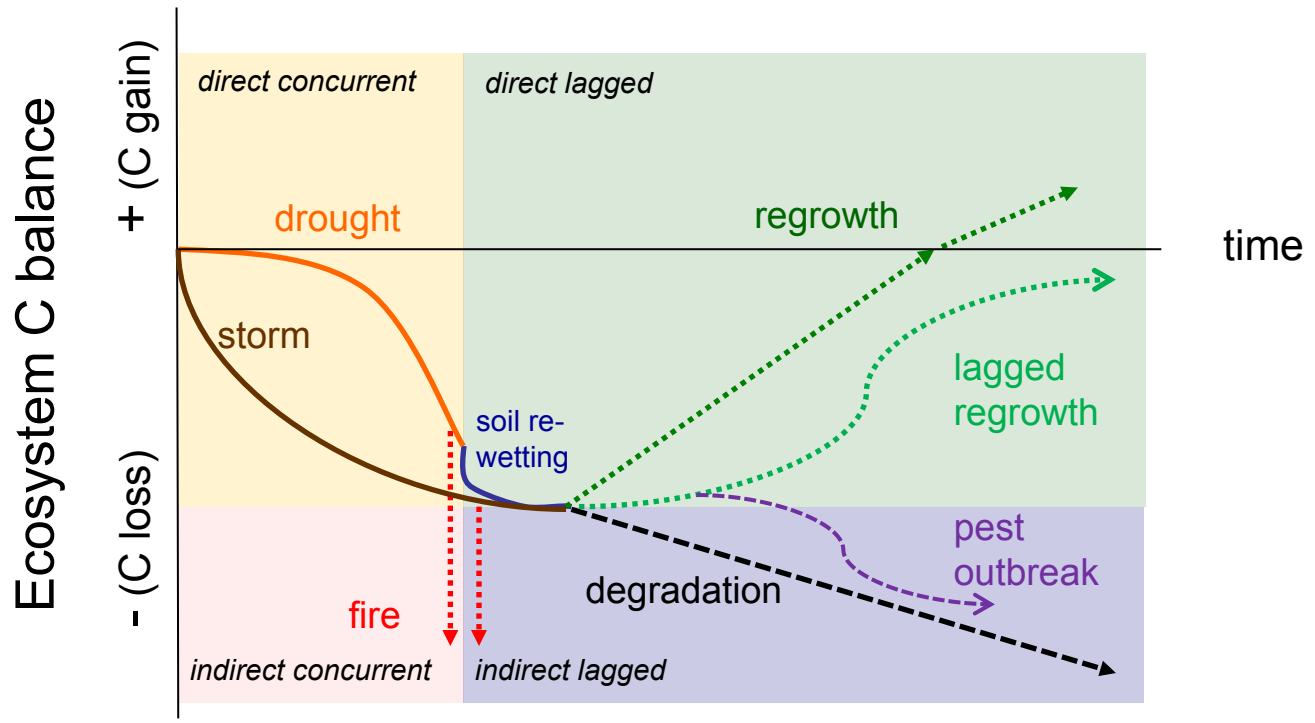
1 MCPFE, 2007; Komonen *et al.*, 2010]; **24** [Trigo *et al.*, 2006; Wendler *et al.*, 2011]; **25** [Kurz  
2 *et al.*, 2008a]; **26** [Øygarden, 2003; Valentin *et al.*, 2008; Thothong *et al.*, 2011]; **27** [Sheik *et*  
3 *al.*, 2011; Yuste *et al.*, 2011; Fuchslueger *et al.*, 2014]; **28** [Sowerby *et al.*, 2008].

4

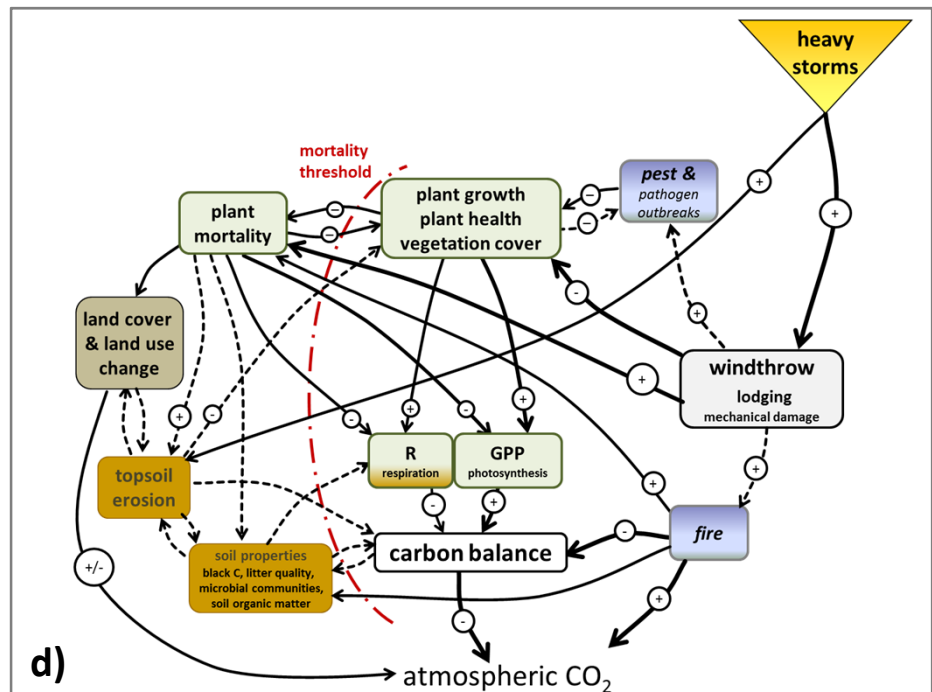
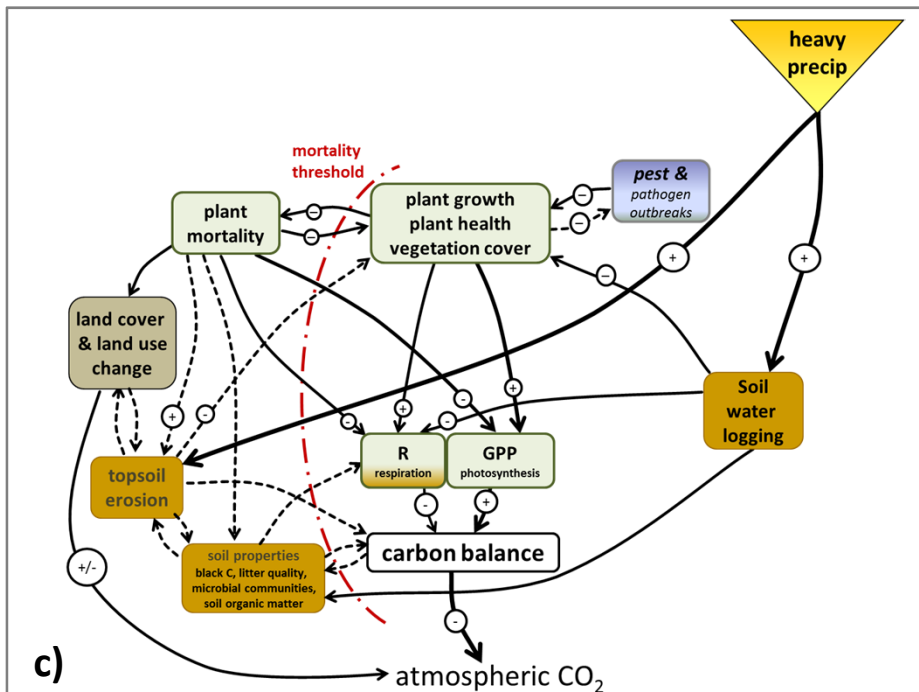
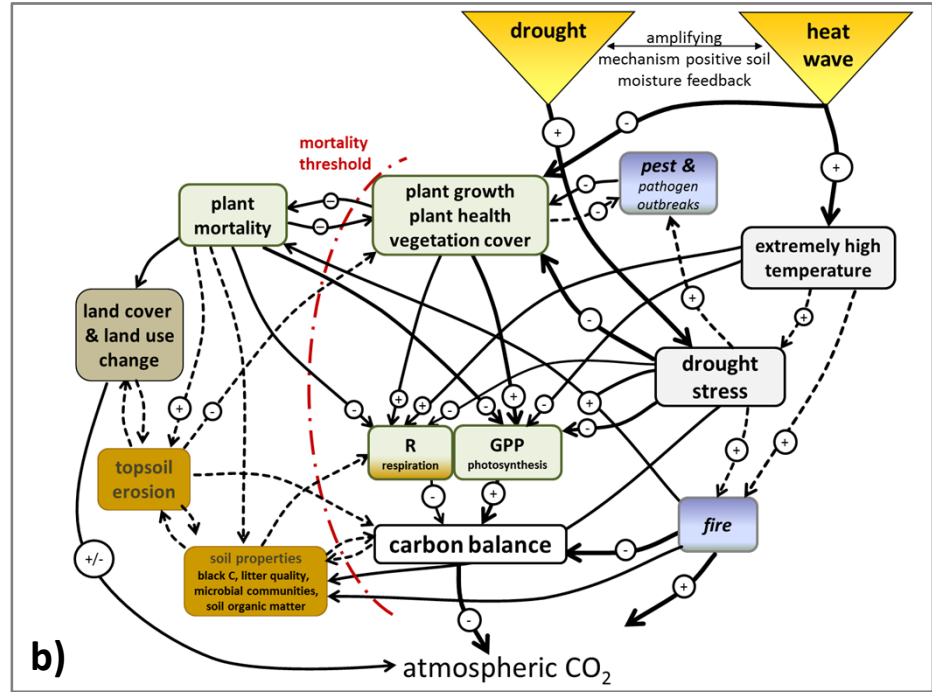
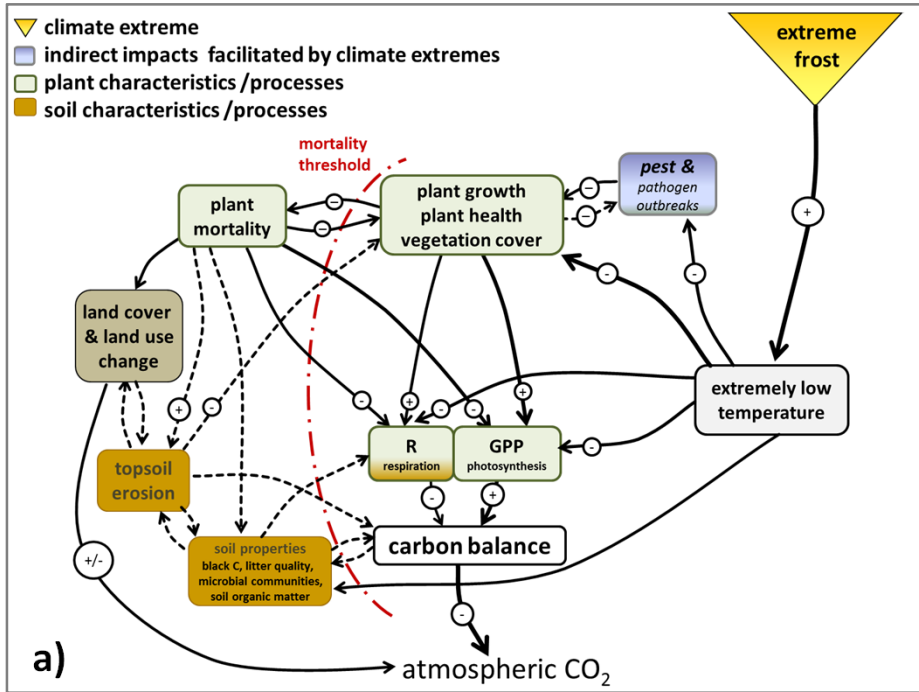
5 Figure 5: Global distribution of extreme events in the terrestrial carbon cycle, and  
6 approximate geographical locations of published climate extremes with impacts on the carbon  
7 cycle. Extreme events in the carbon cycle are defined as contiguous regions of extreme  
8 anomalies of GPP during the period 1982-2011 (modified after Zscheischler *et al.*, 2014b).  
9 Colour scale indicates the average reduction in gross carbon uptake compared to a normal  
10 year due to negative extremes in GPP. Units are gram carbon per square meter per year. The  
11 map highlights the IPCC regions with the following references to the published climate  
12 extremes.

13 References ad Fig. 5: **1** *pest outbreaks Canada/North America* [Soja *et al.*, 2007; Kurz *et al.*,  
14 2008b], **2** *ice storm North America* [Ireland, 2000], **3** *drought US* [Breshears *et al.*, 2005;  
15 Schwalm *et al.*, 2012], **4** *heavy storm Southern US* [Chambers *et al.*, 2007; Zeng *et al.*, 2009;  
16 Negrón-Juárez *et al.*, 2010a], **5** *heavy storm Amazon* [Negrón-Juárez *et al.*, 2010b], **6** *drought*  
17 *Amazon* [Tian *et al.*, 1998; Phillips *et al.*, 2009; Lewis *et al.*, 2011], **7** *heavy storm Europe*  
18 [Fuhrer *et al.*, 2006; Lindroth *et al.*, 2009], **8** *drought and heat extreme Europe* [Ciais *et al.*,  
19 2005; Reichstein *et al.*, 2007], **9** *extreme drought, heat and fire in Russia* [Barriopedo *et al.*,  
20 2011; Konovalov *et al.*, 2011; Coumou & Rahmstorf, 2012; Bastos *et al.*, 2013a], **10** *ice*  
21 *storm China* [Stone, 2008; Sun *et al.*, 2012]), **11** *fire, drought SE Asia* [Page *et al.*, 2002;  
22 Schimel & Baker, 2002], **12** *drought Australia* [Haverd *et al.*, 2013], **13** *heavy precipitation*  
23 *Australia* [Bastos *et al.*, 2013b; Haverd *et al.*, 2013], **14** *heavy precipitation Southern Africa*  
24 [Bastos *et al.*, 2013b].

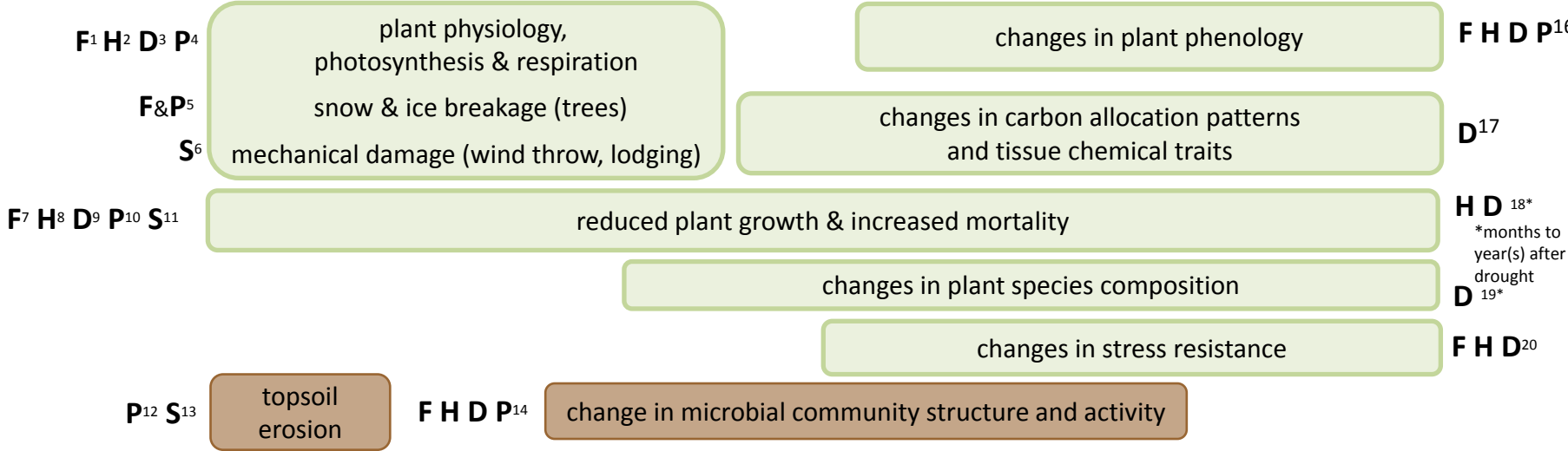




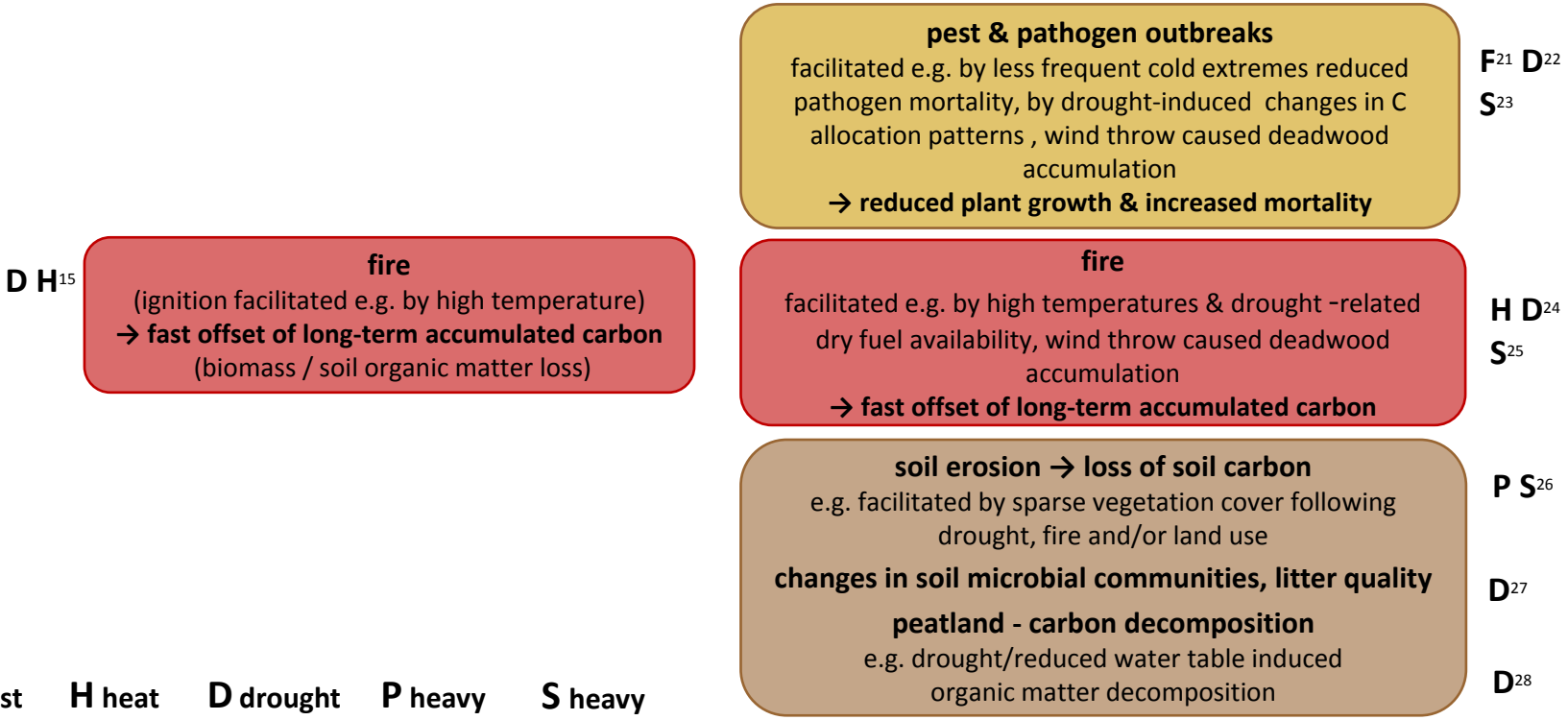




direct impacts

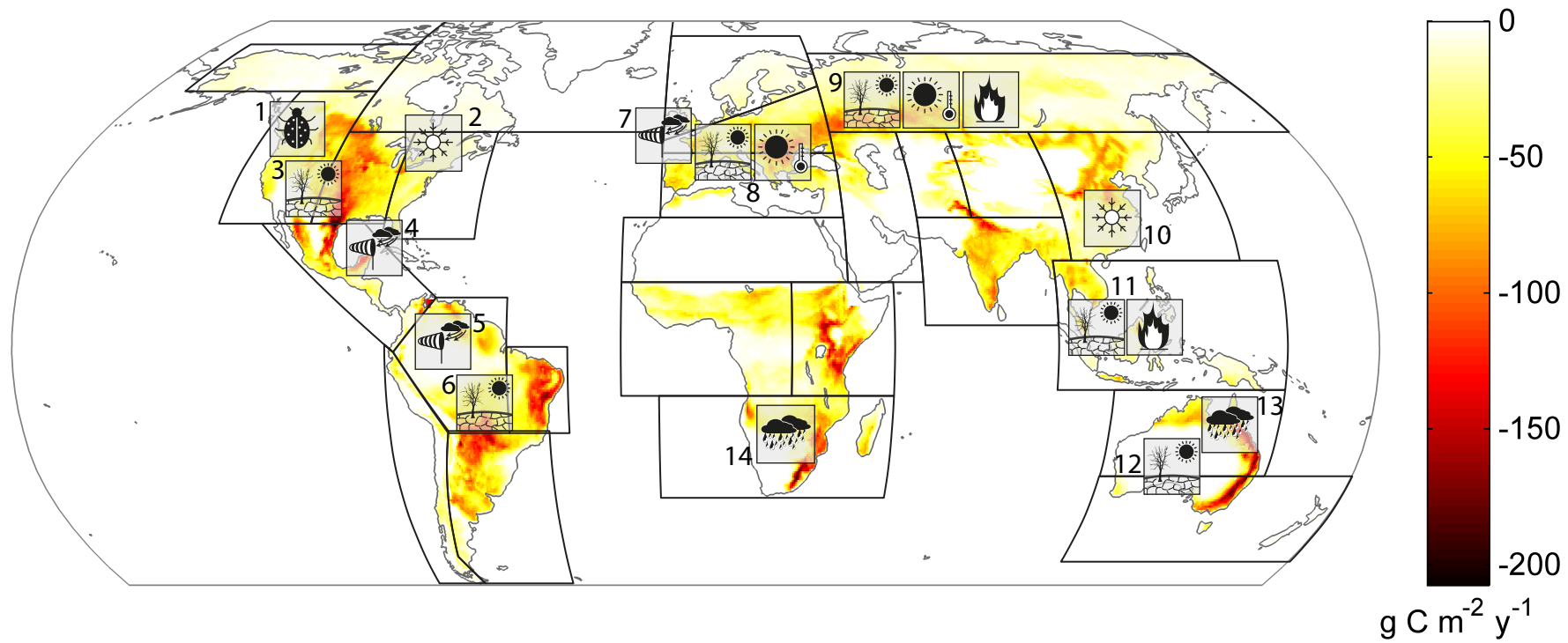


indirect impacts



climate extreme    **F** frost extreme    **H** heat extreme    **D** drought    **P** heavy precipitation    **S** heavy storms

respective references are indicated by numbers in legend



## 1 **Supporting Information S1**

2 Supporting information S1 provides a literature survey about how climate extremes may  
3 possibly act on forests (A), grasslands (B), peatlands (C) and croplands (D).

### 4 **A. Forests**

5 Forests cover about 30% of the global land area and play an important role in the global  
6 carbon cycle (Canadell & Raupach, 2008; FAO, 2010; Pan *et al.*, 2011). In addition to their  
7 large carbon pools and fluxes, characteristics of forests that likely make them susceptible to  
8 climate extremes, in terms of the terrestrial carbon cycle, include:

- 9 - the long lifespan of individual organisms that store carbon in living tissues, structural and  
10 hydraulic infrastructures
- 11 - location of meristems where (re)growth can happen after an extreme event,
- 12 - a high sensitivity to diverse climatic extremes at multiple spatiotemporal scales
- 13 - lagged physiological and cascading ecological processes leading to long-term changes in  
14 growth and/or mortality
- 15 - high vulnerability of carbon stocks and long recovery time to re-gain previous stocks  
16 following extreme event impacts
- 17 - low migration rates in response to environmental changes compared to short-living species

18 We hypothesize drought to be the primary control on both inter-annual variability of forest  
19 productivity and long-term tree survival. In trees, vulnerability to drought-induced hydraulic  
20 failure (Choat *et al.*, 2012, but see Klein *et al.*, 2014) may have both concurrent and lagged  
21 (often carbohydrate and mortality related) consequences for the carbon cycle. Besides  
22 hydraulic failure, tree mortality following drought and heat waves has been suggested to be  
23 caused by carbon starvation and / or cellular metabolism limitation (Adams *et al.*, 2009; Sala  
24 *et al.*, 2010; McDowell *et al.*, 2011, 2013). Repeated stress from one or multiple extreme

1 climate events in combination with non-climatic disturbances can lead to a long-term  
2 recovery-response of a forest or to a downward spiral into decline and mortality thereby  
3 enhancing negative impacts of drought on the carbon sequestration potential (Rouault *et al.*,  
4 2006; Sánchez-Salguero *et al.*, 2012).

5 Similar to temperate regions, drought is a significant driver of the physiology and carbon  
6 cycling of Mediterranean (Granier *et al.*, 2007; Schwalm *et al.*, 2012) and tropical forests  
7 (Tian *et al.*, 1998; Phillips *et al.*, 2009; Clark *et al.*, 2010). Tropical wet forest tree growth  
8 was found to be highly sensitive to the current range of dry season conditions and to moderate  
9 (1–2°C) variations in mean annual night-time temperature (Clark *et al.*, 2010). The severe  
10 droughts in the Amazon during 2005 and 2010 caused a significant large-scale increase in tree  
11 mortality with an estimated committed biomass carbon loss of up to 1.6 Pg C and 2.2 Pg C  
12 (Phillips *et al.*, 2009; Lewis *et al.*, 2011). However, a recent analysis (Cox *et al.*, 2013)  
13 suggests stronger resilience to warming than previously (Cox *et al.*, 2004) reported and  
14 radiocarbon evidence for living trees older than 1000 years demonstrates that trees have  
15 survived though several mega-El-Niño type droughts during the past millennium (Chambers  
16 *et al.*, 1998). Thus to our understanding it remains unclear how vulnerable and how close the  
17 Amazon or other tropical forests, which may be even more sensitive to drought (Meir &  
18 Woodward, 2010), are to climate driven biome shifts.

19 The 2003 European heat wave strongly affected the hydraulic balance in many tree species  
20 with symptoms ranging from partial crown necrosis to death (Martinez-Meier *et al.*, 2008,  
21 Eilmann *et al.*, 2009, 2011), whereas a positive growth response was observed at higher  
22 elevations across the Alps (Jolly *et al.*, 2005). Also, in boreal ecosystems, a positive  
23 temperature extreme during the growing season tends to result in enhanced productivity  
24 (Esper *et al.*, 2002; Babst *et al.*, 2013), but a positive temperature extreme occurring during

1 the winter will most likely tend to increase respiration, and therefore result in a loss of carbon  
2 from the ecosystem (Piao *et al.*, 2008).

3 Heavy snow fall may result in crown, stem breakage, and even fully uproot trees. Nykänen *et*  
4 *al.* (1997) estimated an average annual timber loss of  $4 \times 10^6$  m<sup>3</sup> across Europe due to snow  
5 damage. Spring and autumn snowfall (when deciduous trees still hold foliage) and snow  
6 temperatures around 0°C (high water content and enhanced abilities to accumulate) increase  
7 the likelihood of damage (Nykänen *et al.*, 1997) as do higher wind speeds (Valinger &  
8 Fridman, 1999).

9 Storms are considered to be the most important natural disturbance agent in temperate  
10 European forests and even a small increase in storm frequency could potentially lead to a  
11 long-term reduction of the carbon stock (Fuhrer *et al.*, 2006). The large storm “Lothar” in  
12 central Europe killed the equivalent of 16 Tg C tree biomass (Lindroth *et al.*, 2009), and  
13 hurricanes Katrina and Rita destroyed  $43.9 \pm 8.4$  Tg C and  $37.9 \pm 6.4$  Tg C of living biomass,  
14 respectively (Negrón-Juárez *et al.*, 2010a). Katrina alone caused a total biomass loss  
15 estimated around 50–140% of the net annual U.S. carbon sink of forest trees (Chambers *et al.*,  
16 2007).

17 Forest fires released around half of the average annual 2.0 Pg C globally emitted by fires  
18 between 1997 and 2009 (van der Werf *et al.*, 2010). Fire regimes are regarded as highly non-  
19 linear, where under extreme climate conditions the burnt area can increase by an order of  
20 magnitude (Sukhinin *et al.*, 2004; Vivchar, 2011). Lagged effects due to precipitation deficits  
21 overlaid with spring droughts caused extreme fire events in Siberian permafrost regions  
22 (Forkel *et al.*, 2012).

23 Outbreaks of forest insects damage around  $35 \times 10^6$  ha of forest annually primary in the  
24 temperate and boreal zones (FAO, 2010). Climate extremes may impact the outbreak strength,  
25 timing and frequency as well as the host plant resistance. The European 2003 heat wave

1 showed the importance of soil water status in tree resistance against pest attacks (c.f. Desprez-  
2 Lousteau *et al.*, 2006; Rouault *et al.*, 2006). In north-western North America favourable  
3 climate conditions, such as e.g. reduced minimum winter temperature (i.e. less cold extremes,  
4 cf. Fig. 3a, Fig.4), have resulted in the most extensive and severe bark beetle damages ever  
5 reported (Kurz *et al.*, 2008). Vast expanses of forest have become a net carbon source and this  
6 is predicted to persist at least until 2020.

7

## 8 B. Grasslands

9 Grasslands are characterized by high turnover rates and a rapid recovery from disturbance.  
10 Amongst the climate extremes, drought has the presumably largest effect on the carbon cycle  
11 of grasslands, with substantial implications also for society. For example, during the 2003  
12 summer drought in Central Europe, grassland production ceased completely in certain areas,  
13 resulting in an annual decrease of fodder production across Europe between 30% and 60%  
14 (EEA, 2005). Typically, drought effects are higher for above-ground productivity (e.g.  
15 Kahmen *et al.*, 2005; De Boeck *et al.*, 2011; Fay *et al.*, 2011) than for below-ground  
16 productivity, resulting in changes in carbon allocation belowground and an increased root-to-  
17 shoot ratio (e.g., Dukes *et al.*, 2005; Gilgen & Buchmann, 2009; Burri *et al.*, 2014). As for  
18 forests, soil respiration of grasslands decreases when soil moisture drops below critical  
19 thresholds (Knapp *et al.*, 2002; Bahn *et al.*, 2008; Joos *et al.*, 2010; Burri *et al.*, 2014), with  
20 consequences for annual soil respiration (Ma *et al.*, 2007; Bahn *et al.*, 2010). However,  
21 rainfall following drought may rapidly and strongly stimulate soil CO<sub>2</sub> emissions (Borken &  
22 Matzner, 2009), and in semi-arid grasslands may cause higher respiratory CO<sub>2</sub> losses than  
23 from the rest of dry season (Xu *et al.*, 2004).  
24 The magnitude and direction of carbon cycle responses to reduced precipitation and drought  
25 depend strongly on the climatic context and background soil moisture conditions. While in

1 semiarid and arid climates water availability severely limits ecosystem carbon acquisition  
2 (Hunt *et al.*, 2004) and soil respiratory carbon losses, the response in temperate conditions is  
3 less clear (Bloor *et al.*, 2010). In humid climates and under very wet conditions, reduced  
4 precipitation has even been shown to increase aboveground plant growth and ecosystem  
5 carbon uptake (Jaksic *et al.*, 2006; Gilgen & Buchmann, 2009; Peichl *et al.*, 2011).

6 In addition to the amount, seasonal variability and timing of precipitation and associated  
7 drought may strongly alter key carbon cycling processes and plant community composition  
8 (Knapp *et al.*, 2002; Harper *et al.*, 2005; De Boeck *et al.*, 2011). In fact, the timing of  
9 precipitation may affect carbon cycling even more strongly than changes in rainfall quantity  
10 (Chou *et al.*, 2008; Hovenden *et al.*, 2013). In dry grasslands, the effects from the combined  
11 timing and size of rainfall events are crucial (Thomey *et al.*, 2001) as these factors co-  
12 determine critical soil moisture thresholds (Vargas *et al.*, 2012).

13 Experiments on simplified sown experimental grasslands revealed a high recovery potential  
14 of plant growth (Zavalloni *et al.*, 2008; De Boeck *et al.*, 2011). High resilience of key plant  
15 ecophysiological processes as well as soil carbon fluxes after prolonged droughts was  
16 observed also in managed temperate grasslands (Gilgen & Buchmann, 2009; Joos *et al.*, 2010;  
17 Signarbieux & Feller, 2011). Furthermore, changes in vegetation structure and composition in  
18 response to drought can contribute to the resilience of grasslands, and may alter above- and  
19 belowground productivity and CO<sub>2</sub> fluxes (including their response functions to climate)  
20 beyond the direct physiological response (Kreyling *et al.*, 2008; Talmon *et al.*, 2011; van der  
21 Molen *et al.*, 2011), but might also result in increased weed pressure (Gilgen *et al.*, 2010).

22 Drought may have strong interactive effects with high temperatures, which increase water  
23 vapour pressure deficits and the soil water stress, and can amplify detrimental effects of  
24 drought on the physiology of organisms, e.g. during heat waves (Chaves & Oliveira, 2004; De  
25 Boeck *et al.*, 2011). An anomalously warm year was shown to exert both immediate and



1 lagged effects on the net ecosystem exchange of CO<sub>2</sub> of a tallgrass prairie (Arnone *et al.*,  
2 2008). This extreme decreased NEE immediately via drought effects on net primary  
3 productivity and in the following year by stimulating the respiration of soil heterotrophs. In a  
4 future climate, elevated CO<sub>2</sub> may buffer effects of drought on grassland productivity by  
5 increasing water use efficiency (Owensby *et al.*, 1997). The combination of warming,  
6 elevated CO<sub>2</sub> and limiting soil moisture may favour C<sub>4</sub> over C<sub>3</sub> grasses and may thereby result  
7 in higher productivity in semi-arid grasslands than expected (Morgan *et al.*, 2011).

8 Heavy rainfall, particularly after prolonged drought periods, can lead to degradation via soil  
9 erosion in already degraded grasslands that lack grass cover. While intense rainfall has less  
10 pronounced effects on erosion in grasslands and rangelands than in arable lands (van Oost *et*  
11 *al.*, 2007), once degradation feedbacks come into play, more frequent extreme events may  
12 contribute to a desertification of semi-arid to arid grassland particularly when (over-)grazing  
13 or fire act as an additional pressure. Heavy or prolonged rainfall can also cause water-logging  
14 in grasslands, affecting root mortality, forage quality and quantity, and ultimately vegetation  
15 composition.

16 Fires are an important factor of ecosystem dynamics in (sub-)tropical grasslands or  
17 savannahs, where the vegetation has adapted and co-evolved re-sprouting traits coinciding to  
18 a certain fire frequency (Pausas *et al.*, 2004, 2009). Fires in grasslands and savannahs  
19 contributed 44% to the total global fire carbon emissions during 2001–2009 due to frequent  
20 burning of large areas (van der Werf *et al.*, 2010). Due to vast regeneration of grasslands,  
21 fluxes and species composition can return to pre-fire conditions within a few months. Castaldi  
22 *et al.* (2010) observed that one month after burning a tropical grassland, CO<sub>2</sub> emissions were  
23 significantly lower in burned plots than in the control plots, but after eight months they no  
24 longer differed.

25

### 1 C. Peatlands

2 Peatlands contain in about 400 Mha between 400 to 600 Pg C (Frolking *et al.*, 2011); the  
3 carbon stored in peatlands is protected primarily by the prevailing environmental conditions  
4 that limit decomposition: low temperatures and/or high water levels (Freeman *et al.*, 2001),  
5 which makes peatlands hotspots in terms of potentially large feedbacks to global change.  
6 Peatlands are particularly susceptible to oxidation of the carbon stocks by fire and biological  
7 decomposition processes, which may be induced by drought. Fires cause immediate oxidation  
8 of large amounts of carbon stored in peat soils (van der Werf *et al.*, 2008; Hooijer *et al.*,  
9 2010), whereas droughts can substantially increase soil carbon efflux following soil aeration  
10 (Freeman *et al.*, 2001). Moreover, Sowerby *et al.* (2008) found a persistent stimulation of  
11 decomposition rates in a peatland experiment that was exposed to repeated summer droughts,  
12 which was confirmed by Couwenberg *et al.* (2010) for South-east Asia and Turetsky *et al.*  
13 (2011a) in northern peatlands. This persistent stimulation of soil decomposition was related to  
14 incomplete recovery of the soil moisture content upon rewetting, which was most likely due  
15 to increased soil hydrophobicity. Hence, legacy effects of drought and also of fire, which can  
16 increase soil hydrophobicity (Howell *et al.*, 2006), can substantially increase the impact of a  
17 particular extreme event on the large carbon stocks stored in peatlands.

18 Because of the vast quantities of carbon stored in organic soils (Tarnocai *et al.*, 2009; Page *et*  
19 *al.*, 2011), changes in depth of the water-table from drainage or from drought can expose  
20 large areas of carbon to rapid decomposition and decay.

21 We assume the vulnerability of peatland ecosystems to climate extremes to increase because  
22 of human land use change in tropical regions (Hooijer *et al.*, 2010), and because of chronic  
23 climate change in high-latitude regions (Turetsky *et al.* 2002; Turetsky *et al.*, 2011b).

24

### 25 D. Croplands

1 Climate variability and climate extremes strongly affect crop production and thus the long-  
2 term carbon balance. Lagged ecosystem impacts of more than one year are of minor  
3 importance in croplands; however, lagged impacts do occur due to adaptive changes in the  
4 management of arable systems linked to climate extremes and climate change. Indeed, human  
5 response to climate extremes, in terms of adaptive management, is one of the greatest  
6 uncertainties when attempting to predict the impact of climate extremes on the carbon balance  
7 of croplands (Klein Goldewijk & Ramankutty, 2004; Porter & Semenov, 2005; Ramankutty *et*  
8 *al.*, 2008).

9 Efficient and effective agricultural practice requires that farmers adapt to climate variability.  
10 Climate extremes can impact crops via both negative impacts on plant physiological processes  
11 and direct physical damage, as well as by affecting the timing and conditions of field  
12 operations. The impact of a climate extreme on a certain crop is a function of the timing and  
13 type of climate extreme in relation to the sensitivity of the growth stage of the impacted crop  
14 (e.g. van der Velde *et al.*, 2012). Even during climate extremes, farmers will pursue strategies  
15 to minimize impacts on final crop harvests. Irrigation, for example, can be used during a heat  
16 wave to lower ambient field temperature (by ~3-4 °C at an ambient temperature >35 °C), thus  
17 minimizing crop heat stress and leading to lower crop losses than would otherwise occur (van  
18 der Velde *et al.*, 2010). The use of light-reflecting particle films sprayed over field crops and  
19 orchards is another adaptive measure (Glenn & Puterka, 2005). The use of kaolin powder, for  
20 instance, can effectively induce radiation loads and excessive heat during extreme events by  
21 increasing surface albedo, thus reducing physiological plant damage (Rosati *et al.*, 2006).  
22 Adaptive management actions can be immediate, but can also be longer term, such as the use  
23 of more heat resistant varieties, or changes in the rotation such as shifting to winter crops  
24 (Porter & Semenov, 2005; Lobell *et al.*, 2012; Ramankutty *et al.*, 2008). Adaptive  
25 management may lead to co-benefits or trade-offs; Increased irrigation e.g. may lead to

1 increased root biomass growth, higher microbial activity, or increased erosion rates, variously  
2 leading to either increased or decreased soil organic carbon levels. Expected crop failure – for  
3 instance a crop affected by drought – can also cause a farmer to decide not to harvest the crop,  
4 potentially leading to a larger incorporation of biomass into the soil.

5 Drought stress is one of the most damaging climate extremes affecting crop growth and  
6 productivity, especially if it occurs in connection with high temperatures. The 2003 heat wave  
7 in parts of Europe reduced crop yields by 20% compared to the mean for 1991-1999 (Fuhrer  
8 *et al.*, 2006). Farmers adapt to or mitigate against drought by irrigation. Globally, the area of  
9 irrigated land is increasing due to agricultural intensification with consequences for water  
10 resources (Nellemann *et al.*, 2009). Introduction of drought resistant crops as well as the use  
11 of perennial grain crops with deeper rooting systems (Glover *et al.*, 2010) is another important  
12 longer term adaptation strategy.

13 Long term effects of extreme high temperatures on crop growth and the associated carbon  
14 cycle are uncertain due to the complex interaction of different factors (although threshold  
15 temperatures for damage of enzymatic reactions and shifts in phenology are well defined;  
16 Porter & Semenov; 2005, Lobell *et al.*, 2012). An early effect of heat stress is a change in the  
17 photosynthetic pathways following protein damage, reducing the efficiency of photosynthesis.  
18 If exposure is long, protein damage and enzyme dysfunction become permanent and lead to  
19 irreversible plant damage or death. Effects of extreme high temperatures depend on crop type,  
20 variety and genotype, the development stage of the crop at the time of the event, the duration  
21 of the event, and its combination with other environmental stressors such as ozone (Fuhrer,  
22 2003). High temperatures shift and/or shorten the phenological development stages, which  
23 can also affect yield and biomass production (Larcher, 2003; Porter & Semenov, 2005; Lobell  
24 *et al.*, 2011, 2012). Heat stress can also decrease pollination efficiency and grain production  
25 by seed abortion, thereby decreasing yields. In addition to day-time temperature effects, crops

1 are also affected by high night-time temperatures, which increases the loss of carbon due to  
2 higher respiration rates, and thereby reduces yields in rice and cotton - but uncertainties  
3 concerning net carbon storage remain high (Peng *et al.*, 2004; Loka & Oosterhuis, 2010).

4 Although most of the above-ground biomass in croplands is removed during harvest, biomass  
5 production determines the amount of carbon entering the soil with above- and below-ground  
6 litter ultimately impacting soil organic carbon levels. However, high temperature can also  
7 affect the harvest index, increasing the uncertainty about the net effect of high temperature  
8 events (Porter and Semenov 2005). This is important as soil organic carbon represents the  
9 only long term carbon storage in croplands (Freibauer *et al.*, 2004; Smith 2004; Smith *et al.*,  
10 2010; Ciais *et al.*, 2010; Smith 2012). Importantly, soil organic carbon is in itself temperature  
11 sensitive, which makes the net storage in croplands an uncertain entity (Ciais *et al.*, 2010;  
12 Davidson & Janssens, 2006; Schulze *et al.*, 2009).

13 There are clear indications of the importance of frost damage in affecting changes in the  
14 carbon cycle, especially in winter crops (from plant damage to crop failure), but uncertainty  
15 remains high and evidence is too sparse to estimate the overall net effect (Bélanger *et al.*,  
16 2002; Gu *et al.*, 2008).

17 Heavy rain and storm events can destroy above-ground biomass by damage or destruction of  
18 the crop, and they can lead to erosion and dislocation of soil, and consequently soil organic  
19 carbon loss. Heavy rain can also lead to water logging of soils affecting plant roots,  
20 subsequently leading to suboptimal growth and carbon cycling in soils (Fuhrer *et al.*, 2006).

21 Nevertheless, contrasting crop responses to excess precipitation can also occur, for instance in  
22 2007 high summer precipitation rates in France led to low wheat yields but very high maize  
23 yields (van der Velde *et al.*, 2012). The excessive rain directly impacted the wheat crop, with  
24 excessive soil moisture favouring pest and disease development, increasing lodging, and  
25 reducing grain quality (Mars Bulletin, 2007), followed by poor field accessibility hindering

1 wheat harvest. By contrast, maize productivity was not affected and the dry conditions that  
2 followed the wet spell at the beginning of September 2007, coupled with high residual soil  
3 moisture levels, led to favourable conditions for maize –which in France is not harvested until  
4 mid-October (Mars Bulletin, 2007). Adaptive responses to extreme wind experienced during  
5 storms can include windbreaks, which can contribute to producer profitability and  
6 environmental quality (e.g. Brandle *et al.*, 2004), by protecting cropland fields against  
7 extreme wind impacts on crops and soil. During the 20<sup>th</sup> Century, shorter cereal varieties with  
8 a lower risk of lodging, have replaced taller varieties. Longer term adaptive management to  
9 high winds and heavy rainfall could involve shorter and sturdier varieties.

10 Mid-latitude regions (between about 30° and 50°) can experience hail events that may reach  
11 extreme intensities with the kinetic energy of hailstones proportional to the 4<sup>th</sup> power of their  
12 diameter (Eccel & Ferrari, 1997). Hail fall may cause severe defoliation in the majority of  
13 broad leaf crop species and in corn. Defoliations greater than 90% have been reported for corn  
14 and soybeans. Recent observations in the Eastern Alps show that hail intensities have  
15 significantly increased by 1.22–1.69% per year from 1975 to 2009 (Eccel *et al.*, 2012). The  
16 possibility to predict hail events is low as they may occur under diverse meteorological  
17 conditions (Garcia-Ortega *et al.*, 2011).

18 Tolerable natural soil erosion rates are generally lower than rates experienced in cropland.  
19 Current estimates of soil erosion rates in cropping systems are highly variable and amongst  
20 others dependent on slope and tillage practices. Best estimates suggest that soil erosion rates  
21 are about two to three magnitudes higher than the rate of soil formation through weathering  
22 and dust deposition (Pimentel & Kounang, 1998; Brantley *et al.*, 2007). Single events can  
23 have a substantial impact on sediment load over a given time period (e.g. Thothong *et al.*,  
24 2011). Indeed, single exceptional rainfall events can trigger extreme runoff and widespread  
25 erosion in areas normally not exposed to a high risk of erosion. In Norway, erosion events

1 (>100 tons ha<sup>-1</sup>) resulted from a combination of extreme rainfall, agricultural management  
2 practices, low vegetation cover and a saturated soil overlying a frozen subsoil (Øygarden,  
3 2003). In areas with an increased likelihood of extreme precipitation, erosion and loss of soil  
4 and soil organic carbon away from the impacted cropland is a risk. Also in this case, the use  
5 of perennial grain crops can be seen as possible adaptive measure, as those crops could  
6 potentially reduce the impact of extremes on erosion and soil degradation, NO<sub>3</sub> leaching, and  
7 soil carbon loss (Culman *et al.*, 2013). Their use requires, however, proper assessment of the  
8 net balance between the advantage of increased extreme event adaptation and the  
9 disadvantage of limited yield levels that can be achieved in the good years (Glover *et al.*,  
10 2010).

11 Fire is of minor importance with regard to the carbon balance of croplands globally.  
12 Agricultural waste burning contributed approx. 3% to the total global fire carbon emissions  
13 during 2001–2009 (van der Werf *et al.*, 2010). Reduction in litter input to the soil by burning  
14 can reduce soil organic carbon content (Lal, 2007), but the production and incorporation of  
15 charcoal in soil may have beneficial impacts (Skjemstad *et al.*, 2002); the net effect remains  
16 uncertain.

17 Climate change – specifically increased temperatures and wetness – is generally thought to  
18 spread pests and pathogens beyond their current range, and to introduce alien species into new  
19 croplands, as well as increasing their multiplication rates (Gregory *et al.*, 2009). For instance,  
20 the survival of *O. poecilus* (rice stink bug) is dependent on the off-season rainfall affected by  
21 ENSO (Sutherland & Baharally, 2003). The interactions between crops, pests and pathogens  
22 are complex and poorly understood in the context of climate change, but it is clear that crops  
23 will be more susceptible to pests and diseases if previously weakened by extreme  
24 temperature, drought or other adverse impacts (Gregory *et al.*, 2009). Weed-crop interactions  
25 will change, with positive or negative consequences for the crop, while weeds (like crops) can

1 benefit from a positive CO<sub>2</sub> fertilization effect (Patterson, 1995). In the context of food  
2 security, rodent outbreaks associated with an extreme event, cyclone Nargis, impacted  
3 agricultural production in Asia (Singleton *et al.*, 2010). The overall impact of pests and  
4 pathogens on crops, and the carbon balance of croplands remain uncertain.  
5



## 1 **References**

- 2 Arnone III JA, Verburg PSJ, Johnson DW *et al.* (2008) Prolonged suppression of ecosystem  
3 carbon dioxide uptake after an anomalously warm year. *Nature*, **455**, 383-386.
- 4 Babst F, Poulter B, Trouet V *et al.* (2013) Site- and species-specific responses of forest  
5 growth to climate across the European continent. *Global Ecology and Biogeography*, **22**, 706-  
6 717.
- 7 Bahn M, Rodeghiero M, Anderson-Dunn M *et al.* (2008) Soil respiration in European  
8 grasslands in relation to climate and assimilate supply. *Ecosystems*, **11**, 1352-1367.
- 9 Bahn M, Reichstein M, Davidson EA *et al.* (2010) Soil respiration at mean annual  
10 temperature predicts annual total across vegetation types and biomes. *Biogeosciences*, **7**,  
11 2147-2157.
- 12 Bahn M, Reichstein M, Dukes JS, Smith MD, McDowell NG (2014) Climate-biosphere  
13 interactions in a more extreme world. *New Phytologist*, **202**, 356-359.
- 14 Bélanger G, Rochette P, Castonguay Y, Bootsma A, Mongrain D, Ryan DAJ (2002) Climate  
15 change and winter survival of perennial forage crops in eastern Canada. *Agronomy Journal*,  
16 **94**, 1120-1130.
- 17 Bloor JMG, Pichon P, Falcimagne R, Leadley P, Soussana J-F (2010) Effects of warming  
18 summer drought and CO<sub>2</sub> enrichment on aboveground biomass production, flowering  
19 phenology, and community structure in an upland grassland ecosystem. *Ecosystems*, **13**, 888-  
20 900.
- 21 Brandle JR, Hodges L, Zhou XH (2004) Windbreaks in North American agricultural systems.  
22 *Agroforestry Systems*, **61-62**, 65-78.
- 23 Brantley SL, Goldhaber MB, Ragnarsdottir KV (2007) Crossing disciplines and scales to  
24 understand the critical zone. *Elements*, **3**, 307-314.
- 25 Burri S, Sturm P, Prechsl UE, Knohl A, Buchmann N (2014) The impact of extreme summer

- 1 drought on the short-term carbon coupling of photosynthesis to soil CO<sub>2</sub> efflux in a temperate  
2 grassland. *Biogeosciences* **11**, 961–975.
- 3 Canadell JG, Raupach MR (2008) Managing forests for climate change mitigation. *Science*,  
4 **320**, 1456-1457.
- 5 Castaldi S, de Grandcourt A, Rasile A, Skiba U, Valentini R (2010) CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O fluxes  
6 from soil of a burned grassland in Central Africa. *Biogeosciences*, **7**, 3459-3471.
- 7 Chambers JQ, Higuchi N, Schimel JP (1998) Ancient trees in Amazonia. *Nature*, **391**, 135-  
8 136.
- 9 Chaves MM, Oliveira MM (2004) Mechanisms underlying plant resilience to water deficits:  
10 prospects for water-saving agriculture. *Journal of Experimental Botany*, **55**, 2365-2384.
- 11 Choat B, Jansen S, Brodribb TJ *et al.* (2012) Global convergence in the vulnerability of  
12 forests to drought. *Nature*, **491**, 752-755.
- 13 Chou WW, Silver WL, Jackson RD, Thompson AW, Allen-Diaz B (2008) The sensitivity of  
14 annual grassland carbon cycling to the quantity and timing of rainfall. *Global Change Biology*,  
15 **14**, 1382-1394.
- 16 Ciais P, Wattenbach M, Vuichard N *et al.* (2010) The European Carbon Balance. Part 2:  
17 Croplands. *Global Change Biology*, **16**, 1409-1428.
- 18 Clark DB, Clark DA, Oberbauer SF (2010) Annual wood production in a tropical rain forest  
19 in NE Costa Rica linked to climatic variation but not to increasing CO<sub>2</sub>. *Global Change*  
20 *Biology*, **16**, 747-759.
- 21 Cox PM, Betts RA, Collins M, Harris PP, Huntingford C, Jones CD (2004) Amazonian forest  
22 dieback under climate-carbon cycle projections for the 21st century. *Theoretical and Applied*  
23 *Climatology*, **78**, 137-156.
- 24 Cox PM, Pearson D, Booth BB, Friedlingstein P, Huntingford C, Jones CD, Luke CM (2013)  
25 Sensitivity of tropical carbon to climate change constrained by carbon dioxide variability.

- 1 *Nature*, **494**, 341-344.
- 2 Culman SW, Snapp SS, Ollenburger M, Basso B, DeHaan LR (2013) Soil and water quality  
3 rapidly responds to the perennial grain kernza wheatgrass. *Agronomy Journal*, **105**, 735-744.
- 4 Dukes JS, Chiariello NR, Cleland EE *et al.* (2005) Responses of grassland production to  
5 single and multiple global environmental changes. *Plos Biology*, **3**, 1829-1837.
- 6 Eccel E, Ferrari P (1997) La grandine in Trentino: Risultati dell'analisi climatologica per il  
7 ventennio 1974-1993. *Quaderni di Esperienze & Ricerche, Istituto Agrario di S. Michele*, **3**.
- 8 Eccel E, Cau P, Riemann-Campe K, Biasioli F (2012) Quantitative hail monitoring in an  
9 alpine area: 35-year climatology and links with atmospheric variables. *International Journal*  
10 *of Climatology*, **32**, 503-517.
- 11 Eilmann B, Zweifel R, Buchmann N, Fonti P, Rigling A (2009) Drought-induced adaptation  
12 of the xylem in Scots pine and pubescent oak. *Tree Physiology*, **29**, 1011-1020.
- 13 Esper J, Cook ER, Schweingruber FH (2002) Low-frequency signals in long tree-ring  
14 chronologies for reconstructing past temperature variability. *Science*, **295**, 2250-2253.
- 15 European Environment Agency (EEA) (2005) *Vulnerability and Adaptation to Climate*  
16 *Change. Technical Report No. 7*, Copenhagen, European Topic Centre for Air and Climate  
17 Change (ETC/ACC).
- 18 Fay PA, Blair JM, Smith MD, Nippert JB, Carlisle JD, Knapp AK (2011) Relative effects of  
19 precipitation variability and warming on tallgrass prairie ecosystem function. *Biogeosciences*,  
20 **8**, 3053-3068.
- 21 Food and Agriculture Organization of the United Nations (FAO) (2010) Global Forest  
22 Resources Assessment 2010. Main Report. FAO Forestry Paper 163. Rome, Food and  
23 Agriculture Organization of the United Nations, 340 pp.
- 24 Forkel M, Thonicke K, Beer C, Cramer W, Bartalev S, Schmulius C (2012) Extreme fire  
25 events are related to previous-year surface moisture conditions in permafrost-underlain larch

- 1 forests of Siberia. *Environmental Research Letters*, **7**, Art. 044021.
- 2 Freibauer A, Rounsevell MDA, Smith P, Verhagen J (2004) Carbon sequestration in the  
3 agricultural soils of Europe. *Geoderma*, **122**, 1-23.
- 4 Fuhrer J (2003) Agroecosystem responses to combinations of elevated CO<sub>2</sub>, ozone, and global  
5 climate change. *Agriculture, Ecosystems und Environment*, **97**, 1-20.
- 6 García-Ortega E, López L, Sánchez JL (2011) Atmospheric patterns associated with hailstorm  
7 days in the Ebro Valley, Spain. *Atmospheric Research*, **100**, 401-427.
- 8 Gilgen AK, Signarbieux C, Feller U, Buchmann N (2010) Competitive advantage of *Rumex*  
9 *obtusifolius* L. might increase in intensively managed temperate grasslands under drier  
10 climate. *Agriculture, Ecosystems and the Environment*, **135**, 15-23
- 11 Glenn DM, Puterka GJ (2005) Particle films: a new technology for agriculture. *Horticultural*  
12 *reviews*, **31**, 1-44.
- 13 Glover JD, Reganold JP, Bell LW *et al.* (2010) Increased food and ecosystem security via  
14 perennial grains. *Science* **328**, 1638-1639.
- 15 Gregory PJ, Johnson SN, Newton AC, Ingram JSI (2009) Integrating pests and pathogens into  
16 the climate change/food security debate. *Journal of Experimental Botany*, **60**, 2827-2838.
- 17 Gu L, Hanson PJ, Mac Post W *et al.* (2008) The 2007 eastern US spring freezes: Increased  
18 cold damage in a warming world? *Bioscience*, **58**, 253-262.
- 19 Harper CW, Blair JM, Fay PA, Knapp AK, Carlisle JD (2005) Increased rainfall variability  
20 and reduced rainfall amount decreases soil CO<sub>2</sub> flux in a grassland ecosystem. *Global Change*  
21 *Biology*, **11**, 322-334.
- 22 Hovenden MJ, Newton PCD, Wills KE (2013) Seasonal not annual rainfall determines  
23 grassland biomass response to carbon dioxide. *Nature*, **511**, 583-586.
- 24 Howell J, Humphreys GS, Mitchell PB (2006) Changes in soil water repellence and its  
25 distribution in relation to surface microtopographic units after a low severity fire in eucalypt

- 1 woodland, Sydney, Australia. *Australian Journal of Soil Research*, **44**, 205-217.
- 2 Hunt JE, Kelliher FM, Mcseveny TM, Ross DJ, Whitehead D (2004) Long-term carbon  
3 exchange in a sparse, seasonally dry tussock grassland. *Global Change Biology*, **10**, 1785-  
4 1800.
- 5 Jaksic V, Kiely G, Albertson J, Oren R, Katul G, Leahy P, Byrne KA (2006) Net ecosystem  
6 exchange of grassland in contrasting wet and dry years. *Agricultural and Forest Meteorology*,  
7 **139**, 323-334.
- 8 Jolly WM, Dobbertin M, Zimmermann NE, Reichstein M (2005) Divergent vegetation growth  
9 responses to the 2003 heat wave in the Swiss Alps. *Geophysical Research Letters*, **32**,  
10 doi:10.1029/2005GL023252.
- 11 Joos O, Hagedorn F, Heim A, Gilgen AK, Schmidt MWI, Siegwolf RTW, Buchmann N (2010)  
12 Summer drought reduces total and litter-derived soil CO<sub>2</sub> effluxes in temperate grassland -  
13 clues from a <sup>13</sup>C litter addition experiment. *Biogeosciences*, **7**, 1031-1041.
- 14 Kahmen A, Perner J, Buchmann N (2005) Diversity-dependent productivity in semi-natural  
15 grasslands following climate perturbations. *Functional Ecology*, **19**, 594-601.
- 16 Klein T, Yakir D, Buchmann N, Grünzweig JM (2014) Towards an advanced assessment of  
17 the hydrological vulnerability of forests to climate change-induced drought. *New Phytologist*,  
18 **201** (3), 712-716.
- 19 Klein Goldewijk K, Ramankutty N (2004) Land cover change over the last three centuries due  
20 to human activities: the availability of new global data sets. *Geojournal*, **61**, 335-344.
- 21 Knapp AK, Fay PA, Blair JM *et al.* (2002) Rainfall variability, carbon cycling, and plant  
22 species diversity in a mesic grassland. *Science*, **298**, 2202-2205.
- 23 Kreyling J, Wenigmann M, Beierkuhnlein C, Jentsch A (2008) Effects of extreme weather  
24 events on plant productivity and tissue die-back are modified by community composition.  
25 *Ecosystems*, **11**, 752-763.

- 1 Kurz WA, Dymond CC, Stinson G *et al.* (2008) Mountain pine beetle and forest carbon  
2 feedback to climate change. *Nature*, **452**, 987-990.
- 3 Lal R (2007) Carbon management in agricultural soils. *Mitigation and Adaptation Strategies*  
4 *for Global Change*, **12**, 303-322.
- 5 Lobell DB, Schlenker W, Costa-Roberts J (2011) Climate trends and global crop production  
6 since 1980. *Science*, **333**, 616-620.
- 7 Loka DA, Oosterhuis DM (2010) Effect of high night temperatures on cotton respiration, ATP  
8 levels and carbohydrate content. *Environmental and Experimental Botany*, **68**, 258-263.
- 9 Ma SY, Baldocchi DD, Xu LK, Hehn T (2007) Inter-annual variability in carbon dioxide  
10 exchange of an oak/grass savanna and open grassland in California. *Agricultural and Forest*  
11 *Meteorology*, **147**, 157-171.
- 12 Mars Bulletin (2007) Forecast Update, 21 August. European Commission. Joint Research  
13 Centre, FU2007/05.
- 14 Martinez-Meier A, Sanchez L, Pastorino M, Gallo L, Rozenberg P (2008) What is hot in tree  
15 rings? The wood density of surviving Douglas-firs to the 2003 drought and heat wave. *Forest*  
16 *Ecology and Management*, **256**, 837-843.
- 17 McDowell NG, Ryan MG, Zeppel MJB, Tissue DT (2013) Improving our knowledge of  
18 drought-induced forest mortality through experiments, observations, and modeling. *New*  
19 *Phytologist*, **200**, 289-293.
- 20 Meir P, Woodward FI (2010) Amazonian rain forests and drought: response and vulnerability.  
21 *New Phytologist*, **187**, 553-557.
- 22 Morgan JA, LeCain DR, Pendall E *et al.* (2011) C<sub>4</sub> grasses prosper as carbon dioxide  
23 eliminates desiccation in warmed semi-arid grassland. *Nature*, **476**, 202-205.
- 24 Nellemann C, MacDevette M, Manders T, Eickhout B, Svihus B, Prins AG, Kaltenborn BP  
25 (2009) *The Environmental Food Crisis. The Environment's Role in Averting Future Food*

- 1 *Crises. A UNEP Rapid Response Assessment*, Birkeland Trykkeri AS, Norway, United  
2 Nations Environment Programme.
- 3 Owensby CE, Ham JM, Knapp AK, Bremer D, Auen LM (1997) Water vapour fluxes and  
4 their impact under elevated CO<sub>2</sub> in a C<sub>4</sub>-tallgrass prairie. *Global Change Biology*, **3**, 189-195.
- 5 Page SE, Rieley JO, Banks CJ (2011) Global and regional importance of the tropical peatland  
6 carbon pool. *Global Change Biology*, **17**, 798-818.
- 7 Patterson DT (1995) Weeds in a changing climate. *Weed Science*, **43**, 685-701.
- 8 Pausas JG, Bradstock RA, Keith DA, Keeley JE (2004) Plant functional traits in relation to  
9 fire in crown-fire ecosystems. *Ecology*, **85**, 1085-1100.
- 10 Pausas JG, Keeley JE (2009) A burning story: the role of fire in the history of life. *Bioscience*,  
11 **59**, 593-601.
- 12 Peichl M, Leahy P, Kiely G (2011) Six-year stable annual uptake of carbon dioxide in  
13 intensively managed humid temperate grassland. *Ecosystems*, **14**, 112-126.
- 14 Peng SB, Huang JL, Sheehy JE *et al.* (2004) Rice yields decline with higher night temperature  
15 from global warming. *Proceedings of the National Academy of Sciences of the United States*  
16 *of America*, **101**, 9971-9975.
- 17 Piao SL, Ciais P, Friedlingstein P *et al.* (2008) Net carbon dioxide losses of northern  
18 ecosystems in response to autumn warming. *Nature*, **451**, 49-52.
- 19 Pimentel D, Kounang N (1998) Ecology of soil erosion in ecosystems. *Ecosystems*, **1**, 416-  
20 426.
- 21 Rosati A, Metcalf SG, Buchner RP, Fulton AE, Lampinen BD (2006) Physiological effects of  
22 kaolin applications in well-irrigated and water-stressed walnut and almond trees. *Annals of*  
23 *botany*, **98**, 267-275.
- 24 Sala A, Piper F, Hoch G (2010) Physiological mechanisms of drought-induced tree mortality  
25 are far from being resolved. *New Phytologist*, **186**, 274-281.

- 1 Sánchez-Salguero R, Navarro-Cerrillo RM, Swetnam TW, Zavala MA (2012) Is drought the  
2 main decline factor at the rear edge of Europe? The case of southern Iberian pine plantations.  
3 *Forest Ecology and Management*, **271**, 158-169.
- 4 Schulze ED, Luysaert S, Ciais P *et al.* (2009) Importance of methane and nitrous oxide for  
5 Europe's terrestrial greenhouse-gas balance. *Nature Geoscience*, **2**, 842-850.
- 6 Signarbieux C, Feller U (2011) Non-stomatal limitations of photosynthesis in grassland  
7 species under artificial drought in the field. *Environmental and Experimental Botany*, **71**, 192-  
8 197.
- 9 Singleton GR, Belmain SR, Brown PR, Aplin KP, Htwe NM (2010) Impacts of rodent  
10 outbreaks on food security in Asia. *Wildlife Research*, **37**, 355-359.
- 11 Skjemstad JO, Reicosky DC, Wilts AR, McGowan JA (2002) Charcoal carbon in U.S.  
12 agricultural soils. *Soil Science Society of America Journal*, **66**, 1249-1255.
- 13 Smith P (2004) Carbon sequestration in croplands: the potential in Europe and the global  
14 context. *European Journal of Agronomy*, **20**, 229-236.
- 15 Smith P (2012) Agricultural greenhouse gas mitigation potential globally, in Europe and in  
16 the UK: What have we learnt in the last 20 years? *Global Change Biology*, **18**, 35-43.
- 17 Smith P, Jones M, Osborne B, Wattenbach M (2010) The carbon and greenhouse gas budget  
18 of European croplands. *Agriculture, Ecosystems and Environment*, **139**, V-VI.
- 19 Sukhinin AI, French NHF, Kasischke ES *et al.* (2004) AVHRR-based mapping of fires in  
20 Russia: New products for fire management and carbon cycle studies. *Remote Sensing of*  
21 *Environment*, **93**, 546-564.
- 22 Sutherland JP, Baharally V (2003) The influence of weather on the population dynamics of  
23 rice stink bug and the implications for integrated pest management. *International Journal of*  
24 *Pest Management*, **49**, 335-342.
- 25 Talmon Y, Sternberg M, Grünzweig JM (2011) Impact of rainfall manipulations and biotic



- 1 controls on soil respiration in Mediterranean and desert ecosystems along an aridity gradient.  
2 *Global Change Biology*, **17**, 1108-1118.
- 3 Tarnocai C, Canadell JG, Schuur EaG, Kuhry P, Mazhitova G, Zimov S (2009) Soil organic  
4 carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles*,  
5 **23**, GB2023, doi:2010.1029/2008GB003327.
- 6 Thomey ML, Collins SL, Vargas R, Johnson JE, Brown RF, Natvig DO, Friggens MT (2011)  
7 Effect of precipitation variability on net primary production and soil respiration in a  
8 Chihuahuan Desert grassland. *Global Change Biology*, **17**, 1505-1515.
- 9 Valinger E, Fridman J (1999) Models to assess the risk of snow and wind damage in pine,  
10 spruce, and birch forests in Sweden. *Environmental Management*, **24**, 209-217.
- 11 Vargas R, Collins SL, Thomey ML, Johnson JE, Brown RF, Natvig DO, Friggens MT (2012)  
12 Precipitation variability and fire influence the temporal dynamics of soil CO<sub>2</sub> efflux in an arid  
13 grassland. *Global Change Biology*, **18**, 1401-1411.
- 14 Vivchar A (2011) Wildfires in Russia in 2000-2008: estimates of burnt areas using the  
15 satellite MODIS MCD45 data. *Remote Sensing Letters*, **2**, 81-90.
- 16 Xu L, Baldocchi DD, Tang J (2004) How soil moisture, rain pulses, and growth alter the  
17 response of ecosystem respiration to temperature. *Global Biogeochemical Cycles*, **18**,  
18 GB4002, doi:4010.1029/2004GB002281.