Response to Referee #1's comments

In preparing this revision, we have fully considered the reviewer' comments and have revised the manuscript accordingly.

L16: suggest cutting "as evidenced by the ....topics."
L17, L19: replace "advancements" with "advances"
L19: cut ", but are not limited to,"
L27: awkward, ambiguous wording: "disentangle their relative effects" to "disentangle their [separate and combined] effects"
We have made these changes as suggested by the reviewer.

L30 to 33: wordy, should be stated more succinctly
We have rephrased this sentence for succinctness.

L 36 to 80: I found the use of IAV in MODIS GPP to be a somewhat awkward fit for the papers in the issue. Furthermore, I suggest reducing much of the text from lines 36 to 80, and quickly getting to the content of the present special issue.
We have replaced the interannual variability (IAV) map measured by standard deviation with the map measured by the coefficient of variation (CV; CV=standard deviation/mean). CV betters measures the IAV of carbon fluxes. We have also added a figure of the number of extreme annual values (i.e., outliers) (listed as Fig. 2). We identified the outliers on a per-pixel basis using the Boxplot concept. An outlier is defined as an annual GPP value that is either larger than the 75% quartile+1.5*interquartile range or smaller than the 25% quartile – 1.5 * interquartile range.

L 41: "Some tropical regions (ie...)" is awkward, maybe "IAV is particularly high in tropical regions such as ..."
This sentence has been removed because of the replacement of standard deviation with coefficient of variation (CV).

L 62: This is a fairly general set up and is not specific to the papers of this issue. You might cut or shorten this section, not because it's incorrect or irrelevant but only because a special issue preview might be best to quickly get to the review of the papers therein.
We have retained this paragraph as part of the brief summary of the literature on this topic.

L 64: "long-term observations" is vague, lacks a citation as example, and the sentence structure suggests that EC is long-term.
We added a citation for "long-term observations": Turner, M. G., Collins, S. L., Lugo, A. E., Magnuson, J. J., Rupp, T. S., and Swanson, F. J.: Disturbance dynamics and ecological response: The contribution of long-term ecological research, Bioscience, 53, 46-56.

L 65: Why cite Dong et al. 2011? This seems unrepresentative.
We replaced this reference with a global-scale cross-site synthesis study (Schwalm et al. 2010).

L 89: poor sentence structure, maybe "We highlight the findings in this special issue by grouping manuscripts that emphasize ..."
We have rephrased the sentence as suggested.

L92 to 96: This is somewhat awkward, almost seeming to undermine the usefulness of the works that are presented. I'd recommend saving the comment about need for work on interactive effects for the discussion of future research directions. Also, L92-93 seems redundant with L27, and has the same issue raised above regarding "relative effects".
We have removed these two sentences.

L 110: extreme low precipitation is a key facet of drought, not its opposite. Should this be modified to read "extreme [high] precipitation..." ?
Extreme precipitation events typically refer to exceptionally high precipitation events, and therefore we keep the use of "extreme precipitation events".

L 111 to 115: The setup to this paper's highlight seems to suggest that the study focuses on non-drought conditions. Why then does Line 114 note that soil respiration would decrease if soil moisture continued to decrease? The narrative reasoning is incongruous here and should be fixed.
We clarified that this study examined the response of soil respiration to both drought and extreme high precipitation.

L 120: Replace "positive" and "negative" with something clearer. What is a "positive" response of a biome? Is it higher GPP, higher Respiration, higher NEP, higher biodiversity?
We have rephrased the sentence to clarify that extreme precipitation is likely to increase aboveground net primary productivity (ANPP) of xeric biomes and to reduce ANPP of mesic biomes.

L 139 to 143: This statement does not seem to be justified. Winter and spring are not key seasons for metabolic activity in irrigated croplands so the leading statement about smaller effects on the overall annual carbon balance seems to be misleading.
We have removed this statement.

L 143 to 144: "Combined..." This comment about the importance of timing and magnitude does not appear to be a synthesis statement, pertaining to only one study of those highlighted in the special issue.
L 145 to 147: "[However], extreme temperature events occurr[ing] in the growing season could substantially alter carbon fluxes, while those events occurr[ing] during ..."
L 145 to 147: This statement seems to correct or more correctly state the one above (L139 to 143).
These two sentences are synthesis statements. We have listed them as a separate paragraph to avoid confusion. "occurred" has been replaced with "occurring".

L 155: Include citation to: Ghimire B, Williams CA, Collatz GJ, Vanderhoof M, Rogan J, Kulakowski D, Masek JG (2015) "Large Carbon Release from Bark Beetle Outbreaks across

Western United States Imposes Climate Feedback", Global Change Biology, doi: 10.11/gcb.12933.
This citation has been added.

L 159 to 160: clarify "benefit of herbivory to undamaged trees" and also, does this include understory non-tree species?
We have rephrased the sentence as follows: This study also indicates that the residual forest and the understory vegetation contributed to carbon uptake and could enable the forest to return to carbon neutrality at a faster rate than clear-cuts.

L 161 to 163: It seems the study highlighted here only looked at MPB and if so, how could it suggest that the impacts of herbivore outbreak depend on the type of herbivore?
This study (Mathys et al. 2013) only examined MPB. This study along with previous studies indicated that impacts of herbivore outbreak depend on the type of herbivore and the intensity of disturbance. We have made this clear in the revision.

L 166: It seems redundant to include NEP and "carbon exchange between the land and the atmosphere" given that NEP typically includes CO2 and that non CO2 carboncontaining molecules are rarely emphasized and do not seem to have been emphasized in the studies included in this special issue.
We have deleted "carbon exchange between the land and the atmosphere" to remove redundancy.

L 166: It might make sense to clarify what is meant by "subsequent changes in NEP" by noting the relevant processes such as respiration of disturbance-killed biomass, and any changes to net primary productivity.
We have clarified that the changes in NEP are due to changes in GPP and ecosystem respiration of the remaining live stand and the heterotrophic respiration of the damaged biomass.

L 173 to 174: Check the units on your trend, which should be Tg C yr-1 yr-1... 8 to 18 Tg C yr-1 is pretty big. Should this be over an interval of time?
The units are correct. This is a global-scale study. The rate of decreasing net carbon balance before the 1970s of the 20^{th} century was estimated to be 8 Tg C yr^{-1}, and the increasing rate was 18 Tg C yr^{-1} during the remainder of the 20^{th} century.

L 207: The geographic domain of the Zhou et al. study should be reported. Was it global? Was it in North America or Europe? The Amazon? The quantitative figures reported must be region specific.
This is a global-scale synthesis study. However, the sites are mainly distributed in North America and Europe. We have described this in the revision.

L 220 to 223: this statement is very general and does not offer much in the way of findings.
We have rephrased the statement.

L 222: "vulnerable" seems to be an odd term. All forests would be vulnerable only some are targeted because of economic value and modes of production.

We have rephrased this statement.

L 224: This heading "time since disturbance" does not appear to be a good fit for the studies highlighted below. You might think about a different heading / grouping.
We have changed the heading to "Disturbance legacy".

L 228: "near the site" is vague and unclear.
We have changed "near the site" to "at the site".

L 230: This paper does not seem to belong under the heading "Time since disturbance". Can it be better linked to the flow of the preview?
This paper examines vegetation recovery following fire disturbance and thus fits into this section.

L 232: Replace "found" with "supported the notion that". This is not a new finding, really, and is model based, so it seems somewhat out of place to state that it was "found".
We replaced "found" with "supported the notion that".

L 234: Maybe connect these sentences... "carbon sink conditions, highlighting the importance of ..."
We did not combine these two sentences because of the length of the combined sentence.

L 239 to 245: suggest cutting this paragraph. It seems out of place and is redundant with things already mentioned elsewhere, including an earlier highlight of the Wang et al. 2014 study. It has a discussion of its own with citations to works outside of the scope of the special issue and thus seems out of place.
This paragraph has been removed as suggested.

L 252: which two? Wang et al. is not described as supporting this statement, so the statement seems to apply only to the Bond-Lamberty et al. 2015 study.
We have clarified that this statement only applies to Bond-Lamberty et al. 2015.

L 256: Should there be a new heading here? Maybe "Challenges and Opportunities"?
This paragraph does not include discussion on extreme climate events, and therefore we have decided to keep it as a part of the *Disturbance legacy* sub-section.

L 265: "conforming" to "confirming"
L 274; "will likely help" to "are helping to", and cite (e.g. Williams et al. 2014). Williams CA, Collatz GJ, Masek J, Huang C, Goward S (2014) "Impacts of disturbance history on forest carbon stocks and fluxes: Merging satellite disturbance mapping with forest inventory data in a carbon cycle model framework", Remote Sensing of Environment, 151:57-71, http://dx.doi.org/10.1016/j.rse.2013.10.034.
These changes have been made.

Response to Referee #2's comments

In preparing this revision, we have fully considered the reviewer (Dr. M. van Oijen)' comments and have revised the manuscript accordingly.

This paper provides an introduction to a special issue of Biogeochemistry. The issue consists of 17 papers on the impact of extreme climatic events and disturbances on ecosystem carbon dynamics. Fifteen of the studies are on terrestrial ecosystems, one study is on mangroves and one on lakes. The papers differ strongly in their choice of ecosystem, research question and methodology. That raises the question: what is the purpose of providing an introduction to such a heterogeneous collection? The authors show (Fig. 2) that more than 200 papers are now being published each year on the response of carbon dynamics to extreme events and disturbances, so why do the 17 issue papers merit special attention? The obvious justification for such an introduction is that it provides an opportunity to place recent papers in context, i.e. review the state of the art and identify remaining research gaps. This is attempted in the paper but could be done more systematically, as discussed in the following.
We thank the reviewer for the constructive comments on our preface. We have revised the manuscript as suggested.

The first section of the paper ("Introduction") can be summarised as follows: (1) Interannual variability (IAV) of GPP is especially large in the tropics, (2) extreme events and disturbances can affect carbon dynamics and will become more frequent and intense in the future, (3) their impacts can be studied with measurements and models - and many papers are being published; the ones here were the outcome from AGU-sessions.
This is fine as far as it goes, with the possible exception of the text on IAV measured as multi-annual standard deviation of GPP (Fig. 1), which seems an unnecessary distraction. Extreme events are outliers, not standard deviations, and occur worldwide - and not just in the tropics.
We have replaced the interannual variability (IAV) map measured by standard deviation with the map measured by the coefficient of variation (CV; CV=standard deviation/mean). CV betters measures the IAV of carbon fluxes. We have also added a figure of the number of extreme annual values (i.e., outliers) (listed as Fig. 2). We identified the outliers on a per-pixel basis using the Boxplot concept. An outlier is defined as an annual GPP value that is either larger than the 75% quartile+1.5*interquartile range or smaller than the 25% quartile – 1.5 * interquartile range.

A brief analysis of the existing literature could be added to this introductory section, flagging up both what research has been done and what has not been done. Which ecosystem types, which extreme event types, which disturbances, at which locations and spatiotemporal scales have been studied so far, and which were overlooked? And which are likely to become more important in the future? Can we distinguish direct and indirect effects of disturbances and extreme events both on the same location and elsewhere? Do the 17 papers address any of the research gaps? I think the paper would gain from being more comprehensive and analytical - otherwise there is no added value compared to the special issue papers themselves. I understand that you want to keep the preface short, but you could delete the IAV-text and figure, replacing it with say 20-30 lines on the state of the art.
We agree that an overview of the literature would be of interest but, as noted in Figure 3 (originally listed as Figure 2), a large number of manuscripts have been published on the topic of

‘extreme events’ and on ‘disturbances’. Any brief summary of this body of literature would barely do it justice. We feel that in this instance, a full review paper may be able to adequately (but probably not comprehensively) synthesize existing literature. We highlight the novel findings of the manuscripts - this is designed to communicate the gaps in knowledge addressed by each. Instead, we improved Figure 1 to also include an outlier analysis as an alternate approach for identifying regions of the globe that are prone to annual GPP values that exceed the normal statistical range.

The final section ("Conclusions") states future research needs. Three topics are men-tioned: (1) studying interactions between extreme events and disturbances, (2) collecting more data on disturbances, (3) improving models for disturbances. Whilst these certainly constitute worthwhile efforts, they seem an arbitrary and small selection of topics; many others could have been mentioned. And are there no research needs left for extreme events rather than disturbances? Also, there is no discernible relationship between the three listed research needs and the 17 papers of the special issue, so it remains unclear what the papers collectively have contributed. For example, at least five of the 17 papers used models: if those models still need to be improved, does that disqualify their current results?
We have revised this section by adding research needs for extreme events. The need for further improve does not disqualify the current results of these models but indicates our understanding of the underlying mechanisms of extreme climate events and disturbances and their representation in models are still limited.

SPECIFIC COMMENTS

l. 36-37: The Introduction begins with discussion of "terrestrial biosphere" and "Terrestrial carbon fluxes". This suggests that the special issue only considers terrestrial ecosystems, which is not the case. Begin by setting the scene (what kind of studies are being introduced by you) before delving into details like the IAV.
We have removed “terrestrial”, and changed “terrestrial carbon fluxes” to “biospheric carbon fluxes”.

l. 41: Add a reference to the MODIS work.
We have added a reference for the MODIS data product (Zhao et al. 2005).

l. 99-100: Those reductions of 28 and 38% are for which period? During the event, the year following the event, : : :?
The drought reduced GPP and carbon sink by 28% and 38% in the drought year – 2012. We have clarified this.

l. 172-174: What happened around 1970 that caused the trend break?
l. 215-216: Here you explain what partial cutting is, after having discussed the impacts of it already on l. 207.
We have moved the explanation of partial cutting to where the phrase first appeared in the paragraph.

l. 231-238: This section seems to ignore the current understanding that it is increased N-deposition, not elevated CO2, that has increased forest sink strength.
We have explicitly mentioned that N deposition – a factor enhancing ecosystem carbon uptake was not explicitly considered, although the effects of nitrogen deposition carbon sink strength have been controversial (Magnani et al., 2007; Nadelhoffer et al., 1999).

l. 252: Which two studies?
We have clarified what this study only applies to Bond-Lamberty et al. 2015.

TECHNICAL CORRECTIONS

l. 24: Missing space after "by".
l. 28: Remove "layers".
We have made these changes.

l. 42: "the Amazon" should be "Amazonia".
l. 43, 45, 46: Remove "on the order".
l. 50-51: Remove "terrestrial"?
l. 59-61: "We can only : : : scales" can safely be removed.
l. 65: Replace "mechanistic responses" by "mechanisms underlying responses".
l. 71: Add "the" before "consequences".
l. 76: The total number increases by 200 articles per year, not 20. Replace "total" with "annual".
We have made these changes.

l. 82: AGU meeting: in which year(s)?
We have clarified that the AGU meeting was in 2011-2013.

l. 85-87: "We feel : : : change" can be removed.
We have retained this sentence as part of our evaluation of the authors' contribution..

l. 93-96: "That being said, : : : 2008": more waffling, please remove.
l. 110: Replace "have" with "has".
l. 145-146: replace "occurred" with "occurring".
l. 179: Remove "potential".
l. 182: Replace first dash with a space.
l. 201: Write "hurricanes".
l. 203: Remove "annual".
l. 256: Why write "data layers" instead of simply "data"? There is some GIS-jargon here (including the "polygons" of line 259 and two further "layers" in lines 290 and 292).
l. 260: "source of information".
l. 265: What does "conforming" mean?
l. 293: Remove "systematically".
These changes have been made as suggested.

Preface: Impacts of extreme climate events and disturbances on carbon dynamics

Jingfeng Xiao[1], Shuguang Liu[2], and Paul C. Stoy[3,4]

[1]Earth Systems Research Center, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824, USA

[2]U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center, Sioux Falls, SD 57198, USA

[3]Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, MT 59717, USA

[4]Institute on Ecosystems, Montana State University, Bozeman, MT 59717, USA

Correspondence to: J. Xiao (j.xiao@unh.edu)

Abstract The impacts of disturbances and extreme climate events and disturbances (ECE&D) on the carbon cycle have received growing attention in recent years. as evidenced by the increasing number of journal articles published on these topics. This special issue showcases a collection of recent advancesadvancements in understanding the impacts of ECE&D on disturbances and extreme events on the carbon cyclingcycle. Notable advancesadvancements include, but are not limited to, quantifying how harvesting activities impact forest structure, carbon pool dynamics, and recovery processes; observed drastic increases of the

concentrations of dissolved organic carbon and dissolved methane in thermokarst lakes in western Siberia duringin a summer warming event; disentangling the roles of herbivores and fire on forest carbon dioxide flux; direct and indirect impacts of fire on the global carbon balance; and improved atmospheric inversion of regional carbon sources and sinks by incorporatingbyincorporating disturbances. Combined, studies herein indicate several major research needs. First, disturbances and extreme events can interact with one another, and it is important to understand their overall impacts and also disentangle their relative effects on the carbon cycle. Second, current ecosystem models are not skillful enough to correctly simulate the underlying processes and impacts of ECE&D (e.g., tree mortality and carbon consequences). Third, benchmark data layers characterizing the timing, location, type, and magnitude of disturbances must be systematically created to improve our ability to quantify carbon dynamics over large areas. Finally, improving the representation of ECE&D in regional climate/earth system models and accounting for the resulting feedbacks to climate are essential for understanding the interactions between climate and ecosystem dynamics.Third, current ecosystem models are not skillful enough to correctly simulate the impacts of disturbances such as disturbance-induced tree mortality and its carbon consequences, and therefore must be improved to correctly represent underlying processes and impacts.

1 Introduction

The terrestrial biosphere plays an important role in regulating atmospheric carbon dioxide concentrations and thereby climate. ExtremeTerrestrial carbon fluxes often exhibit pronounced interannual variability (IAV), and disturbances and extreme climate events such as droughtare primary sources of IAV (Eimers et al., 2008; Reichstein et al., 2013; Xiao et al.,

Paul Stoy 5/15/2016 10:52 AM
Formatted: Don't adjust space between Latin and Asian text, Don't adjust space between Asian text and numbers

2014) and disturbances such as fire . For example, gross primary productivity (GPP) exhibited significant IAV over the period 2000-2014 on the global scale as identified by MODIS, with important regional differences (Fig. 1). Some tropical regions (e.g. Indonesia and parts of the Amazon) had the largest IAV with standard deviation in annual GPP on the order of 200-250 g C m^{-2} or greater, while the remaining vegetated areas in the tropics also had relatively large IAV in annual GPP (with standard deviations on the order of ~150 g C m^{-2}) and vegetated temperate regions had intermediate IAV (with standard deviation on the order of 80-120 g C m^{-2}). Extreme climate events such as drought (Xiao et al., 2009; Zhao and Running, 2010), hurricanes and disturbances such as fire (Bowman et al., 2009), wind stormshurricanes (Chambers et al., 2007; Dahal et al., 2014; Xiao et al., 2011), and insect outbreaks (Kurz et al., 2008a) can substantially alter ecosystem structure and function and influence terrestrial carbon dynamics. ECE&D are projected to increase in both frequency and severity during the remainder of the 21st century (IPCC, 2013), with important consequences for terrestrial carbon cycling. Projecting the impacts of these future events remains a challenge given the substantial uncertainty in forecasting these events and the insufficient representation of ECE&D in ecosystem and land surface models. A better understanding of the impacts of ECE&D on carbon dynamics across different ecosystems is essential for projecting ecosystem responses to future climate change and feedbacks to the climate system.

Biospheric carbon fluxes often exhibit pronounced interannual variability (IAV) and ECE&D are believed to be primary sources of the IAV (Eimers et al., 2008; Reichstein et al., 2013; Xiao et al., 2014), which can be pronounced. For example, gross primary productivity (GPP) exhibited significant IAV over the period 2000-2014 on the global scale as identified by the MODIS GPP product , wind storms (McCarthy et al., 2006), and insect outbreaks (Kurz et al., 2008) can substantially alter ecosystem structure and function and influence terrestrial carbon dynamics. A better understanding of the impacts of disturbances and extreme climate events on terrestrial carbon dynamics across different ecosystems is essential for projecting ecosystem responses to future climate change and feedbacks to the climate system.

Extreme climate events and disturbances are projected to increase in both frequency and severity during the remainder of the 21st century (IPCC, 2013), with important consequences for terrestrial carbon cycling. Projecting the impacts of these future events remains a challenge given the substantial uncertainty in forecasting these events and the insufficient representation of ecological disturbances and extreme climate events in ecosystem and land surface models. We can only make progress in this grand challenge in Earth system science by understanding how different ecosystems respond to different disturbances at different time scales.

Various approaches have been used to assess the impacts of disturbances and extreme climate events on ecosystem carbon dynamics. At the ecosystem scale, in-situ methods including field experiments (Barbeta et al., 2013), with important regional differences (Fig. 1). The IAV is measured by the coefficient of variation (CV), defined as the standard deviation divided by the mean. Australia and southern Africa had the largest IAV; the U.S. Great Plains, the U.S. Southwest, Alaska, India, part of the Tibetan Plateau, eastern Mongolia, Kazakhstan, the Sahel region, and eastern Amazon had intermediate IAV; the remaining regions had relatively low IAV.

Paul Stoy 5/15/2016 10:52 AM
Formatted: Font color: Auto

ECE&D can lead to exceptionally high or low annual carbon fluxes. We used the annual GPP data from the MODIS GPP product , long-term observations, and the eddy covariance technique (Amiro et al., 2010; Dong et al., 2011) to identify extreme GPP values (outliers) that exceed the statistical normal range presumably caused by extreme climate events and/or disturbances (Fig. 2). For each grid cell, the outliers of annual GPP over the period 2000-2014 were identified using interquartile range (IQR) and quartiles (Q1: 25% quartile; Q3: 75% quartile). The outliers on the higher end were determined as values beyond IQR + 1.5 × Q3, and the outliers on the lower end were identified as values below IQR – 1.5 × Q1. Outliers on the lower end were observed in parts of Europe, Russia, North America, the Amazonia, and Africa (Fig. 2). These exceptionally low annual GPP were likely caused by drought, extreme low temperature, fire disturbance, or harvesting. Outliers on the higher end were observed in Alaska, the U.S. Southwest, Australia, and parts of the Amazonia and southern Africa (Fig. 2). These exceptionally high annual GPP were likely caused by exceptionally moist conditions and/or warm temperatures. The U.S. Great Plains and Kazakhstan had large IAV and outliers on the lower end; part of Australia and southern Africa also exhibited large IAV but had outliers on the higher end; the large IAV of GPP did not correspond to outliers for other regions (Figs. 1 and 2). The IAV of carbon fluxes was likely driven by both outliers and moderate to strong anomalies in fluxes.

seek to understand the mechanistic responses of ecosystem processes to disturbances and extreme climate events. Modeling approaches including process-based ecosystem models (Liu et al., 2011) or data-driven upscaling approaches (Jung et al., 2009; Xiao et al., 2008) have been used for regional to global assessments, which also rely heavily on satellite remote sensing (e.g. Xiao et al, 2014). Synthesizing these findings is an ongoing challenge, and multiple approaches are required to understand consequences of different extreme climate events and disturbances for carbon cycling.

The impacts of ECE&Ddisturbances and extreme climate events on carbon dynamics have received growing attention. We searched the number of journal articles on these topics using Web of Science (Fig. 32) and found a total of 497421 and 15931495 journal articles for extreme climate events and disturbances, respectively, over the period from 2000 to 20152014. Notably, the annualtotal number of publications on the impacts of these events on carbon dynamics has been growing at an average rate of 18 articles per year from 2000 to 2015 and at an average rate of 2520 articles per year over the past decade (2006-20152005-2014) (Fig. 2), emphasizing the growing scientific interest in these important topics.

Various approaches have been used to assess the impacts of ECE&D on ecosystem carbon dynamics. At the ecosystem scale, in-situ methods including field experiments (Barbeta et al., 2013), long-term observations (Turner et al., 2003), and the eddy covariance technique (Amiro et al., 2010; Schwalm et al., 2010) seek to understand the mechanisms underlying responses of ecosystem processes to ECE&D. Modeling approaches including process-based ecosystem models (Liu et al., 2011) or data-driven upscaling approaches (Jung et al., 2009; Xiao et al., 2008) have been used for regional to global assessments, which also rely heavily on satellite remote sensing (Xiao et al., 2014). Synthesizing these findings is an ongoing challenge, and multiple approaches are required to understand the consequences of different ECE&D for carbon cycling.

Spatially, the locations of the previous research activities have been largely aligned with the geography of the occurrence of ECE&D. For example, we have witnessed pronounced impacts of insect outbreaks and fires in the northern Rocky Mountains (Hicke et al., 2012b; Kurz et al., 2008b; Law et al., 2004), the widespread deforestation in Amazon and other tropical regions (Achard et al., 2014; DeFries et al., 2002; Harris et al., 2012), peatland fires in Indonesia (Page et al., 2002; Turetsky et al., 2015), tropical cyclones in the United States (Dahal et al., 2014a), and drought and heat waves in Europe (Bréda et al., 2006; Ciais et al., 2005a; Reichstein et al., 2007) and the southwestern United States (Allen et al., 2010a; Carnicer et al., 2011; Zeppel et al., 2013). Temporally, most of the research has been on the impacts of individual ECE&D, with fewer studies involving long-term observations and monitoring records (Dahal et al., 2014a; Seidl et al., 2014). Abundant evidence has been collected globally in the past decades on increased tree mortality resulting from climate events such as prolonged mega droughts and heat waves (Allen et al., 2010a; McDowell, 2011; Meddens et al., 2015; Meir et al., 2015). However, the mechanisms behind this increased mortality and the consequences on carbon dynamics still remain to be unveiled (Meddens et al., 2015; Meir et al., 2015).

The present special issue is the outcome of special sessions on the impacts of ECE&Dextreme climate events and disturbances on carbon dynamics at the American Geophysical Union Fall Meeting (2011-2013). This issue. It consists of 17 articles: 6 on extreme climate events and 11 on disturbances. This special issue, along with the special issue on climate extremes and biogeochemical cycles in *Biogeosciences* (Bahn et al., 2015), reflects recent advances in assessing how ECE&Ddisturbances and extreme climate events influence terrestrial carbon cycling. We feel that the authors have provided a timely and valuable contribution to the research communities of carbon cycle and global change.

2 Methods and Findings

We highlight the findings in this special issue by grouping manuscripts that emphasizeWe separate the impacts of drought and extreme precipitation events, herbivory (namely insect outbreaks), fire, interactions between herbivory and fire, natural hazards (e.g. hurricanes and typhoons), and forest management. when describing the findings of the manuscripts in this special issue. These events interact with one another as noted, and it can be difficult to disentangle their relative effects on the carbon cycle. That being said, it is important to study and synthesize how different extreme events and disturbances impact carbon cycling in our quest to understand every aspect of of the carbon cycle (Baldocchi, 2008).

Drought and extreme precipitation events

Piayda et al. (2014) quantified the impacts of the extreme drought event in 2012 on carbon and water cycling in a Mediterranean woodland. The drought reduced overstory GPP in 2012 by 28% and carbon sink strength by 38% compared to 2011. Results indicated that successful simulation of drought effects on the montado ecosystem requires the incorporation of variable apparent maximum carboxylation rate, stomatal conductance, and vapor pressure deficit sensitivity into photosynthesis-stomatal conductance modeling.

The simulations of a process-based ecosystem model showed that drought from 2000 to 2011 led to significant reduction in both GPP and net ecosystem productivity (NEP)NEP of China's terrestrial ecosystems at regional to national scales (Liu et al., 2014). Relative to the long-term mean, the nationwide annual NEP in 2001, 2006, 2009, and 2011 decreased by *ca*. 63, 88, 170, and 61 Tg C yr^{-1}, respectively, due to droughts (Liu et al., 2014). These two studies were consistent with several previous synthesis and modeling studies indicating that severe droughts could reduce annual GPP and net ecosystem productivity (NEP), and the reduction in NEP was largely driven by the decrease in GPP due largely to reductions in GPP due largely to reductions in GPP (Ciais et al., 2005; Schwalm et al., 2010; Xiao et al., 2009).

The opposite of drought – extreme precipitation events - have received less attention in carbon cycle studies. Jiang et al. (2013) conducted a field experiment in three subtropical forests to study the responses of soil respiration to both drought and extreme high precipitation and found that altered precipitation strongly influenced soil respiration not only by controlling soil moisture but also by modifying moisture and temperature sensitivity of soil respiration. Their results indicate that soil respiration was more sensitive to of these subtropical forests would decrease if soil moisture continues to decrease in the presence of drought, andfuture; higher precipitation in the wet season could have a limited effect on the response of soil respiration to rising temperatures (Jiang et al., 2013).

Zeppel, Wilks, and Lewis (2014) reviewed studies of extreme precipitation and seasonal changes in precipitation on carbon metabolism in grassland and forested ecosystems. They found that extremely highon average xeric biomes are likely to respond positively to extreme precipitation is likely to increase aboveground net primary productivity (ANPP) of xeric biomes and reduce ANPP of, but mesic biomes. Changes are likely to respond negatively, and that changes in precipitation during the growing season are likely to have a greater impact on carbon cycle dynamics than precipitation during the non-growing season (Zeppel et al., 2014). These studies indicated that the direction and magnitude of the impacts of extreme precipitation events on carbon fluxes depend on the season (wet versus dry) and biome type (xeric versus mesic).

Extreme temperature events

Extreme temperature events have been a feature of recent climate change, especially at high latitudes (IPCC, 2013). Previous studies showed that extreme temperature events often reduce GPP and NEP of terrestrial ecosystems (Ciais et al., 2005; Qu et al., 2016). The effects of extreme temperature on the carbon dynamics of aquatic ecosystems, however, have received little attention. Pokrovsky et al. (2013) studied the impacts of the 5 – 15 °C summer warming event of 2012 on the carbon dynamics of thermokarst lakes in western Siberia. Dissolved organic carbon concentrations increased by a factor of two as a result of the warming event despite limited changes in conductivity and pH, and the concentration of dissolved methane increased by nearly fivefold (Pokrovsky et al., 2013). These results demonstrate a substantial increase in the methane emission capacity from lakes as a result of summertime warming in areas of permafrost thaw.

Unknown
Field Code Changed

De Simon et al. (2013) examined the effects of manipulated warmer or cooler late winter/early spring conditions on the carbon budget and yield of soybean crops. Their results demonstrate that extreme temperature events in late winter did not result in significant changes in the net carbon balance , indicating that increasing heat and cold waves might have smaller effects on the overall annual carbon balance of irrigated croplands than expected (De Simon et al., 2013). These events may have larger impacts on natural ecosystems by advancing or delaying leaf-out dates.

. Combined, these studies indicate that the effects of extreme temperature events on ecosystem carbon dynamics depend on the timing and magnitude of these events. Extreme temperature events occurringoccurred in the growing season could substantially alter carbon fluxes, while those events occurringoccurred during the remainder of the year had smaller effects than expected.

Insect outbreaks

The coniferous forests of western North America have experienced an unprecedented herbivore outbreak over millions of hectares over the past decades (Hicke et al., 2012; Raffa et al., 2008), part of the global tree die-off due to the combined effects of elevated temperatures, drought, and associated herbivory (Allen et al., 2010). Measurements of the impacts of this disturbance at the site scale find minimal ecosystem carbon loss or even net uptake shortly after eruptive herbivory (Brown et al., 2010), which contrasts regional estimates of substantial carbon losses to the atmosphere (Ghimire et al., 2015; Kurz et al., 2008a).(Kurz et al., 2008). Mathys et al. (2013) in this issue used the eddy covariance technique to study carbon dioxide flux after a mountain pine beetle (*Dendroctonus ponderosae*, Hopkins) attack over a two-year period and compared these to an adjacent clearcut. They found that the mountain pine beetle-damaged forest was a carbon sink of *ca.*

Paul Stoy 5/15/2016 10:52 AM
Formatted: Space Before: 0 pt

Paul Stoy 5/15/2016 10:52 AM
Formatted: Font color: Auto

50 g C m^{-2} $year^{-1}$ two years after attack. This study also indicates that the residual forest and the understory vegetation contributed to carbon uptake and could enable the forest to return to carbon neutrality at a faster rate than clearcuts. The and suggested that benefit of herbivory to undamaged trees needs to be accounted for when considering ecosystem-scale carbon cycle consequences of herbivory (Mathys et al., 2013). These observations suggest that the impacts of herbivore outbreak depend on the type of herbivore (e.g. foliavores *versus* phloem-feeders) and the intensity of disturbance (Allen et al., 2010b; Brown et al., 2010; Ghimire et al., 2015; Hicke et al., 2012a; Kurz et al., 2008a; Mathys et al., 2013; Raffa et al., 2008)..

Fire

Fire causes direct and immediate carbon emissions into the atmosphere from biomass burning (the direct effect), and subsequent changes in NEP (the indirect effect) through changes in GPP and ecosystem respiration of the remaining live stand and the heterotrophic respiration of the damaged biomass.and carbon exchange between the land and the atmosphere (the indirect effect). Li et al. (2014) in this special issue provided a quantitative assessment of the direct and indirect impacts of fire on the net carbon balance of global terrestrial ecosystems during the 20th century. Their results show that fire decreased the net carbon gain of global terrestrial ecosystems by 1.0 Pg C yr^{-1} averaged across the 20th century, as a result of the fire direct effect (1.9 Pg C yr^{-1}) partly offset by the indirect effect (−0.9 Pg C yr^{-1}). The effect of fire on the net carbon balance significantly declined until 1970 with a trend of 8 Tg C yr^{-1} due to an increasing indirect effect, and increased subsequently with a trend of 18 Tg C yr^{-1} due to an increasing direct effect (Li et al., 2014). These results help constrain the global-scale dynamics of fire and the terrestrial carbon cycle.

Insect outbreaks versus *fire*

Paul Stoy 5/15/2016 10:52 AM
Formatted: Font color: Auto

Paul Stoy 5/15/2016 10:52 AM
Formatted: Font color: Custom Color(RGB(0,112,192))

Paul Stoy 5/15/2016 10:52 AM
Formatted: Space Before: 0 pt, After: 0 pt

At the regional scale, Caldwell et al. (2013) simulated and evaluated the long-term impacts of the two characteristic disturbances in the Southern Rocky Mountains forests (i.e., the outbreak of mountain pine beetle and high-severity wildfire) on potential changes in species composition and carbon stocks. Wildfire caused larger changes in both patterns of succession and distribution of carbon among biomass pools than did mountain pine beetle disturbance; carbon in standing -live biomass returned to pre-disturbance levels after 50 versusvs. 40 years following wildfire and mountain pine beetle disturbances, respectively (Caldwell et al., 2013).

Unknown
Field Code Changed

Clark et al. (2014) used the eddy covariance technique to study the impacts of fire and gypsy moth (*Lymantria dispar* L.) disturbance in oak-dominated, pine-dominated, and mixed forests in eastern North America. The net ecosystem exchange (NEE),, GPP, and water use efficiency were of greater magnitude in the oak-dominated forest before disturbance during summer. Water use efficiency declined by 60% at the oak-dominated stand and by nearly 50% at the mixed stand after gypsy moth disturbance, but prescribed fire had little impact on water use efficiency in the mixed or pine stands (Clark et al., 2014). These results demonstrate the importance of forest type, disturbance type, and time since disturbance on coupled carbon and water cycle functioning in temperate forests.

Hurricanes and typhoons

Hurricane events in the U.S. have significant effects on regional carbon dynamics (Dahal et al., 2014b).(Dahal et al., 2014). Typhoons are natural disturbances to subtropical mangrove forests in Asia, and their effects on ecosystem carbon dynamics of mangroves are not well understood. Chen et al. (2014) examined the short-term effects of frequent strong typhoons on defoliation and the NEE of subtropical mangroves. The responses of daily NEE following typhoons were highly variable in mangrove ecosystems (Chen et al., 2014), demonstrating that the characteristics of the typhoon and antecedent ecosystem conditions are important for understanding hurricane impacts on carbon stocks and fluxes. Severe hurricaneshurricane and typhoons that destroy a large number of trees could have significant effects on regional carbon cycling, while those that lead merely to defoliation likely had transient effects on annual ecosystem carbon exchange.

Forest management

Accurate quantification of the effects of partial cutting or clearcutting is essential for a better understanding of forest carbon dynamics and for informing forest management. Zhou et al. (2013a) conducted a meta-analysis on the impacts of partial cutting (i.e., cutting events with aboveground biomass removal rate < 90%) on forest carbon stocks by collecting data on cutting intensity, forest structure, and carbon stock components. This is a global-scale meta-analysis, but the majority of the sites are distributed in the U.S. and Europe. The results showed that partial cutting reduced aboveground carbon by 43% and increased understory carbon storage by nearly 400% on average, but did not have significant effects on forest floor or mineral soil carbon stocks (Zhou et al., 2013a). This effort provides a new perspective on the impacts of forest harvesting as it covers the spectrum of harvest disturbances from partial cutting to clearcut and goes beyond previous reviews that mostly concentrated on the impacts of clearcutting (Johnson and Curtis, 2001; Nave et al., 2010). The impacts of partial cutting can be significant; for example, partial cutting (i.e., cutting events with aboveground biomass removal rate < 90%) accounted for about three quarters of the total C loss from timber harvesting in the eastern United States from 2002 to 2010 (Zhou et al., 2013b).

Unknown
Field Code Changed

Wang et al. (2014) used a process-based forest ecosystem model, PnET-CN, to evaluate how clearcutting alters ecosystem carbon fluxes, biomass, and leaf area index in northern temperate forests. They found that harvest disturbance in northern temperate forests had significant effects on forest carbon fluxes and stocks, and increased harvesting intensity would delay the recovery of NEP. Evergreenevergreen needleleaf forests were slowermore vulnerable to recover to full carbon assimilation capacity after stand-replacing harvests than deciduous broadleaf forests (Wang et al., 2014). Future modeling studies of disturbance effects should incorporate forest population dynamics (e.g., .

Disturbance legacy

Time since disturbance

The time since disturbance is an important controlling factor of carbon dynamics. Berryman et al. (2013) tested the impacts of experimental pinyon pine (*Pinus edulis* Englem.) mortality on microbial respiration. They found that litter respiration responded to water availability at both treatment and control sites, and that soil respiration decreased atnear the site with experimental mortality. These results demonstrate ecosystem-level consequences of tree mortality that differs as a function of water availability (Berryman et al., 2013).

Yue et al. (2013) compared observations from post-fire vegetation trajectories in the boreal forest with simulations from the process-based ORCHIDEE vegetation model and supported the notionfound that the increase in atmospheric CO_2 concentrations andin addition to vegetation recovery were jointly responsible for current carbon sink conditions. It should be noted that nitrogen deposition – a global change factor enhancing ecosystem carbon uptake was not explicitly considered, although the effects of nitrogen deposition carbon sink strength have been controversial (Magnani et al., 2007; Nadelhoffer et al., 1999). Nevertheless, theirTheir results highlight the importance of understanding how global change and disturbance events interact to determine current – and likely future – carbon cycle dynamics (Yue et al., 2013). These two studies demonstrate that the legacy of disturbance and environmental factors jointly control the carbon dynamics following disturbance.

Paul Stoy 5/15/2016 10:52 AM
Moved down [1]: regeneration and mortality) and relationships between age-related model parameters and state variables (e.g., leaf area index).

Unknown
Field Code Changed

Modeling approaches have been widely used to simulate ecosystem carbon dynamics following disturbance. Wang et al. (2014) in this special issue simulated the dynamics of carbon fluxes and stocks following harvest. The simulated NEP and aboveground carbon stock after clearcutsclear-cuts generally followed the hypothesized trajectories (Chapin, 2011; Odum, 1969) while the decline in NEP was due to relatively stable GPP and gradually increasing ecosystem respiration (ER). Evergreen needleleaf forests recovered more slowly from a net carbon source to a net sink, and lost more carbon than deciduous broadleaf forests.

Disturbance-induced tree mortality regulates the forest carbon balance, but tree mortality and its carbon consequences are not well represented in ecosystem models (Bond-Lamberty et al., 2015). Bond-Lamberty et al. (2015) tested whether three ecosystem models – the classic big-leaf model Biome-BGC and the gap-oriented models ZELIG and ED - could reproduce the resilience of forest ecosystems to moderate disturbances. The models replicated observed declines in aboveground biomass well but could not fully capture observed post-disturbance carbon fluxes. This study indicatesThese two studies indicate that ecosystem models are yet unable to correctly simulate the effects of disturbances, and future modeling studies of disturbance effects should incorporate forest population dynamics (e.g., regeneration and mortality) and relationships between age-related model parameters and state variables (e.g., leaf area index)..

Paul Stoy 5/15/2016 10:52 AM
Moved (insertion) [1]

Lack of critical geospatial data layers on disturbances and associated impacts on ecosystems has been identified as one of the main challenges in quantifying carbon dynamics over large areas (Liu et al., 2011). Recently, a continental-scale forest stand age map was developed for North America using forest inventory data, large fire datapolygons, and remotely sensed data, providing a new source of information that can benefit quantification of the carbon sources and sinks across the continent and contribute to studies of disturbance (Pan et al., 2011). Deng et al. (2013) in this special issue used these continental stand age maps as an additional constraint to atmospheric CO_2 inversions. They found that regions with recently disturbed or old forests are often nudged towards carbon sources while regions with middle-aged productive forests are shifted towards sinks, confirmingconforming stand age effects observed from many eddy covariance flux towers (Deng et al., 2013). These results were generally consistent with the synthesis results from eddy covariance flux data across North America (Amiro et al., 2010) but they were inconsistent with some other studies showing that old-growth forests were still carbon sinks (Desai et al., 2005; Luyssaert et al., 2008). At the sub-continental level, their inverted carbon fluxes agreed well with continuous estimates of NEEnet ecosystem carbon exchange (NEE) upscaled from eddy covariance flux data (Xiao et al., 2008; 2011). Recent development in characterizing the timing, location, type, and magnitude of disturbances (Huang et al., 2010; Kennedy et al., 2010; Masek et al., 2013; Zhu and Woodcock, 2014) are helping to will likely help advance diagnosis and monitoring of carbon dynamics over large areas.

3 Conclusions

The contributions of this special issue reflect some of the most recent advances in the impacts of ECE&Ddisturbances and extreme climate events on carbon dynamics. These studies address the impacts of different types of extreme events including forest management, hurricanes and typhoons, drought, extreme precipitation events, extreme temperature events, insect outbreaks, and fire as well as ecosystem recovery since disturbance. The direction and magnitude of the effects of these events on ecosystem carbon fluxes depend on the nature of the events (type, duration, and intensity), the timing of the events (e.g., wet versus dry season, summer versus winter), and the biome type (e.g., xeric versus mesic). These events typically have negative effects on net carbon uptake while some events such as extreme precipitation events may also have positive effects on net carbon uptake depending on antecedent conditions and the nature of the extreme eventsevent.

Importantly, studies in this special issue collectively indicate several major research needs. First, ECE&Ddisturbances and extreme events can interact with one another, and it is important to disentangle their relative effects on the carbon cycle. Second, the lack of data layers on major disturbances is still one of the main challenges that hinder the improvement of quantifying carbon dynamics over large areas, and benchmark data layers characterizing the timing, location, type, and magnitude of disturbances must be systematically created. Third, current ecosystem models in general are not skillful enough to correctly simulate the impacts of ECE&Ddisturbances such as disturbance-induced tree mortality and its carbon consequences, and therefore ecosystem models must be improved to correctly represent the underlying processes and impacts (Liu et al., 2011; Reichstein et al., 2013). For example, the processes of drought effects on ecosystem respiration are not well represented in models. Third, the lack of data on major disturbances is still one of the main challenges that hinder the improvement of quantifying carbon dynamics over large areas, and benchmark data characterizing the timing, location, type, and magnitude of disturbances must be created. With the ongoing continuous monitoring of earth surface conditions using a constellation of satellites and emerging data mining technologies, the characterization and understanding of the impacts of ECE&D are expected to improve drastically over the next 5 to 10 years. However, major challenges still remain on how to translate those conditional changes into carbon fluxes and understand the specific roles of ECE&D in particular. Finally, besides carbon fluxes and stocks, other biogeophysical properties such as albedo, evapotranspiration (ET), and surface energy exchange are also altered by ECE&D. Improving the representation of ECE&D in regional climate/earth system models and accounting for the resulting feedbacks to the climate are essential for understanding the interactions between climate and ecosystem dynamics.. Ongoing research in these areas will continue to improve our emerging understanding of the impacts of ECE&Dextreme events on carbon cycling and the feedbacks to the climate.

Paul Stoy 5/15/2016 10:52 AM
Formatted: Font color: Auto

Acknowledgements

We would like to thank all of the scientists who contributed to this special issue. JX acknowledges support from the National Science Foundation (NSF) through the Emerging Frontiers Macrosystems Biology Program (award numbers 1065777) and the National Aeronautics and Space Administration (NASA) through the Carbon Cycle Science Program (award number NNX14AJ18G) and the Terrestrial Ecology Program (award number NNX12AK56G). PCS acknowledges the support of NSF Macrosystems Biology Program (award number 1241810), the NSF Division of Environmental Biology (award number 1552976) and the Alexander von Humboldt-Foundation. SL acknowledges the support from the U.S. Geological Survey Land Change Science Program. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. We thank Dr. M. van Oijen and an anonymous reviewer for their constructive comments on the manuscript.

References:

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D. D., Hogg, E. H., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J. H., Allard, G., Running, S. W., Semerci, A., and Cobb, N.: A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests, For. Ecol. Manage., 259, 660-684, 10.1016/j.foreco.2009.09.001, 2010.

Amiro, B. D., Barr, A. G., Barr, J. G., Black, T. A., Bracho, R., Brown, M., Chen, J., Clark, K. L., Davis, K. J., Desai, A. R., Dore, S., Engel, V., Fuentes, J. D., Goldstein, A. H., Goulden, M. L., Kolb, T. E., Lavigne, M. B., Law, B. E., Margolis, H. A., Martin, T., McCaughey, J. H., Misson, L., Montes-Helu, M., Noormets, A., Randerson, J. T., Starr, G., and Xiao, J.: Ecosystem carbon dioxide fluxes after disturbance in forests of North America, J. Geophys. Res., 115, 10.1029/2010jg001390, 2010.

Bahn, M., Reichstein, M., Guan, K., Moreno, J. M., and Williams, C.: Preface: Climate extremes and biogeochemical cycles in the terrestrial biosphere: impacts and feedbacks across scales, Biogeosciences, 12, 4827-4830, 10.5194/bg-12-4827-2015, 2015.

Baldocchi, D.: Breathing of the terrestrial biosphere: lessons learned from a global network of carbon dioxide flux measurement systems, Aust. J. Bot., 56, 1-26, 10.1071/bt07151, 2008.

Barbeta, A., Ogaya, R., and Penuelas, J.: Dampening effects of long-term experimental drought on growth and mortality rates of a Holm oak forest, Glob. Change Biol., 19, 3133-3144, 10.1111/gcb.12269, 2013.

Berryman, E., Marshall, J. D., Rahn, T., Litvak, M., and Butnor, J.: Decreased carbon limitation of litter respiration in a mortality-affected pinon-juniper woodland, Biogeosciences, 10, 1625-1634, 10.5194/bg-10-1625-2013, 2013.

Bond-Lamberty, B., Fisk, J. P., Holm, J. A., Bailey, V., Bohrer, G., and Gough, C. M.: Moderate forest disturbance as a stringent test for gap and big-leaf models, Biogeosciences, 12, 513-526, 10.5194/bg-12-513-2015, 2015.

Bowman, D., Balch, J. K., Artaxo, P., Bond, W. J., Carlson, J. M., Cochrane, M. A., D'Antonio, C. M., DeFries, R. S., Doyle, J. C., Harrison, S. P., Johnston, F. H., Keeley, J. E., Krawchuk, M. A., Kull, C. A., Marston, J. B., Moritz, M. A., Prentice, I. C., Roos, C. I., Scott, A. C., Swetnam, T. W., van der Werf, G. R., and Pyne, S. J.: Fire in the Earth System, Science, 324, 481-484, 10.1126/science.1163886, 2009.

Brown, M., Black, T. A., Nesic, Z., Foord, V. N., Spittlehouse, D. L., Fredeen, A. L., Grant, N. J., Burton, P. J., and Trofymow, J. A.: Impact of mountain pine beetle on the net ecosystem production of lodgepole pine stands in British Columbia, Agric. For. Meteorol., 150, 254-264, 10.1016/j.agrformet.2009.11.008, 2010.

Caldwell, M. K., Hawbaker, T. J., Briggs, J. S., Cigan, P. W., and Stitt, S.: Simulated impacts of mountain pine beetle and wildfire disturbances on forest vegetation composition and carbon stocks in the Southern Rocky Mountains, Biogeosciences, 10, 8203-8222, 10.5194/bg-10-8203-2013, 2013.

Chambers, J. Q., Fisher, J. I., Zeng, H. C., Chapman, E. L., Baker, D. B., and Hurtt, G. C.: Hurricane Katrina's carbon footprint on U. S. Gulf Coast forests, Science, 318, 1107-1107, 10.1126/science.1148913, 2007.

Chapin, F. S., Matson, P.A., Vitousek, P.M.: Principles of Terrestrial Ecosystem Ecology, Springer, New York, 2011.

Chen, H., Lu, W., Yan, G., Yang, S., and Lin, G.: Typhoons exert significant but differential impacts on net ecosystem carbon exchange of subtropical mangrove forests in China, Biogeosciences, 11, 5323-5333, 10.5194/bg-11-5323-2014, 2014.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogee, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A. D., Friedlingstein, P., Grunwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J. M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J. F., Sanz, M. J., Schulze, E. D., Vesala, T., and Valentini, R.: Europe-wide reduction in primary productivity caused by the heat and drought in 2003, Nature, 437, 529-533, 10.1038/nature03972, 2005.

Clark, K. L., Skowronski, N. S., Gallagher, M. R., Renninger, H., and Schafer, K. V. R.: Contrasting effects of invasive insects and fire on ecosystem water use efficiency, Biogeosciences, 11, 6509-6523, 10.5194/bg-11-6509-2014, 2014.

Dahal, D., Liu, S. G., and Oeding, J.: The Carbon Cycle and Hurricanes in the United States between 1900 and 2011, Scientific Reports, 4, 10.1038/srep05197, 2014.

De Simon, G., Alberti, G., Delle Vedove, G., Peressotti, A., Zaldei, A., and Miglietta, F.: Short-term cropland responses to temperature extreme events during late winter, Biogeosciences, 10, 5545-5553, 10.5194/bg-10-5545-2013, 2013.

Deng, F., Chen, J. M., Pan, Y., Peters, W., Birdsey, R., McCullough, K., and Xiao, J.: The use of forest stand age information in an atmospheric CO_2 inversion applied to North America, Biogeosciences, 10, 5335-5348, 10.5194/bg-10-5335-2013, 2013.

Desai, A. R., Bolstad, P. V., Cook, B. D., Davis, K. J., and Carey, E. V.: Comparing net ecosystem exchange of carbon dioxide between an old-growth and mature forest in the upper Midwest, USA, Agric. For. Meteorol., 128, 33-55, 10.1016/j.agrformet.2004.09.005, 2005.

Dong, G., Guo, J. X., Chen, J. Q., Sun, G., Gao, S., Hu, L. J., and Wang, Y. L.: Effects of spring drought on carbon sequestration, evapotranspiration and water use efficiency in the Songnen Meadow Steppe in Northeast China, Ecohydrology, 4, 211-224, 10.1002/eco.200, 2011.

Eimers, M. C., Buttle, J., and Watmough, S. A.: Influence of seasonal changes in runoff and extreme events on dissolved organic carbon trends in wetland- and upland-draining streams, Can. J. Fish. Aquat. Sci., 65, 796-808, 10.1139/f07-194, 2008.

Hicke, J. A., Allen, C. D., Desai, A. R., Dietze, M. C., Hall, R. J., Hogg, E. H., Kashian, D. M., Moore, D., Raffa, K. F., Sturrock, R. N., and Vogelmann, J.: Effects of biotic disturbances on forest carbon cycling in the United States and Canada, Glob. Change Biol., 18, 7-34, 10.1111/j.1365-2486.2011.02543.x, 2012.

Huang, C. Q., Coward, S. N., Masek, J. G., Thomas, N., Zhu, Z. L., and Vogelmann, J. E.: An automated approach for reconstructing recent forest disturbance history using dense Landsat time series stacks, Remote Sens. Environ., 114, 183-198, 10.1016/j.rse.2009.08.017, 2010.

IPCC: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Jiang, H., Deng, Q., Zhou, G., Hui, D., Zhang, D., Liu, S., Chu, G., and Li, J.: Responses of soil respiration and its temperature/moisture sensitivity to precipitation in three subtropical forests in southern China, Biogeosciences, 10, 3963-3982, 10.5194/bg-10-3963-2013, 2013.

Johnson, D. W. and Curtis, P. S.: Effects of forest management on soil C and N storage: meta analysis, For. Ecol. Manage., 140, 227-238, 10.1016/s0378-1127(00)00282-6, 2001.

Jung, M., Reichstein, M., and Bondeau, A.: Towards global empirical upscaling of FLUXNET eddy covariance observations: validation of a model tree ensemble approach using a biosphere model, Biogeosciences, 6, 2001-2013, 2009.

Kennedy, R. E., Yang, Z. G., and Cohen, W. B.: Detecting trends in forest disturbance and recovery using yearly Landsat time series: 1. LandTrendr - Temporal segmentation algorithms, Remote Sens. Environ., 114, 2897-2910, 10.1016/j.rse.2010.07.008, 2010.

Kurz, W. A., Dymond, C. C., Stinson, G., Rampley, G. J., Neilson, E. T., Carroll, A. L., Ebata, T., and Safranyik, L.: Mountain pine beetle and forest carbon feedback to climate change, Nature, 452, 987-990, 10.1038/nature06777, 2008.

Li, F., Bond-Lamberty, B., and Levis, S.: Quantifying the role of fire in the Earth system - Part 2: Impact on the net carbon balance of global terrestrial ecosystems for the 20th century, Biogeosciences, 11, 1345-1360, 10.5194/bg-11-1345-2014, 2014.

Liu, S. G., Bond-Lamberty, B., Hicke, J. A., Vargas, R., Zhao, S. Q., Chen, J., Edburg, S. L., Hu, Y. M., Liu, J. X., McGuire, A. D., Xiao, J. F., Keane, R., Yuan, W. P., Tang, J. W., Luo, Y. Q., Potter, C., and Oeding, J.: Simulating the impacts of disturbances on forest carbon cycling in North America: Processes, data, models, and challenges, J. Geophys. Res., 116, 10.1029/2010jg001585, 2011.

Liu, Y., Zhou, Y., Ju, W., Wang, S., Wu, X., He, M., and Zhu, G.: Impacts of droughts on carbon sequestration by China's terrestrial ecosystems from 2000 to 2011, Biogeosciences, 11, 2583-2599, 10.5194/bg-11-2583-2014, 2014.

Luyssaert, S., Schulze, E. D., Borner, A., Knohl, A., Hessenmoller, D., Law, B. E., Ciais, P., and Grace, J.: Old-growth forests as global carbon sinks, Nature, 455, 213-215, 10.1038/nature07276, 2008.

Masek, J. G., Goward, S. N., Kennedy, R. E., Cohen, W. B., Moisen, G. G., Schleeweis, K., and Huang, C. Q.: United States forest disturbance trends observed using Landsat time series, Ecosystems, 16, 1087-1104, 10.1007/s10021-013-9669-9, 2013.

Mathys, A., Black, T. A., Nesic, Z., Nishio, G., Brown, M., Spittlehouse, D. L., Fredeen, A. L., Bowler, R., Jassal, R. S., Grant, N. J., Burton, P. J., Trofymow, J. A., and Meyer, G.: Carbon balance of a partially harvested mixed conifer forest following mountain pine beetle attack and its comparison to a clear-cut, Biogeosciences, 10, 5451-5463, 10.5194/bg-10-5451-2013, 2013.

McCarthy, H. R., Oren, R., Kim, H. S., Johnsen, K. H., Maier, C., Pritchard, S. G., and Davis, M. A.: Interaction of ice storms and management practices on current carbon sequestration in forests with potential mitigation under future CO_2 atmosphere, J. Geophys. Res., 111, 10.1029/2005jd006428, 2006.

Nave, L. E., Vance, E. D., Swanston, C. W., and Curtis, P. S.: Harvest impacts on soil carbon storage in temperate forests, For. Ecol. Manage., 259, 857-866, 10.1016/j.foreco.2009.12.009, 2010.

Odum, E. P.: The strategy of ecosystem development, Science, 164, 262-270, 1969.

Pan, Y., Chen, J. M., Birdsey, R., McCullough, K., He, L., and Deng, F.: Age structure and disturbance legacy of North American forests, Biogeosciences, 8, 715-732, 10.5194/bg-8-715-2011, 2011.

Piayda, A., Dubbert, M., Rebmann, C., Kolle, O., Silva, F. C. E., Correia, A., Pereira, J. S., Werner, C., and Cuntz, M.: Drought impact on carbon and water cycling in a Mediterranean *Quercus suber* L. woodland during the extreme drought event in 2012, Biogeosciences, 11, 7159-7178, 10.5194/bg-11-7159-2014, 2014.

Pokrovsky, O. S., Shirokova, L. S., Kirpotin, S. N., Kulizhsky, S. P., and Vorobiev, S. N.: Impact of western Siberia heat wave 2012 on greenhouse gases and trace metal concentration in thaw lakes of discontinuous permafrost zone, Biogeosciences, 10, 5349-5365, 10.5194/bg-10-5349-2013, 2013.

Qu, L. P., Chen, J. Q., Dong, G., Jiang, S. C., Li, L. H., Guo, J. X., and Shao, C. L.: Heat waves reduce ecosystem carbon sink strength in a Eurasian meadow steppe, Environ. Res., 144, 39-48, 10.1016/j.envres.2015.09.004, 2016.

Raffa, K. F., Aukema, B. H., Bentz, B. J., Carroll, A. L., Hicke, J. A., Turner, M. G., and Romme, W. H.: Cross-scale drivers of natural disturbances prone to anthropogenic amplification: The dynamics of bark beetle eruptions, Bioscience, 58, 501-517, 10.1641/b580607, 2008.

Reichstein, M., Bahn, M., Ciais, P., Frank, D., Mahecha, M. D., Seneviratne, S. I., Zscheischler, J., Beer, C., Buchmann, N., Frank, D. C., Papale, D., Rammig, A., Smith, P., Thonicke, K., van der Velde, M., Vicca, S., Walz, A., and Wattenbach, M.: Climate extremes and the carbon cycle, Nature, 500, 287-295, 10.1038/nature12350, 2013.

Schwalm, C. R., Williams, C. A., Schaefer, K., Arneth, A., Bonal, D., Buchmann, N., Chen, J. Q., Law, B. E., Lindroth, A., Luyssaert, S., Reichstein, M., and Richardson, A. D.: Assimilation exceeds respiration sensitivity to drought: A FLUXNET synthesis, Glob. Change Biol., 16, 657-670, 10.1111/j.1365-2486.2009.01991.x, 2010.

Wang, W., Xiao, J., Ollinger, S. V., Desai, A. R., Chen, J., and Noormets, A.: Quantifying the effects of harvesting on carbon fluxes and stocks in northern temperate forests, Biogeosciences, 11, 6667-6682, 10.5194/bg-11-6667-2014, 2014.

Xiao, J. F., Ollinger, S. V., Frolking, S., Hurtt, G. C., Hollinger, D. Y., Davis, K. J., Pan, Y. D., Zhang, X. Y., Deng, F., Chen, J. Q., Baldocchi, D. D., Law, B. E., Arain, M. A., Desai, A. R., Richardson, A. D., Sun, G., Amiro, B., Margolis, H., Gu, L. H., Scott, R. L., Blanken, P. D., and Suyker, A. E.: Data-driven diagnostics of terrestrial carbon dynamics over North America, Agric. For. Meteorol., 197, 142-157, 10.1016/j.agrformet.2014.06.013, 2014.

Xiao, J. F., Zhuang, Q. L., Baldocchi, D. D., Law, B. E., Richardson, A. D., Chen, J. Q., Oren, R., Starr, G., Noormets, A., Ma, S. Y., Verma, S. B., Wharton, S., Wofsy, S. C., Bolstad, P. V., Burns, S. P., Cook, D. R., Curtis, P. S., Drake, B. G., Falk, M., Fischer, M. L., Foster, D. R., Gu, L. H., Hadley, J. L., Hollinger, D. Y., Katul, G. G., Litvak, M., Martin, T. A., Matamala, R., McNulty, S., Meyers, T. P., Monson, R. K., Munger, J. W., Oechel, W. C., Paw U, K. T., Schmid, H. P., Scott, R. L., Sun, G., Suyker, A. E., and Torn, M. S.: Estimation of net ecosystem carbon exchange for the conterminous United States by combining MODIS and AmeriFlux data, Agric. For. Meteorol., 148, 1827-1847, 10.1016/j.agrformet.2008.06.015, 2008.

Xiao, J. F., Zhuang, Q. L., Law, B. E., Baldocchi, D. D., Chen, J. Q., Richardson, A. D., Melillo, J. M., Davis, K. J., Hollinger, D. Y., Wharton, S., Oren, R., Noormets, A., Fischer, M. L., Verma, S. B., Cook, D. R., Sun, G., McNulty, S., Wofsy, S. C., Bolstad, P. V., Burns, S. P., Curtis, P. S., Drake, B. G., Falk, M., Foster, D. R., Gu, L. H., Hadley, J. L., Katulk, G. G., Litvak, M., Ma, S. Y., Martinz, T. A., Matamala, R., Meyers, T. P., Monson, R. K., Munger, J. W., Oechel, W. C., Paw U, K. T., Schmid, H. P., Scott, R. L., Starr, G., Suyker, A. E., and Torn, M. S.: Assessing net ecosystem carbon exchange of U.S. terrestrial ecosystems by integrating eddy covariance flux measurements and satellite observations, Agric. For. Meteorol., 151, 60-69, 10.1016/j.agrformet.2010.09.002, 2011.

Xiao, J. F., Zhuang, Q. L., Liang, E. Y., McGuire, A. D., Moody, A., Kicklighter, D. W., Shao, X. M., and Melillo, J. M.: Twentieth-century droughts and their impacts on terrestrial carbon cycling in China, Earth Interact., 13, 10.1175/2009ei275.1, 2009.

Yue, C., Ciais, P., Luyssaert, S., Cadule, P., Harden, J., Randerson, J., Bellassen, V., Wang, T., Piao, S. L., Poulter, B., and Viovy, N.: Simulating boreal forest carbon dynamics after stand-replacing fire disturbance: insights from a global process-based vegetation model, Biogeosciences, 10, 8233-8252, 10.5194/bg-10-8233-2013, 2013.

Zeppel, M. J. B., Wilks, J. V., and Lewis, J. D.: Impacts of extreme precipitation and seasonal changes in precipitation on plants, Biogeosciences, 11, 3083-3093, 10.5194/bg-11-3083-2014, 2014.

Zhao, M. S. and Running, S. W.: Drought-induced reduction in global terrestrial net primary production from 2000 through 2009, Science, 329, 940-943, 10.1126/science.1192666, 2010.

Zhou, D., Zhao, S. Q., Liu, S., and Oeding, J.: A meta-analysis on the impacts of partial cutting on forest structure and carbon storage, Biogeosciences, 10, 3691-3703, 10.5194/bg-10-3691-2013, 2013a.

Zhou, D. C., Liu, S. G., Oeding, J., and Zhao, S. Q.: Forest cutting and impacts on carbon in the eastern United States, Scientific Reports, 3, 10.1038/srep03547, 2013b.

Zhu, Z. and Woodcock, C. E.: Continuous change detection and classification of land cover using all available Landsat data, Remote Sens. Environ., 144, 152-171, 10.1016/j.rse.2014.01.011, 2014.

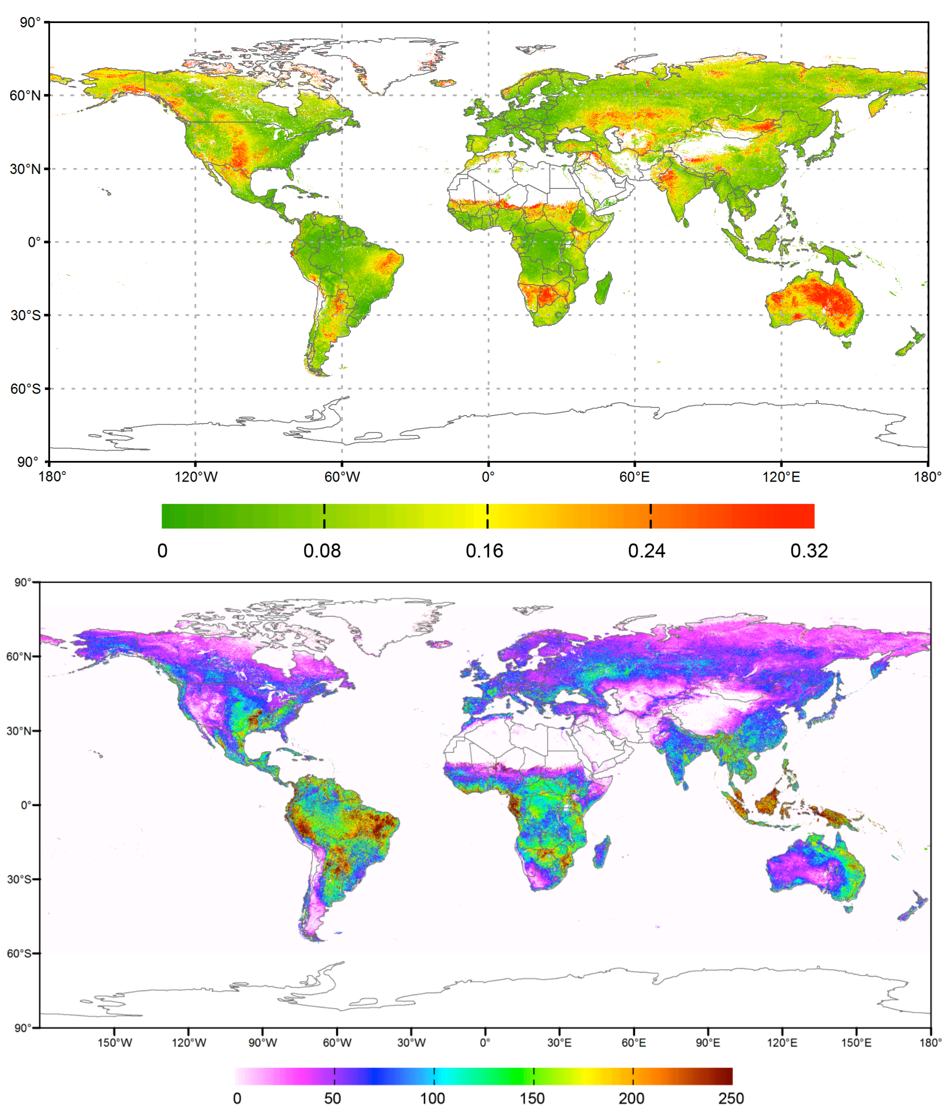


Fig. 1. The standard deviation (as a metric of the interannual variability (as measured by the coefficient of variation or CV, IAV) of annual gross primary productivity (GPP) over the period 2000- to 2014 from the MODIS GPP product (MOD17A3). The CV is unitless.

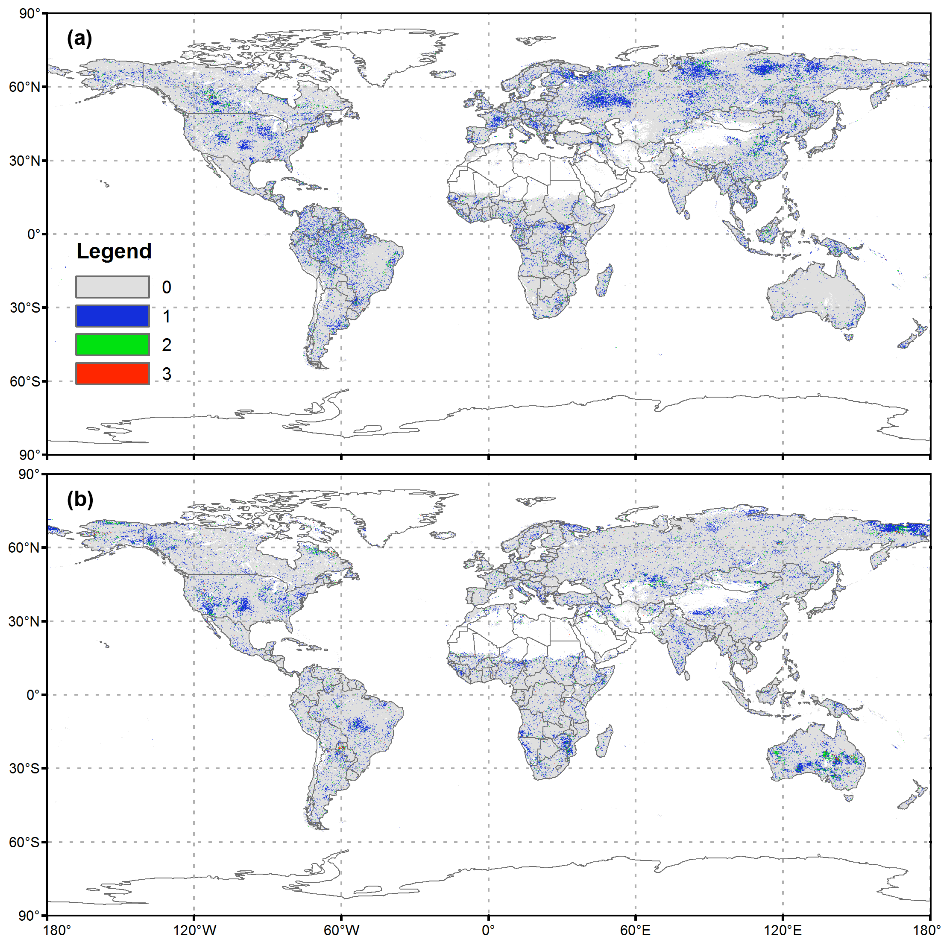
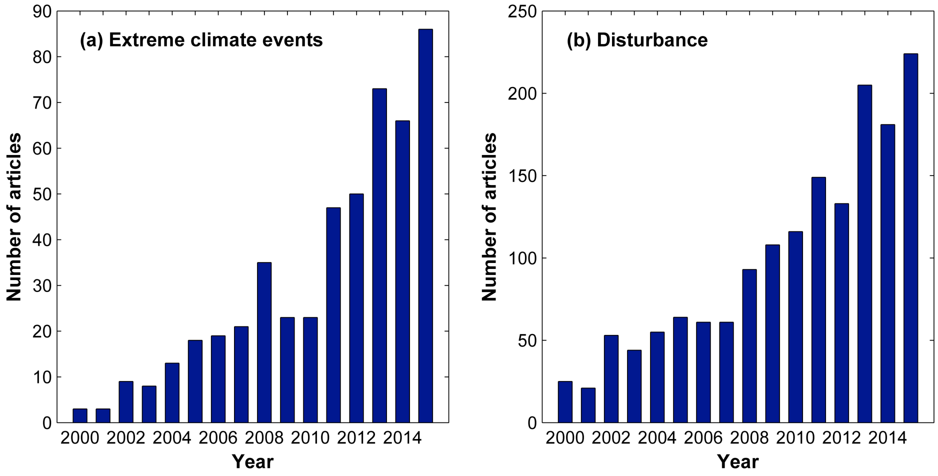


Fig. 2. The number of extreme years characterized by the number of outliers of the annual gross primary productivity (GPP) distribution over the period 2000-2104: (a) outliers on the lower end (i.e., exceptionally low annual GPP); (b) outliers on the higher end (i.e., exceptionally high annual GPP). The annual GPP values (Units are g C m^{-2} $year^{-1}$) were derived from the MODIS GPP product (MOD17A3)..



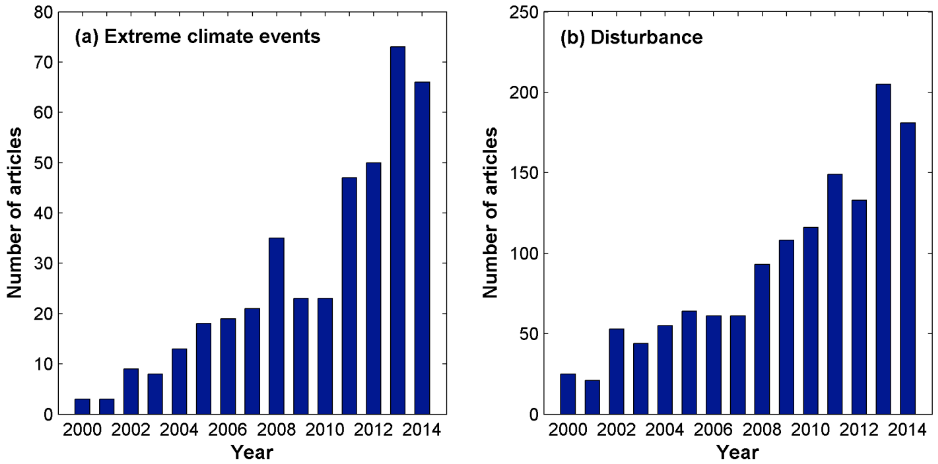


Fig. 32. The number of journal articles published over the period from 2000 to 20152014 as identified by Web of Science™ for the impacts of (a) extreme climate events and (b) disturbance on carbon dynamics. The combination of key words that we used to represent 'extreme climate events' is: TS=("extreme climate events" OR "climate extremes" OR drought OR "extreme precipitation") AND TS=("carbon dynamics" OR "carbon cycle" OR "carbon flux" OR "carbon stock" OR "carbon pool"), where TS stands for Topic. The combination of key words used to represent 'disturbance' is: TS=(disturbance OR fire OR

harvesting OR logging OR hurricane or "insect outbreaks") AND TS=("carbon dynamics" OR "carbon cycle" OR "carbon flux" OR "carbon stock" OR "carbon pool").