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

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Abstract The impacts of disturbances and extreme climate 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 advancements in understanding the impacts of disturbances and extreme events on the carbon cycle. Notable advancements 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 in a summer warming event; disentangling the roles of herbivores and fire on

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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 byincorporating 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, 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. 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. Terrestrial carbon fluxes often exhibit pronounced interannual variability (IAV), and disturbances and extreme climate events are primary sources of IAV (Eimers et al., 2008; Reichstein et al., 2013; Xiao et al., 2014). 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) and disturbances such as fire (Bowman et al., 2009), hurricanes (Chambers et al., 2007; Dahal et al., 2014; Xiao et al., 2011), 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), long-term observations, and the eddy covariance technique (Amiro et al., 2010; Dong et al., 2011) 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

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understand consequences of different extreme climate events and disturbances for carbon cycling.

The impacts of disturbances 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. 2) and found a total of 421 and 1495 journal articles for extreme climate events and disturbances, respectively, over the period from 2000 to 2014. Notably, the total number of publications on the impacts of these events on carbon dynamics has been growing at an average rate of 20 articles per year over the past decade (2005-2014) (Fig. 2), emphasizing the growing scientific interest in these important topics.

The present special issue is the outcome of special sessions on the impacts of extreme climate events and disturbances on carbon dynamics at the American Geophysical Union Fall Meeting. 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 disturbances 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 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

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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 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 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) 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 drought and extreme 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 of these subtropical forests would decrease if soil moisture continues to decrease in the future; 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 on average xeric biomes are likely to respond positively to extreme precipitation, but mesic biomes 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.

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

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smaller effects on the overall annual carbon balance of irrigated croplands than expected (De Simon et al., 2013). 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 occurred in the growing season could substantially alter carbon fluxes, while those events occurred 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 (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*. 50 g C m^{-2} $year^{-1}$ two years after attack 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.

Fire

Fire causes direct and immediate carbon emissions into the atmosphere from biomass burning (the direct effect), and subsequent changes in NEP 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*

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 vs. 40 years following wildfire and mountain pine beetle disturbances, respectively (Caldwell et al., 2013).

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 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

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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., 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 hurricane 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 on forest carbon stocks by collecting data on cutting intensity, forest structure, and carbon stock components. 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

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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).

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 evergreen needleleaf forests were more vulnerable to stand-replacing harvests than deciduous broadleaf forests (Wang et al., 2014).

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 near 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 found that the increase in atmospheric CO_2 concentrations in addition to vegetation recovery were jointly responsible for current carbon sink conditions. Their 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

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the legacy of disturbance and environmental factors jointly control the carbon dynamics following disturbance.

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 clear-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. These 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).

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 polygons, and remotely sensed data, providing a new source information that can benefit quantification of the carbon sources and

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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, conforming 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 net 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) 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 disturbances 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 event.

Importantly, studies in this special issue collectively indicate several major research needs. First, disturbances 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 are not skillful enough to correctly simulate the impacts of disturbances 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. Ongoing research in these areas will continue to improve our emerging understanding of the impacts of extreme events on carbon cycling.

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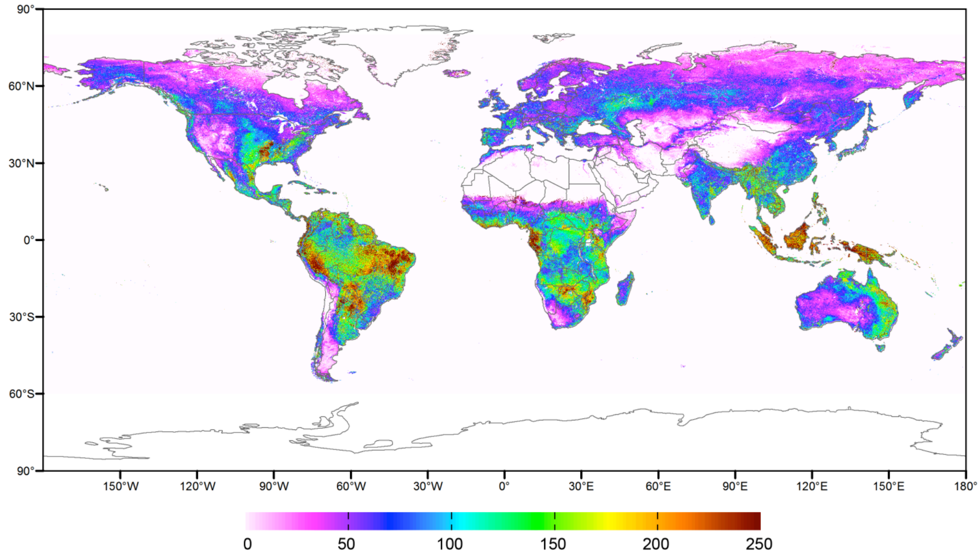

Fig. 1. The standard deviation (as a metric of the interannual variability, IAV) of annual gross primary productivity (GPP) over the period 2000 to 2014 from the MODIS GPP product (MOD17A3). Units are g C m^{-2} $year^{-1}$.

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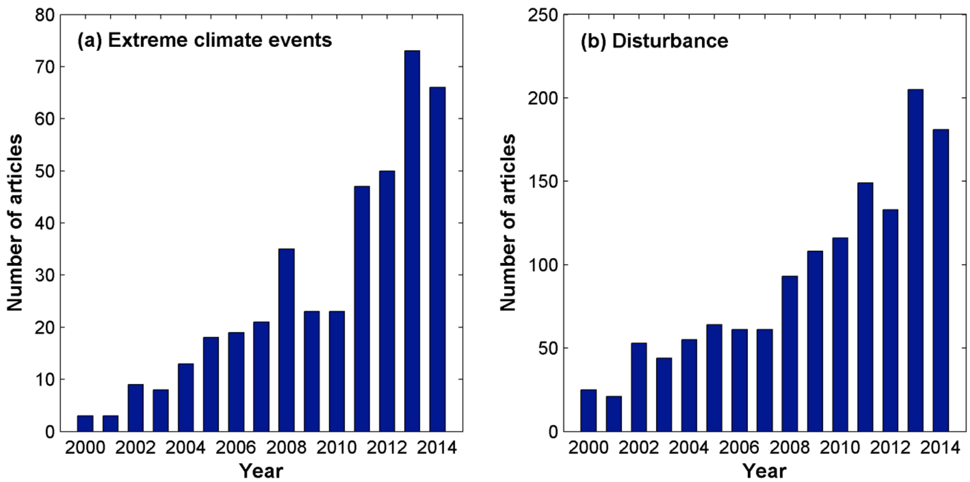

Fig. 2. The number of journal articles published over the period from 2000 to 2014 as identified by Web of Science™ for the impacts of (a) extreme climate events and (b) disturbance on carbon dynamics. The combination of key words that we used to represent 'extreme climate events' is: TS=("extreme climate 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").