Climate Extremes and the Carbon Cycle

CARBO-Extreme

The Terrestrial Carbon Cycle
under Climate Variability and Extremes
– a Pan-European Synthesis

Preface

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It is now beyond scientific doubt that climate change is occurring and that it is being driven by human activity. Atmospheric concentrations of carbon dioxide (CO_2), one of the greenhouses gases responsible for climate change, have reached levels that are higher than any time during the past million years. Increasing atmospheric concentrations of greenhouse gases do not only lead to gradual 'global warming', but also to changed patterns of rain and snowfall (precipitation), more weather extremes such as heat waves, longer dry spells, variability of growing season length, recurrent heavy rainfall, and storms. There is general concern that climate change will have fundamental impacts on our natural environment, our economic activities and life.

Ecosystems – like humans – are not bound by an 'average climate', but by the actual temperature, moisture, wind etc. Climate variability does not only act on human health – e.g. with more than 70,000 casualties exceeding the statistical expectances from reference time periods during the 2003 European heat wave – but also on forests, crop and grassland productivity and the capacity of our ecosystems to lock up carbon from the atmosphere, a process called carbon sequestration.

The growing recognition of the importance of climate extremes has led to a steadily growing number of studies about their impact in recent years, and awareness in public media, e.g. during the European and Russian heat waves in 2003 and 2010, Hurricane Katrina in the USA in 2005, large forest fires in Greece in 2007 and the extreme droughts in the Amazon basin in 2005 and 2010.

According to the latest assessments, the European terrestrial biosphere, comprising all European land, is a net carbon sink, which means that it removes more carbon from the atmosphere than it emits, but the future fate of this sink is highly uncertain. There is evidence from observations that there has been a change in the occurrence and frequency of some extremes, and we do know that climate variability and extremes will play an important role for the carbon cycle. But climate variability and extreme weather events have not, until now, been sufficiently accounted for in modelling and experimental studies, leading to a critical knowledge gap about the future fate of the European carbon cycle. As a result of this, in 2007, the European Commission launched a call in its 7th Framework Program (FP7) to address this gap. In 2009, the FP7-project CARBO-Extreme brought together a team of leading European scientists from different fields to obtain a better and more predictive understanding of the responses of the European terrestrial carbon cycle to climate variability and extreme weather events, to identify the most sensitive and vulnerable carbon pools and processes under different scenarios, and to map the most likely trajectory of carbon pools in Europe over the 21st century, including uncertainties in these estimates.

With this brochure, we want to introduce you to the topic of climate variability, extreme event impacts and the carbon cycle, how CARBO-Extreme researchers have worked to better understand the terrestrial carbon cycle under climate variability and extremes, what has been discovered, and what we still need to learn to better understand the future fate of the European carbon cycle.

Jena, January 2013

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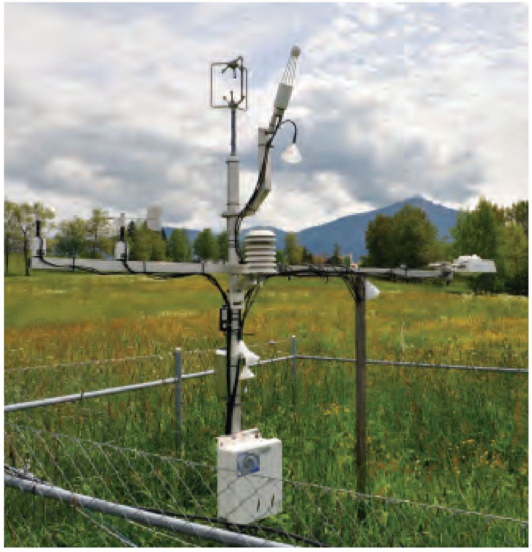
Fire at the rain exclusion plots at Las Majadas, Spain. Photo: Miguel A. Zavala.

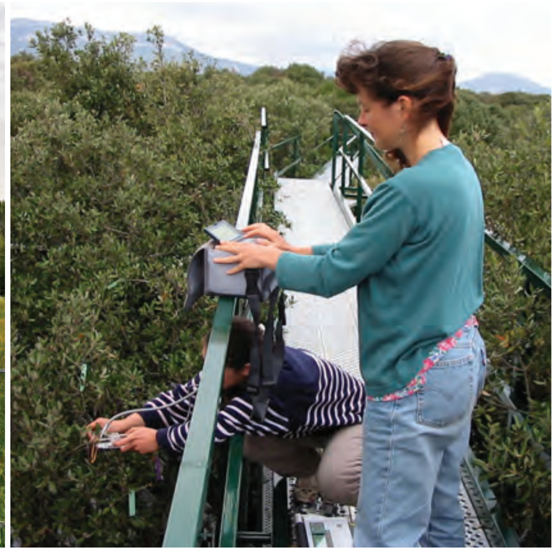
Rainout shelters on a mountain meadow at 1850 m, Kaserstattalm, Stubai, Austria. Photo: Eva Fessler.

Flooded agricultural field, Mid-Lothian, Scotland. Photo: Marcel van Oijen.

Climate strongly influences terrestrial ecosystems and their carbon cycle. Climate change is expected to lead not only to rising mean temperatures across Europe with decreasing precipitation (i.e. rainfall) in southern regions and increasing precipitation (rainfall and snow) in northern regions, but also to changes in the magnitude and frequency of extreme weather events. The terrestrial carbon cycle causes important feedbacks to the climate and is itself particularly susceptible to extreme climate events.

By definition, climatic extremes occur infrequently, e.g. on average once every 30 years. Yet, the disproportionate impacts of extreme climatic events on terrestrial ecosystems, their huge consequences on societal and economic well-being, and the projected increases in intensity and/or frequency of environmental extremes are all reasons for concern. Severe droughts, heat waves, extreme precipitation or storms can impact the structure and functioning of terrestrial ecosystems, thus their carbon cycle and their ability to lock up carbon from the atmosphere, called their carbon sequestration potential. Weather extremes can cause direct impacts on carbon fluxes to and from the atmosphere, e.g. on photosynthesis and respiration via extreme temperature and/or drought. They have the potential to cause rapid losses from





accumulated carbon stocks (e.g. the rapid release of very large amounts of carbon stored in forest biomass due to fire), as well as long-lasting impacts on the carbon cycle due to direct and lagged effects on plant growth and mortality, often going beyond the duration of the extreme event itself. Examples for such (often) lagged phenomena are forest mortality in the year(s) after extreme droughts, wildfires associated to heat waves and droughts, and pest and pathogen outbreaks after trees are blown over by strong winds, when insects can develop in the dead wood, possibly favored by untypically warm winters.

In CARBO-Extreme, we have combined diverse observations of ecosystem responses to climate extremes with computer modeling in a new model-data integration framework to improve our diagnostic and prognostic understanding of climate-carbon interactions on different time-scales. In order to obtain a global estimate of the impact of climate extremes on the carbon cycle, satellite observations of vegetation activity were merged with direct observations of CO_2 fluxes. CARBO-Extreme results indicate that approximately half of the carbon cycle extremes we have detected were associated with droughts, which are globally the most important type of climate extreme, though other extreme events also have an impact.

All land use types in Europe (largely comprising croplands, grasslands and forests) are vulnerable to climate extremes to some degree. While there will be less water available for agriculture and forest growth in southern Europe and, (some) crop yields are projected to fall due to heat waves and droughts in central and southern Europe, growing conditions may improve in other areas. The growing season for several crops, native plants and forest species has lengthened in Europe and this trend is projected to continue, alongside their expansion into more northerly latitudes. In general, with both their large carbon stocks and long generation time, forests are expected to experience the largest, most diverse, and longest lasting consequences for carbon cycling from climate extremes compared to other land-cover types. However, if no adaptive measures are taken in grassland and cropping systems severe impacts of climate extremes could also be triggered.

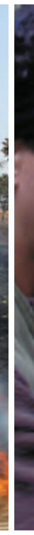
Top from left to right:

Tree core sampling for tree ring analysis, Torneträsk, Northern Sweden. Photo: Flurin Babst.

Eddy covariance tower on a sub-alpine grassland near lake Zug in Switzerland. Photo: Lutz Merbold.

Measurements at the experimental site in Puechabon, France. Photo: Jean Marc Ourcival.

Introduction



A small change in the mean of a climate variable, in its variance or its shape of probability distribution - or a combination of those - inherently leads to substantial changes in the frequency of its extremes.

(Meehl et al. 2000, Nicholls and Alexander 2007, Seneviratne et al. 2012)

Top left: Agricultural landscape prone to drought because of shallow soils and low summer precipitation, Island of Simi, Greece. Photo: Marcel van Oijen.

Top right: Burning African Savannah. Photo: Dorothea Frank.

There is general concern that climate change will have fundamental impacts on our ecosystems, since increasing atmospheric concentrations of greenhouse gases do not only lead to a gradual 'global warming' with rising mean temperatures, but also to changes in climate variability and the occurrence of extreme weather events. It is known that climate strongly influences our terrestrial biosphere, the functioning of terrestrial ecosystems and therefore their carbon cycling and their ability to lock up carbon from the atmosphere, called their carbon sequestration potential. But since extreme events are rare, there are less data available on their impacts, which means it is more challenging to identify long-term changes for extreme events than for gradually changing climate variables (e.g. rising temperature).

About extremes

The effect of changes in temperature distribution on extreme temperature values, for present and future climate, is shown in Fig. 1: Clearly, the distribution of temperatures often resembles a normal distribution, but even a small increase of the mean temperature (Fig. I.1A) leads to more heat waves and extreme hot weather. A changed shape of the probability distribution of the temperature due to an increased variability (without change of the mean temperature) leads to more (extreme) cold and hot weather (Fig. I.1B), whereas effects on an altered shape, e.g. an asymmetry towards the hotter part of the distribution (Fig. I.1C) leads towards more (extreme) hot weather without big changes in the probability of cold extremes occurring (IPCC 2012).

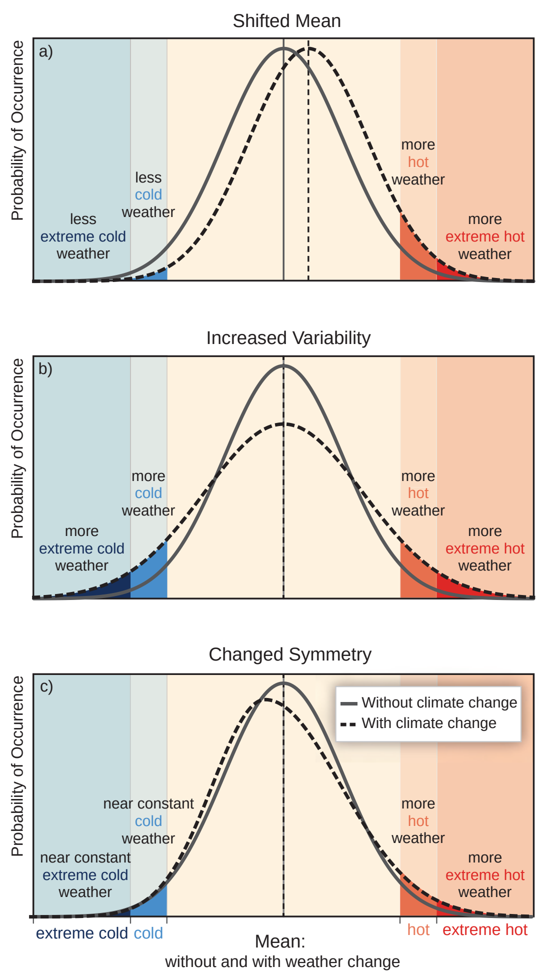


Figure I.1: Effects of changes in temperature distribution on temperature extremes for present and future climate (IPCC SREX 2012, Fig. SPM 3).

Extreme climate events, such as heavy precipitation, storms, heat waves and droughts or extreme cold have direct and indirect impacts on photosynthesis and respiration, plant growth and the terrestrial carbon balance through a web of complex interactions (see Fig. I.2; after Reichstein et al. 2013). These extremes have the potential to cause rapid losses from accumulated carbon stocks, as well as long-lasting impacts on the carbon cycle since direct and lagged effects on plant growth and mortality, and subsequent potential land cover changes, often go beyond the duration of the extreme event.

The CARBO-Extreme approach

In CARBO-Extreme, scientists from different fields work together to gain a better understanding of the terrestrial carbon cycle under a more variable climate regime, with more extreme weather events (see Fig. I.3 for CARBO-Extreme's integrative approach). To understand how the carbon cycle of different ecosystems responds to climate variability and to extreme events from a daily to decadal time scale, a diversity of existing long-term, carbon cycle-related observation data sets have been collected and analyzed. These include regional statistics of crop yields, and forest growth and mortality, as well as tree rings, detailed ecosystem observations and global satellite remote sensing.

Data from a network of 13 Ecosystem Manipulation Experiment sites (EMEs) across Europe were collected, where the impacts of extreme weather conditions are simulated experimentally through direct treatments and the ecosystem responses to warming, changing precipitation patterns and increasing CO_2 concentrations are measured.

By bringing together existing long-term carbon cycle-related observation data sets and ecosystem manipulation experiments, where e.g. drought conditions are simulated and the reaction of the ecosystem is measured, we gather more information about how our terrestrial ecosystems react under extreme weather conditions. This information is collected in a harmonized database and used by the computer modeling groups to further develop, parameterize and test their models.

This is done using a strong model-data integration framework, compiling and adapting the latest regional climate scenarios. By reducing uncertainties in our ability to simulate and predict carbon cycle responses to climate extremes, we are able to improve our predictions about the future fate of the terrestrial carbon cycle, and identify the most vulnerable regions, carbon pools and processes.

The CARBO-Extreme approach:

- *Bringing together and analyzing existing long-term carbon cycle related observations.*
- *Synthesizing and harmonizing new experimental approaches.*
- *Compiling and adapting latest regional climate scenarios.*
- *Using a strong model-data integration framework.*

Top: Sampling tree-rings in pine plantations with forest dieback after drought in Andalusia, Spain. Photo: Raúl Sánchez-Salguero.

Introduction

This brochure highlights the most relevant issues regarding how climate extremes affect the terrestrial carbon cycle and how research is being carried out to improve this understanding. In the highlight chapter ***When it gets hot and dry - droughts, heat waves and fire*** (pg. 8) we provide an overview on hot and dry extreme events, while insights towards the more windy, cold and wet extremes can be found at ***Storms, floods and frost*** (pg. 10).

Methodological aspects are highlighted in the following chapters: Insights about the different scales on which extreme weather events impact the CO_2, water vapor and energy fluxes between ecosystems and the overlying atmosphere are given in ***Observing the response of carbon and water cycles to climate extremes*** (pg. 12). ***Tree-rings archiving the impacts*** (pg. 14) shows how tree-ring investigations extend precisely dated growth measurements and biomass estimates backwards in time, constituting a valuable archive to understand impacts of climate extremes on ecosystems over the past decades to centuries. ***Global detection and characterization of extreme impacts from satellites*** (pg. 16) explains how a global estimate of the impact of climate extremes on the carbon cycle can be obtained by exploring satellite observations of vegetation activity, merged with direct observations of CO_2 fluxes. Several feedback mechanisms can lead to the occurrence or amplification of extreme climate events, as described in the highlight chapter ***Climate feedbacks: triggering or amplifying extremes*** (pg. 18).

Rising CO_2 concentrations can enhance plant growth as well as higher mean temperatures (e.g. in actually cold-temperature limited regions), but extreme events can potentially override any (positive) effects of mean climate change on carbon sinks, as shown for example in the European 2003 heat wave. As extreme events are expected to become more frequent in future, simulations are needed for a better and more predictive understanding of the carbon cycle. Experiments are an indispensable tool for unraveling effects of increased climate variability and weather extremes on ecosystems. ***Simulating the future: insights from experiments*** (pg. 20) shows

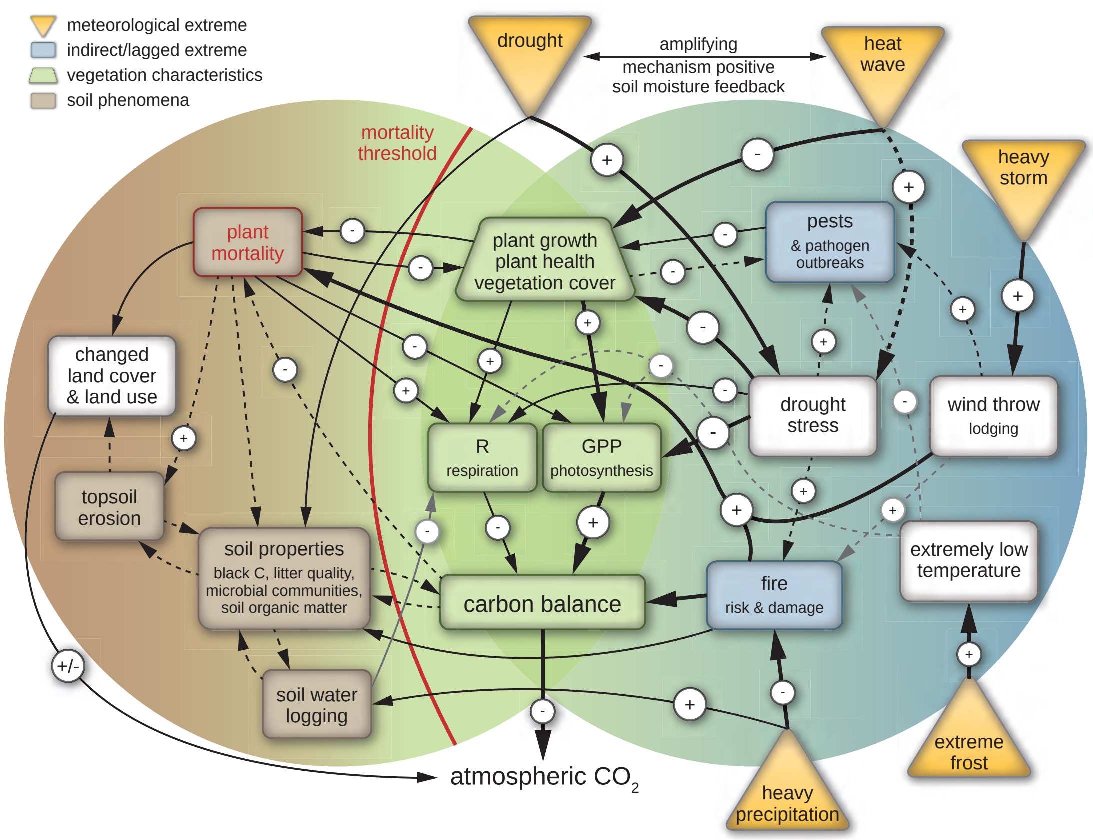


Figure I.2: Extreme events and their (in-)direct impacts on CO_2 fluxes, soil, plant growth and mortality. (In-)direct effects (dashed) arrows, positive/enhancing impacts with a '+' and negative/reducing impacts with a '-' sign. Modified after Reichstein et al. 2013.

how experiments allow questions to be addressed on how the duration, intensity and timing of an extreme event affects various carbon cycle processes simultaneously. The findings from these experiments are not only insightful in themselves, they also provide useful input parameters for ecosystem models. Observing ecosystem responses to changing environmental conditions at site level is essential for our understanding of ecosystem functioning and modeling ability. We explain how we bring together models, (long term) observations and responses to extreme events to improve our diagnostic and prognostic modeling ability in ***Simulating the future: insights from ecosystem modeling*** (pg. 22). As the day-to-day variability of weather conditions, and the frequency of extreme events might affect ecosystems more than a gradual change in climate, ***Simulating the future: insights from continental modeling*** (pg. 24) examines this question using terrestrial ecosystem models with datasets that simulate more frequent occurrence of extreme events.

Extreme events have the potential to impact the carbon balance of terrestrial ecosystems through. How forests, grasslands and crops are differently affected by the various types of extremes is explained in ***Extremes and their impact on agriculture & forestry*** (pg. 26).

Mediterranean hotspot: climate change impacts on forests at the edge (pg. 30) focuses on how Mediterranean forests are expected to suffer important changes with climate change.

The highlight chapter ***Carbon vulnerability assessment for Europe*** (pg. 32) proposes a probabilistic risk assessment method to evaluate the vulnerability of the European carbon cycle to extreme drought and heat events. Future research needs and unresolved questions of the terrestrial carbon cycle under extreme weather events are discussed in ***Outlook & open scientific questions*** (pg. 34).

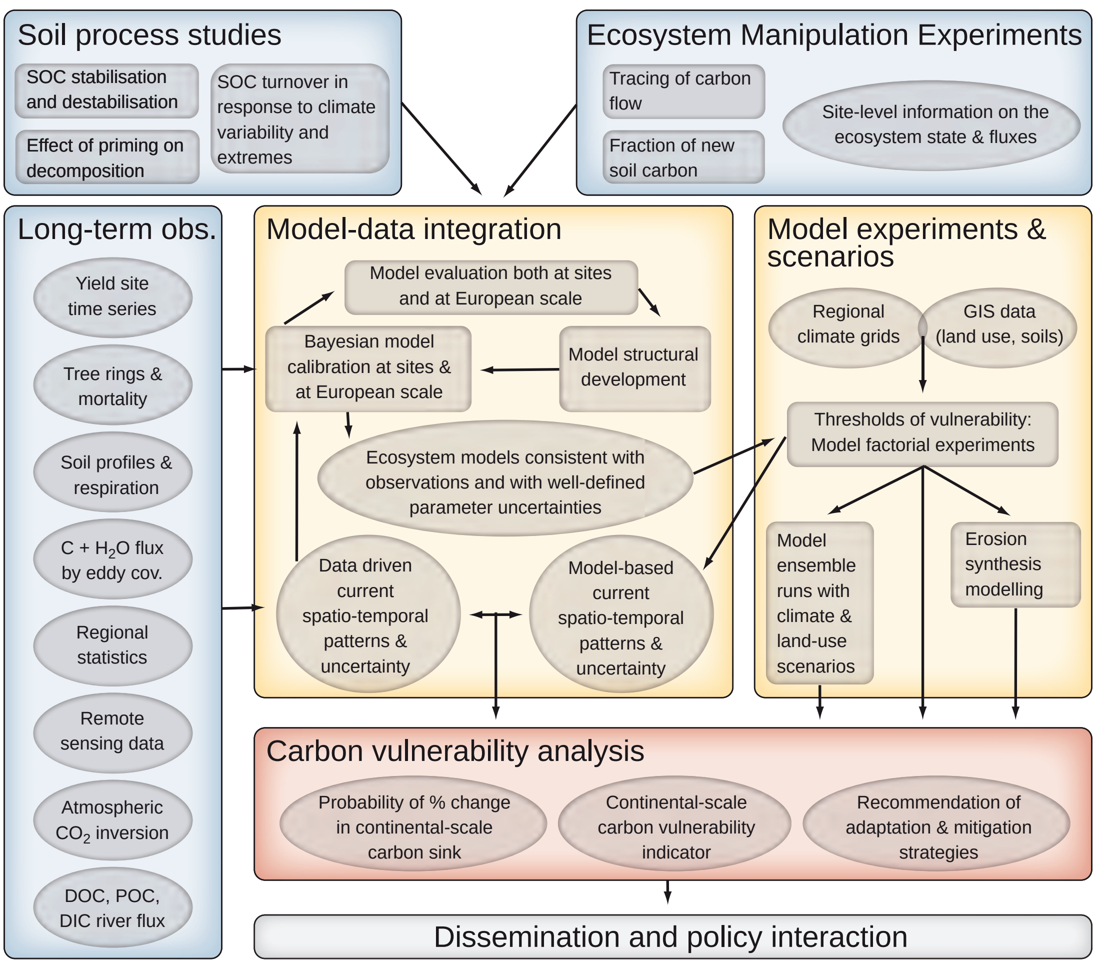


Figure I.3: CARBO-Extreme's integrative approach with an observation component (blue: soil process studies, ecosystem manipulation experiments and analysis of long-term observation data), a modeling component (yellow: model-data integration and model experiments & scenarios) and assessment component (red: carbon vulnerability analysis).
SOC = soil organic carbon,
DOC = dissolved organic carbon,
POC = particulate organic carbon,
DIC = dissolved inorganic carbon.

Highlight Chapter 1

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Droughts, often associated with heat waves and fire, can have severe impacts on vegetation, human health and economic activities. They strongly impact carbon fluxes and the ability of terrestrial ecosystems to lock up carbon from the atmosphere (i.e. their carbon sequestration potential). The impact depends on severity, duration, and timing. Heat waves, droughts and fires are projected to increase with climate change in many areas of the world.

Droughts are the main threat to the terrestrial carbon sequestration in many regions...

Extremely high temperatures and droughts can cause severe impacts on the vegetation, human health and our economic activities. Within the past decade an exceptional number of extreme heat waves occurred around the world (Anderson and Kostinski, 2010, Coumou and Rahmstorf 2012). Record breaking temperatures struck central Western Europe in 2003, causing a large number of human deaths due to heat stress, and South-Eastern Europe in 2007, with dramatic wildfires e.g. in Greece. In 2010 an extraordinary heat wave with maximum temperature records led, together with huge forest fires, to very poor air quality in western Russia and large increases in deaths and other impacts, e.g. in Moscow, an annual crop failure of around 25% and an economic loss of approx. US$15 billion (Barriopedro et al. 2011). In the United States, the 2011-2012 drought was reported as one of the most severe droughts ever recorded, with economic losses of billions of dollars and severe crop damage and loss.

During the European 2003 heat wave, impacts on the carbon cycle were primarily due to a lack of water and not primarily caused by the high temperatures (Granier et al. 2007, Reichstein et al. 2007). An amount of CO_2 comparable to what had been absorbed by the terrestrial ecosystems during the previous three to five years under normal weather conditions was lost. Contrary to previous years, Europe, in 2003, was a net source of carbon to the atmosphere (Ciais et al. 2005). Plant photosynthesis and respiration are temperature dependent, as well as microbial activity and the decomposition of soil organic matter. Temperature extremes directly impact the CO_2 fluxes of terrestrial ecosystems, whereas droughts have manifold impacts on the carbon cycle via the phenology and the physiology of plants, as well as on soil microbial activity and the structure of soil microbial communities.

Heat waves and droughts

Drought results from an imbalance between moisture demand and moisture supply provided by rainfall. The need of water for evapotranspiration [i.e. the water extracted by plants from the soil and lost via its leave stomata, plus the direct evaporation of water from moist surfaces like bare soils, lakes, water on the leave surfaces] is higher at high temperatures. The lack of rainfall together with more water demand at higher temperatures leads to less water in the soil. If soil moisture becomes limiting for evapotranspiration, the evaporative cooling is suppressed, causing a positive regional temperature feedback, i.e. higher temperatures leading towards more drought.

(cf. highlight chapter 'Climate feedbacks: triggering and amplifying extremes' pg. 18, Seneviratne et al. 2006, 2010, Fischer et al. 2007, Diffenbaugh and Ashfaq 2010, Hirschi et al. 2011)

Top left: Soil after drought, Island of Milos, Greece. Photo: Marcel van Oijen.

Top right: Pine suffering extended drought conditions in Central Spain. Photo: Jaime Madrigal-González.

When it gets hot and dry - droughts, heat waves and fire

Drought conditions, as well as high temperatures, cause a significant reduction in the net rate at which CO_2 is fixed in plant tissues, as respiration has a higher temperature optimum than photosynthesis, and droughts have larger negative physiological effects on plant photosynthesis than on respiration.

In addition to severity and duration, the timing of droughts is a crucial factor as many land uses and ecosystems are seasonally highly variable. Drought events occurring outside the main growing season (e.g. of crops) have only a small impact, whereas extreme (spring) droughts may strongly alter phenology (development of leaves, flowers and fruits) and physiology (e.g. photosynthesis) of Mediterranean forests (Misson et al. 2010, 2011), and thus the amount of carbon they remove from the atmosphere.

Large uncertainties are reported for droughts at global scale (IPCC 2012, Seneviratne et al. 2012), but in some regions like Southern Europe and the Mediterranean the existing evidence suggests that drought trends have increased already, and will intensify further in the 21st century due to reduced precipitation and/or high temperature increased evapotranspiration.

Drought effects may last longer than the drought event itself due to delayed (and ecosystem specific) recovery and/or secondary impacts such as altered mortality in the year(s) following the drought event, pest and pathogen invasions (due to reduced plant health and weaker defense) or an increased fire risk. More severe drought conditions also increase the risk of a greater number and severity of fires.

Current projections show an increase of this climatic fire risk, and even extreme fire risk for many parts of Europe. Consensus is that Southern Europe will experience a higher fire risk, whereas temperate or boreal regions might experience a rather moderate increase or no change. If, in addition to the climate warming trend, climate variability increases, further extreme fires might contribute to vegetation shift along biome borders between temperate and Mediterranean-type or steppe vegetation. Further research is required to investigate the question of whether more extreme fires could shift biome boundaries and release more carbon than if climate variability remains at current levels. The vulnerability of fire-adapted vs. non-fire adapted vegetation (or forest species) will be key in this assessment.

Fire occurrence

Fires are caused by climatic and conditions within terrestrial ecosystems. Humans are responsible for a large proportion of fires, which are set either intentionally to manage the landscape or accidentally. Drought is only one pre-condition of many other driving factors: wind, the slope of the terrain, the flammability of the living vegetation, the amount of especially fine dead biomass and the dryness of the dead biomass on the ground. For example, the extreme fires in 2007 in Greece were caused by such a combination: an extreme heat wave with high winds ignited fires in mountainous areas, where dense but non-fire adapted forests were growing (Koutsias et al. 2012).

... and are likely to be more severe in many regions, also imposing a higher fire risk.

Top left: Recently burned forest near Tura, Krasnoyarsk Krai, Siberia. Photo: Martin Thurner.

Top right: Burned forest on the island of Levkas, Greece. Photo: Marcel van Oijen.

Highlight Chapter 2




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Storms, floods and frost can have devastating impacts on ecosystems and societies. Hurricanes can destroy forests, heavy rain causes erosion from unprotected soils and frost can damage crops and trees. Cold, wet and windy extremes will profoundly alter short-term carbon cycling processes, and often lead to the transport of carbon out of the affected ecosystem. Nevertheless, the ultimate impact on long term carbon storage and uptake will depend on ecosystem type, state and the fate of the released carbon.

In European forests, windthrow (when trees are blown over by high winds) is one of the most important natural disturbances with major implications for the carbon cycle. In 1999, storm 'Lothar' caused a reduction of the European carbon balance by ca. 16 million tons C, nearly 30% of the net biome productivity in Europe (Lindroth et al. 2009). Windthrow typically turns a slowly growing carbon sink, i.e. an intact forest, quickly into a large carbon source before regrowth can again result in a carbon sink (Fig. 2.1).

Windthrow can also lead to subsequent insect outbreaks or massive fires due to large amounts of dry dead wood. Notwithstanding this, carbon stored in the dead wood in the soil, and renewed establishment of young saplings can also lead to increased carbon storage. Therefore, accounting for all stages of succession (regrowth of the trees) including disturbances and regeneration is necessary to correctly estimate the carbon balance at landscape level (Knohl et al. 2002, Lindroth et al. 2009). Depending on management strategy, the broken wood can be extracted and used for low quality wood products, or can be left at the site for decomposition with additional possible positive effects on nutrition and biodiversity.

Extreme events such as heavy rain, deep frost, hail storms and flooding can lead to crop failures by physically damaging crop canopies, changing soil CO_2 fluxes and CO_2 uptake during water logging phases, and limiting root and plant function due to anoxic soil conditions. Extreme conditions can also delay key field operations such as planting and harvesting (van der Velde et al. 2012).

The timing of extreme events with respect to crop development stage is crucial for the resulting ecosystem impact. A period of frost in April before flowering of, for example, apple trees might cause minor damage whereas the same event in May might destroy most of the harvest of apples for that year. A cold period after some unusual warm winter days leading to the advanced development of leaves and flowers in trees and crops can lead to much more damage during the subsequent freezing period compared to the same event after prolonged cold and snowy conditions. However, the lack of frequent cold days (i.e. an extremely warm winter) can also increase damage to ecosystems, for instance by larger populations of mountain pine beetle in forests, because the insect mortality is directly related to the occurrence of cold days.

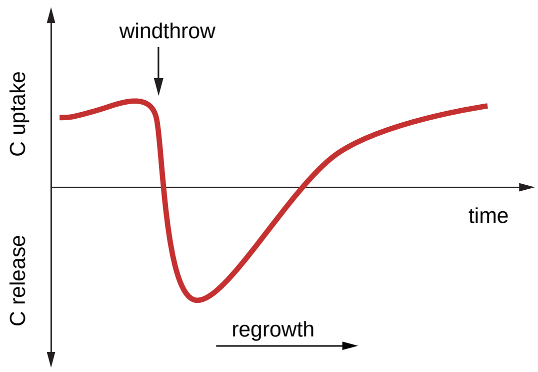
Top from left to right:

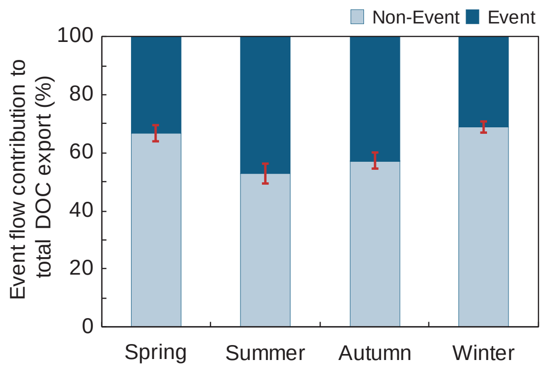
Crop lodging following strong winds, Germany.

Snow break in forest, Lens monitoring site near Sion, Switzerland. Photo: David Frank.

Flooded crops, Poland.

Water logging from heavy rains on compacted soils, Balerno, Scotland. Photo: Marcel van Oijen.





Left, Figure 2.1: Wind throw turns a carbon sink quickly into a carbon source.

Right, Figure 2.2. The contribution of extreme flow events to total transport of dissolved organic carbon (DOC) based on a set of UK headwater streams. The transport of DOC occurring during the highest flows (flows that are exceeded only 5% of the time based a monthly moving threshold) accounted for approximately 30% to 50% of the total annual DOC fluxes (Dinsmore et al. in prep).

Heavy rainfall also renders soils susceptible to erosion especially if vegetation cover is low, for instance in grasslands after droughts or during field preparation or the fallow period of crops. Soil erosion leads to lateral transport of soil organic carbon out of the impacted ecosystem and affects the productive capacity of soil by deteriorating overall soil quality. The net-effect of erosion on carbon sequestration is not straightforward. If eroded carbon is not transformed to CO_2, but trapped in structures leading to longer residence times than in the original soil, then soil erosion can also be a net sink. The release of soil-derived dissolved organic carbon (DOC) into river systems is a major carbon transport pathway in many upland catchments, particularly where organic-rich soils dominate (Dinsmore et al. 2010). Extreme events account for a significant loss of catchment carbon (Fig. 2.2). The downstream fate of DOC is still uncertain, but likely a significant proportion is lost to the atmosphere as CO_2.

Predicting the nature of future extreme events is difficult. Analysis and future projections of extreme winds suggest a long-term upward trend of European storminess (Donat et al. 2011; Fig. 2.3). This would be especially important for forests, where even a small increase in storm frequency can lead to a long-term reduction of the carbon stock. Concerning rainfall, it is likely that 'the frequency of heavy precipitation or the proportion of total rainfall from heavy falls will increase in the 21st century over many areas of the globe' and that there is 'medium confidence that, in some regions, increases in heavy precipitation will occur despite projected decreases in total precipitation in those regions' (IPCC 2012). Lenderink and Meijgaard (2008) showed that one-hour precipitation extremes increase twice as fast with rising temperatures with significant potential impacts including local flooding, erosion and water damage.

Rainstorms and extreme flows contribute disproportionally to carbon transport in streams...

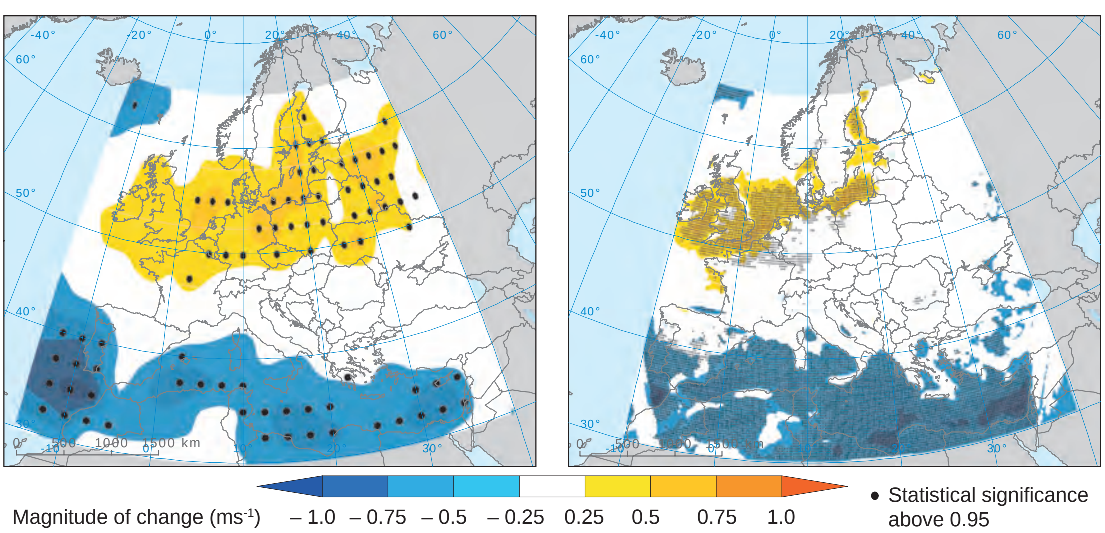


Figure 2.3: Projected changes in extreme wind speed based on GCM and RCM ensembles (European Environment Agency 2012; http://www.eea.europa.eu/data-and-maps/figures/future-changes-in-european-winter).

Highlight Chapter 3

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Greenhouse gas fluxes into and out of ecosystems can be directly measured by a technique called eddy covariance. There are large global networks of towers using this equipment (FLUXNET) and these can be combined with remote sensing data (from satellite observation) and computer models, to analyze the effect of extreme climate conditions (such as drought and heat waves) on the gain and loss of carbon in terrestrial ecosystems. Differences in response according to the vegetation present and the management practices used on the land can also be examined.

Eddy covariance flux tower observations allow continuous and minimally invasive observations of ecosystems' response to climate variability and extremes.

Top three left: Wooded savanna ecosystem and eddy covariance tower, Las Majadas, Spain. Photos: Arnaud Carrara.

Top right: Eddy covariance tower at Puechabon, France. Photo: Jean Marc Ourcival.

Climate extremes disrupt CO_2, water vapor and energy fluxes between ecosystems and the overlying atmosphere. In specific cases, extreme climate conditions, such as drought causing fire, or storms causing windthrow (trees being blown over), can result into sporadic and massive losses of CO_2 to the atmosphere by ecosystems, and could cause damage in the ecosystem structure and functions requiring years to recover. It is only a decade since continuous measurements of CO_2, water and heat fluxes by the eddy covariance technique started to be made, and these measurements have enabled us to quantify changes of ecosystem fluxes during extreme events.

Globally, there are more than 500 eddy covariance stations which are organized in regional networks and collaborate with standardized methods and products under the FLUXNET initiative (www.fluxdata.org). The micrometeorological data also allow for the separate characterization of the response of ecosystem productivity and respiration to environmental factors, allowing a better understanding of which processes are more affected by extreme climatic conditions. One key finding from the global analysis of Schwalm et al. (2010), based on eddy-covariance data and focusing on effects of drought on ecosystem fluxes, was that photosynthesis (which leads to carbon uptake) was reduced under drought by, on average, 1.5 times more than ecosystem respiration (which leads to carbon loss), thus causing an overall CO_2 loss to the atmosphere. During extreme and persistent drought and heat waves, such as the summer 2003 heat wave in Western Europe, a similar response was found to be widespread (Ciais et al. 2005, Reichstein et al. 2007) over scales of hundreds of kilometers, with some ecosystems being less vulnerable than others.

The presence in the FLUXNET network of different managed sites (in particular crops, grassland and short rotation forests) also allows analysis of the effect of the cultural and ecosystem management practices in contrasting the stresses due to extreme and unfavorable climate conditions, providing useful information to land managers and farmers. To interpolate findings from local eddy-covariance stations in

Observing the response of carbon and water cycles to climate extremes




space and time, remote sensing data, such as long time series of vegetation greenness, have proven to be particularly useful, for instance to discover lagged responses between periods of very dry soils and vegetation activity for different vegetation types (Vicente-Serrano et al. 2013) or, when used in up-scaling models, to identify the major climatic drivers for productivity and evapotranspiration variability at global scale (Jung et al. 2010, Beer et al. 2010).

One remaining research question is, whether severe droughts will kill trees and cause forest dieback if these events become more frequent in the future in sub-tropical and mid-latitudes (Christensen et al. 2007). Flux tower records are probably still too short and also too local to answer this research question, while global, moderate-resolution remote sensing data give some clues on forest mortality. Perhaps one of the most interesting new findings comes from recent work by Choat et al. (2012) who showed, from data on the ability of trees to move up water from soils to leaves for transpiration, that many tree species operate surprisingly close to a state called embolism when extreme dryness can cause damage to the hydraulic vessels which transport sap in a tree. If drought becomes more frequent or more severe in the future, such a low 'safety margin' could lead to forest dieback and loss of tree cover (which would reduce the current forest carbon sink (Pan et al. 2011) or convert it into a source of CO_2 to the atmosphere). Also, we expect a change in the tree species composition in favor of those more adaptable to the new drought condition, such as Mediterranean species with deep root systems that are able to maximize carbon uptake during the period without water limitation (Baldocchi et al. 2010).

Severe droughts may kill trees and cause forest dieback if these events become more frequent in the future.

Top from left to right:

Eddy covariance tower in the dark Taiga, Siberia, Russia. Photo: Dario Papale.

ICOS ETC ecosystem test site, Roccarespampani, Italy. Photo: Michele Tomassucci.

Eddy covariance tower at LeBray, France. Photo: Denis Loustau.

Eddy covariance tower during winter in the Dischma valley near Davos, Switzerland. Photo: Lutz Merbold.

Left: Spring at Roccarespampani, Italy. Photo: Michele Tomassucci.

Highlight Chapter 4

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By definition, climatic extremes occur infrequently, perhaps once every 30 years. Yet, the disproportionate impacts of extreme climatic events on terrestrial ecosystems, their severe consequences on societal and economic well-being, and the projected increases in intensity and/or frequency of environmental extremes are all reasons for concern. Long-term records, providing a baseline and capturing the ecosystem response and recovery from one or more extreme events, are needed to reduce uncertainties about the possible impacts of extreme events on the carbon cycle. Tree-ring investigations extend precisely-dated growth measurements and biomass estimates backwards in time and are thus a valuable archive to understand the impacts of climate extremes on ecosystems over the past decades to centuries.

As part of the CARBO-Extreme project, annual tree-ring data from nearly 1000 sites across Europe were compiled and harmonized to quantify the large-scale response of trees to climate variation (Fig. 4.1). The impacts of climate fluctuations occurring prior to any systematic satellite observations or flux tower stations were assessed. For example, in 1976, summer temperatures in Central Europe were hot and precipitation was low; these extreme climate conditions resulted in greatly reduced radial growth and presumably total tree carbon sequestration across

Tree-rings capture ecosystem responses to climate variations and extremes over the past decades to centuries.

Top from left to right:

Microcore sampling in a Scots pine plantation, Andalusia, Spain. Photo: Raúl Sánchez-Salguero.

Microcore in Trephor coring tool, Sierra de Los Filabres, Spain. Photo: Raúl Sánchez-Salguero.

Measurement of tree rings in the lab. Photo: Raúl Sánchez-Salguero.

Sampling with borer at breast height. Photo: Raúl Sánchez-Salguero.

Tree-rings and the terrestrial carbon cycle

- *Fluctuations in tree-ring width and density are part of the carbon cycle response to environmental change and directly archive the impacts of climatic extremes on tree growth (Babst et al. 2013).*

- *Tree-ring time-series can be developed wherever the annual climatic cycle induces a regular dormant season – this includes most temperate and even many tropical forest ecosystems (Fritts 1976) and thus a significant fraction of the Earth's living terrestrial biomass.*

- *Tree-rings provide a continuous, annually-resolved record of radial stem growth over individual trees' lifespans. These archives enable impacts of climate extremes on forest growth, including lagged responses and long-term consequences, to be quantified (Babst et al. 2012a). Extensions of tree-ring sequences from living trees with overlapping calendar dated tree-ring time-series from relict wood preserved in archeological sites or natural settings, provides records of growth over many centuries or even millennia (Esper et al. 2002).*

- *Tree physiological processes and responses to extreme events are also fingerprinted in the isotope composition of carbon, oxygen, and hydrogen locked into the wood cells during their formation (McCarroll and Loader 2004). For example, trees have been shown to decrease the water use to assimilate a given amount of carbon during drought stress as well as under increased atmospheric CO_2 concentrations (Saurer et al. 2004, Penuelas et al. 2011).*

- *Close links between climate and tree-growth in boreal ecosystems have made tree-ring records one of the key data sources to reconstruct temperatures over the past millennium and quantify carbon-cycle climate feedbacks on policy relevant time-scales (Frank et al. 2010).*

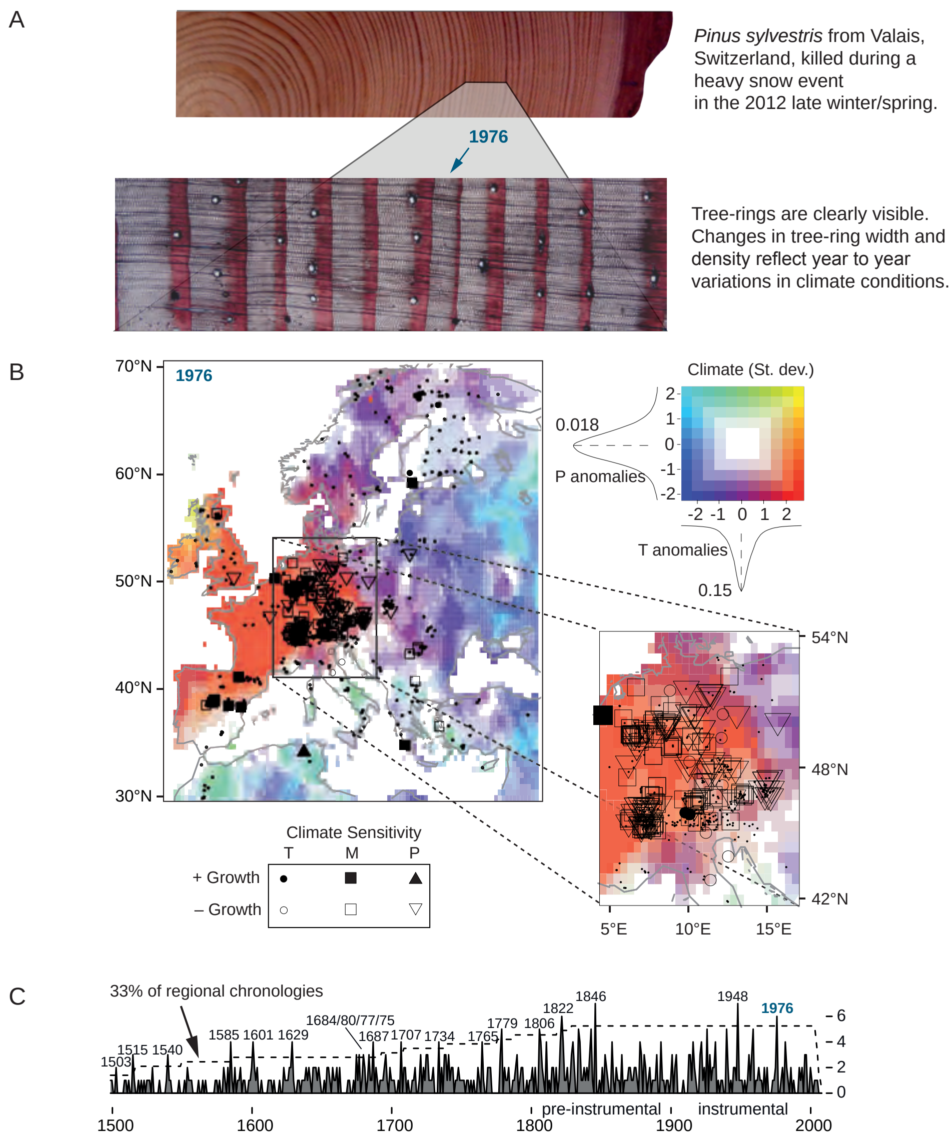

Figure 4.1: Impacts of climate extremes on the terrestrial carbon cycle archived in tree-rings.

A) Annual variation in tree-ring width and density in a sample from a Scots pine in Southern Switzerland - note the narrow and low density ring formed in 1976.

B) Summer climate conditions and growth differences across central and western Europe during 1976 were both hot and dry (red colors) causing narrow rings at many tree sites (see inset) where growth is known to be limited by precipitation availability (P; triangle) or mixtures of thermal and hydrological limitations (M; squares).

C) 500 years of growth extremes across Europe. Years where more than 1/3 of the regional growth series (maximum of 15) showed growth extremes are labeled. Figure extended from Babst et al. (2012a).

several hundred kilometers (Fig. 4.1B). While fewer tree-ring datasets were collected after 2003, it appears that the 2003 summer heat wave was associated with stronger growth reductions in 2004 demonstrating the delayed impacts on forested ecosystems from climatic extremes and the complexity of ecosystem responses. Growth extremes reconstructed for the past 500 years across Europe suggested strong carbon cycle impacts in, for example, 1948, 1846, 1601, and 1540 (Fig. 4.1C). Documentary evidence has confirmed the widespread impacts on European societies during 1540, and has led to speculation that impacts in this year were more severe than those from 2003 (Wetter and Pfister 2012).

Parallel efforts on other continents, finding tight links between tree-ring growth and climate extremes, have included recent investigations in the arid southwest US (Williams et al. 2012). Here, as well as in Europe, narrow tree-ring widths – associated with environmental stress – are also linked with increased mortality. While existing tree-ring datasets can be used to understand connections between tree growth and climate, new sampling schemes will be needed to obtain quantitative estimates of carbon uptake at annual resolution (Babst et al. 2012b, Brienen et al. 2012). Furthermore, CARBO-Extreme efforts have identified promising avenues to use tree-ring data to validate or falsify, and ultimately improve, the climatic sensitivities and feedbacks in dynamic global vegetation models and coupled earth system models (Tan et al. 2013 in review).

... opportunities to reduce uncertainties in earth system models...

Highlight Chapter 5

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Climate extremes can alter the carbon balance of terrestrial ecosystems, weakening the ability of ecosystems to remove carbon from the atmosphere, known as their C sequestration potential. In order to obtain a global estimate of the impact of climate extremes on the C cycle, we explored satellite observations of vegetation activity, merged with direct observations of CO_2 fluxes. Our results indicate that approximately half of the detected extremes can be associated with extremely low levels of water availability, and that drought globally plays a more critical role than extreme heat events, although the latter are also important.

Recent climate projections show that we may experience an increase of climate extremes over the next decades. Climate extremes can substantially alter the functions of terrestrial ecosystems, for instance their potential in sequestering CO_2. Under normal conditions, many ecosystems are expected to take more carbon up than losing via respiration and leaching. However, once climate extremes are manifested e.g. in droughts, fire events, or heat waves, most of these ecosystems tend to loose CO_2. One ardent research question is therefore, whether or not the effects of anomalous ecosystem responses under extreme conditions override the global C sequestration function of our ecosystems in the long term. If the latter were the case, then we would not only loose one ecosystem service (the C sequestration); we would have to consider yet another feedback in the climate system that could induce an additional accumulation of CO_2 in the atmosphere.

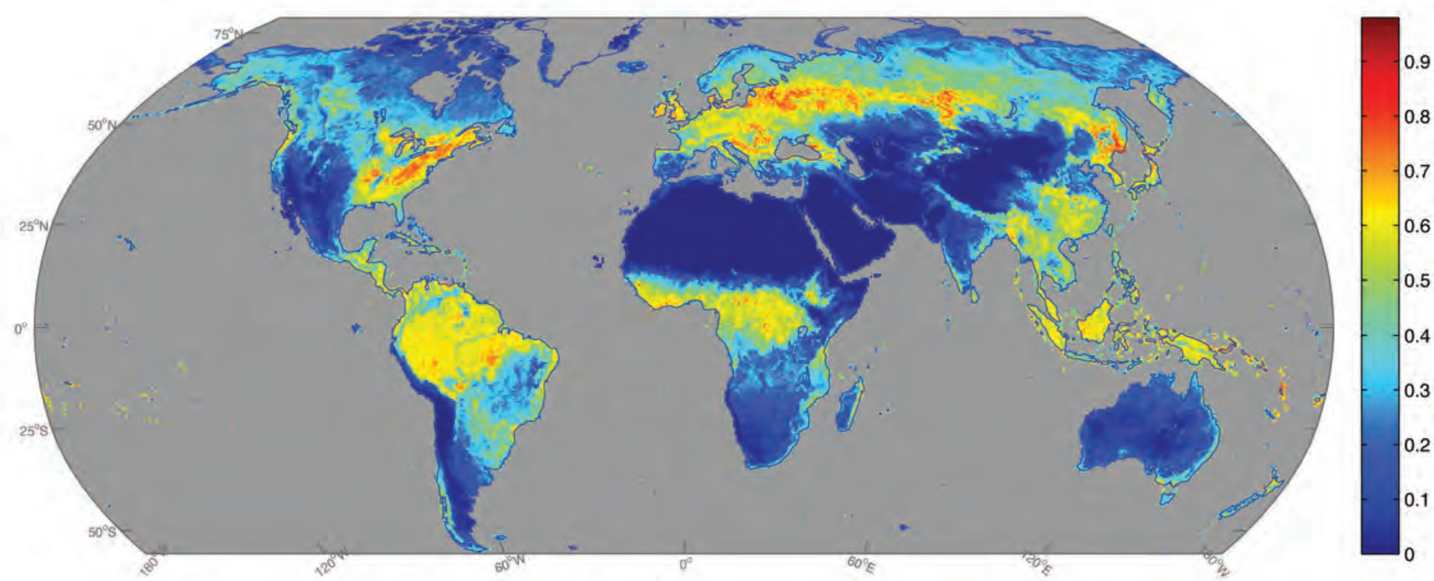


Figure 5.1: Monthly averaged fraction of Absorbed Photosynthetically Active Radiation (fAPAR) in June 2011 on a 0.5° global grid. Since fAPAR is a fraction, it ranges between 0 and 1.

Global detection and characterization of extreme impacts from satellites

Our research in CARBO-Extreme emphasizes the question how to achieve a consistent and objective global assessment of the impacts of extreme events on the carbon cycle. The intended global assessment is complicated by the fact that different ecosystems respond differently to various types of climate extremes such as droughts, heat waves, storms or fires. The idea of CARBO-Extreme is therefore to directly estimate anomalous events in ecosystems, rather than analyzing various climate extremes and estimating their impacts on a case-by-case basis.

Our impact perspective can be put into practice today by exploring satellite remote sensing data. Satellites have continuously observed the state of the vegetation on a global scale over more than three decades. Photosynthetic activity of the vegetation, governing the uptake of carbon by plants from the atmosphere, for instance, is measured by a variable called fAPAR (fraction of Absorbed Photosynthetically Active Radiation, Fig. 5.1). Looking for extremes in fAPAR can be interpreted as detecting large fluctuations in the photosynthetic activity – fluctuations which are tightly linked to the carbon uptake of plants. With fAPAR, and the help of site level data from FLUXNET stations (a global network of eddy covariance observations in tandem with site level meteorology, cf. pg. 12), global CO_2 uptake can be estimated. With this so called upscaled data, it is possible to compute the decrease in carbon uptake associated with extreme events in fAPAR compared to normal years. Figure 5.2 shows a global map of the largest 100 extremes in fAPAR averaged over the last 30 years with the corresponding decrease in carbon uptake per year and pixel. If only extremes are included that occur 5% or less of the time, the 100 largest extremes in fAPAR account for a decrease in carbon uptake of about 1 Petagram carbon per year (10^{15} g C/year) over the years 1982 to 2011.

The next question to explore then is: what kind of climate extremes have led to the detected extreme changes in carbon uptake. To answer this question, we analyzed the potential effects of temperature extremes, water availability and fire events. All of these data were analyzed over the same time periods and regions where the extremes in fAPAR have occurred. It turns out that limitation of water most often coincides with large decreases in carbon uptake. Out of 100 extremes in fAPAR, 49 could be associated with extremely low levels of water availability. Nonetheless, also fires and extreme heat could be associated with extreme decreases in carbon uptake (6 and 14 events out of 100, respectively).

Top pg. 16 from left to right:

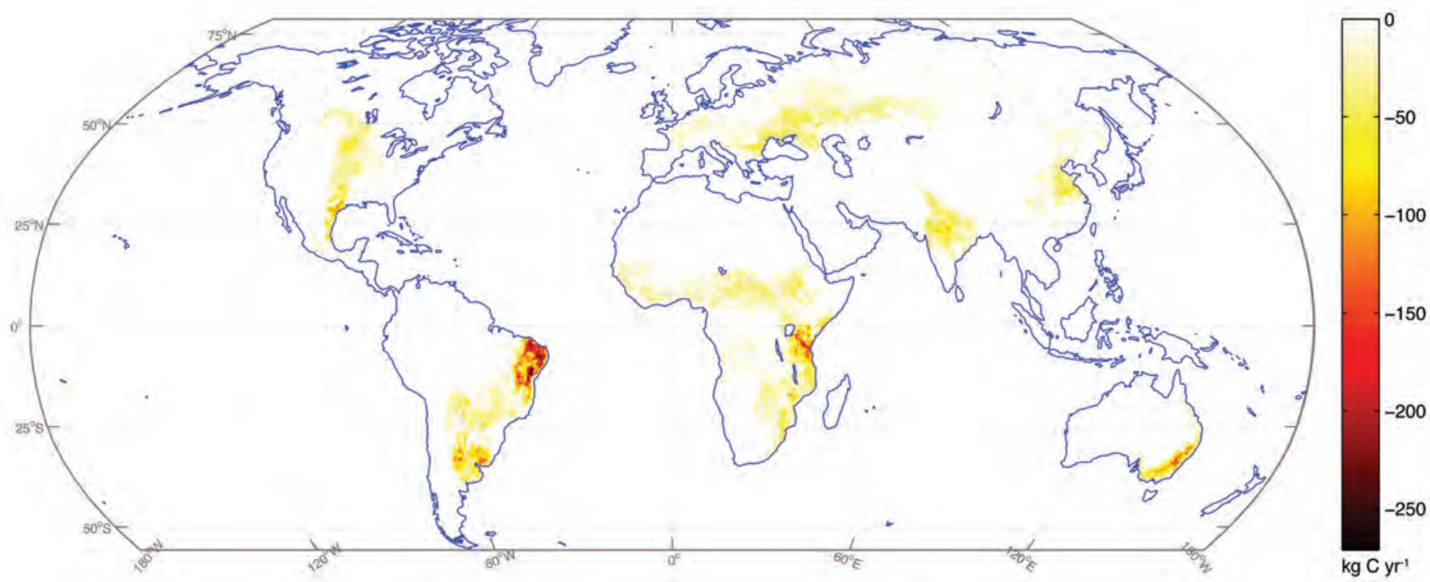
Recently burned forest near Tura, Krasnoyarsk Krai, Siberia. Photo: Martin Thurner.

Corn field during drought, Italy.

Bark beetle damage, Großer Rachel, Bavarian Forest National Park, Germany. Photo: Martin Thurner.

Satellite data enable us to detect extreme anomalies in vegetation activity across the globe.

Figure 5.2: Global map of 100 largest extremes in fAPAR with an occurrence probability of 1% or less, averaged over the years 1982-2011. Decrease in carbon uptake is given in kg/year per grid cell. The spatial resolution is 0.5°.



Highlight Chapter 6

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While there is no doubt that climate extremes have a strong impact on ecosystems and their carbon cycle, less is known about possible feedbacks from the ecosystems to the climate itself. These feedbacks do not only operate through the carbon cycle, but in particular via water and energy exchange. Those in turn depend strongly on vegetation growth and functioning, which are intimately linked with the carbon cycle. Hence the climate and biosphere build a complex coupled sub-system, where the carbon cycle plays an important, but not the only role. Carbon-cycle and biophysical feedbacks cannot be separated. It is possible that deforestation leads to local enhancement of climate extremes, and that feedback mechanisms which amplify the effects become important, in particular, under non-natural vegetation (i.e. in managed ecosystems).

Top: Aerial photos of a sharp vegetation boundary in Australia where convective clouds are confined to above native forest vegetation. Photos: Peter Schwerdtfeger/Jorg M. Hacker.

Impacts of climate on vegetation and ecosystems have long been known, not least since direct observations of plant health and growth in relation to climate have been crucial for agricultural cultivation for thousands of years. However, it has only relatively recently been recognized that biological processes can influence climate in a regionally and globally significant way. Terrestrial ecosystems constitute a major player in this respect: they can release or absorb globally relevant greenhouse gases such as carbon dioxide (CO_2), methane and nitrous oxide, they emit aerosols and aerosol precursors, and they control exchanges of energy, water and momentum between the atmosphere and the land surface. Hence all impacts of climate extremes on ecosystems may exert feedbacks to the climate system, directly or indirectly. Hence, these feedbacks, in the short- or long-term, can alter the frequency, duration and intensity of climate extremes, but exact knowledge is lacking. Short-term feedbacks which operate within days can lead to the immediate regional occurrence or amplification of extreme climate events. In particular feedbacks with surface conditions are relevant, such as soil moisture content (see Fig. 6.1). For the former, the physiological response of vegetation to drought is crucial (because this determines arrows A in Fig. 6.1), and can for instance control the intensity and persistence of hot extremes in several regions of the world (e.g. Seneviratne et al. 2010, Hirschi et al. 2011, Mueller and Seneviratne et al. 2012; Fig. 6.2). This response can also vary with different land cover and soil types and also as a function of the drought persistence and intensity (Teuling et al. 2010).

Another regional to global feedback operates through changes in vegetation albedo,

i.e. the fraction of sunlight that is reflected back into the atmosphere. A low albedo leads to absorption of energy by the land surface and thus surface warming, and possible stronger convection. Low snow cover, e.g. after a dry winter, can lower spring albedo due to earlier snow melt. Human- or climate-induced change in vegetation cover also affects albedo, evapotranspiration and atmospheric convective processes. This is illustrated in the photos on pg. 18, where clouds are more likely to form over forests than over non-forest vegetation. Consequently, deforestation is increasingly thought to be a co-factor causing droughts and other climate extremes, particularly in South America (Malhi et al. 2008, Medvigy et al. 2011).

Because of very fast mixing of CO_2 in the atmosphere, carbon cycle feedbacks are expected to operate only globally through the well-known greenhouse effect. The research question is how much carbon is released from ecosystems into the atmosphere through climate extremes globally, and will that substantially change the climate-carbon cycle feedback. Results from CARBO-Extreme indicate the potential for an enhanced warming through this climate-extreme carbon-cycle feedback, but a final answer requires more long-term observations, dedicated experimental research, and improved biosphere models.

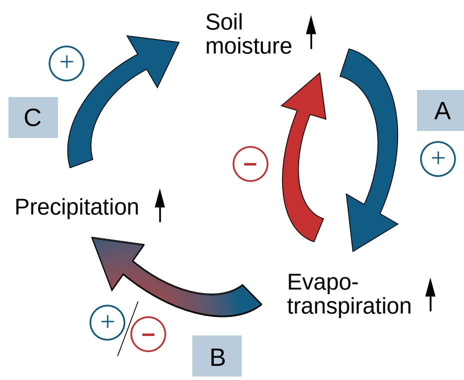

Figure 6.1: Processes contributing to soil moisture–precipitation. Positive arrows (blue) indicate processes leading to a positive soil moisture precipitation feedback (wetting for positive soil moisture anomaly, drying for negative soil moisture anomaly), the negative arrow (red) indicates a potential negative feedback damping the original soil moisture anomaly, and the red-blue arrow indicates the existence of both positive and negative feedbacks between evapotranspiration and precipitation anomalies. Source: Senevirtane et al. 2010, Earth Science Reviews, Fig. 10.

Ecosystems actively affect climate extremes, inducing two-way interactions.

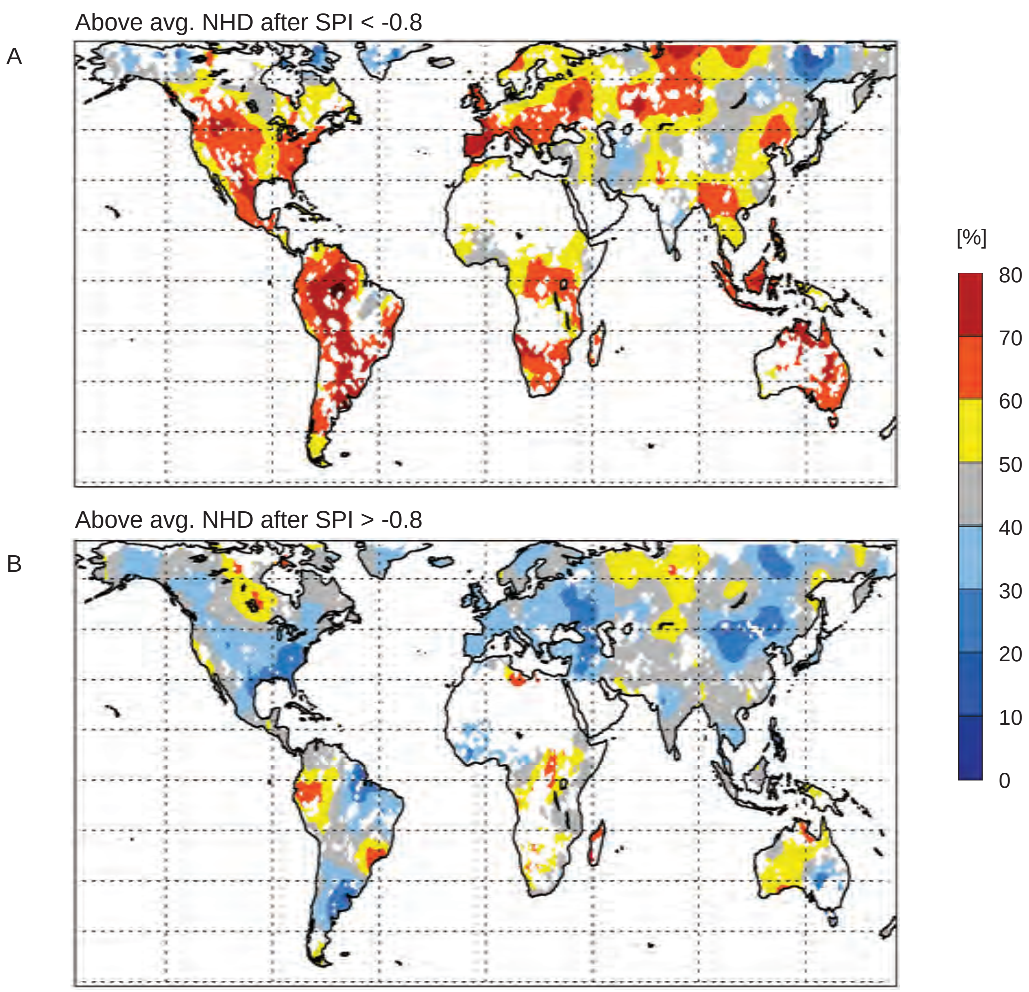

Figure 6.2: Hot day occurrence probability after dry versus wet conditions. Percentage probability of an above-average number of hot days (NHD) in the respective regions' hottest month of each year after:

A) a 3-month dry period (Standardized Precipitation Index (SPI) < -0.8);

B) a 3-month wet period (SPI > 0.8).

The employed datasets are the ERA-Interim reanalysis for NHD and the precipitation dataset from Climatic Research Unit (CRU) for SPI. Results are similar for other available datasets. The drought impact on hot days is mediated by the vegetation response to decreased water availability and resulting effects on evaporative cooling.

Source: Mueller and Seneviratne 2012, Fig. 4, © 2012 National Academy of Sciences, USA.

Highlight Chapter 7

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A glimpse into the future – Ecosystem Manipulation Experiments!

Top left: Rainout shelters on a mountain meadow at 1850 m, Kaserstattalm, Stubai, Austria. Photo: Michael Bahn.

Top right: Measuring drought effects on the CO_2 exchange between a mountain meadow and the atmosphere. Photo: Eva Fessler.

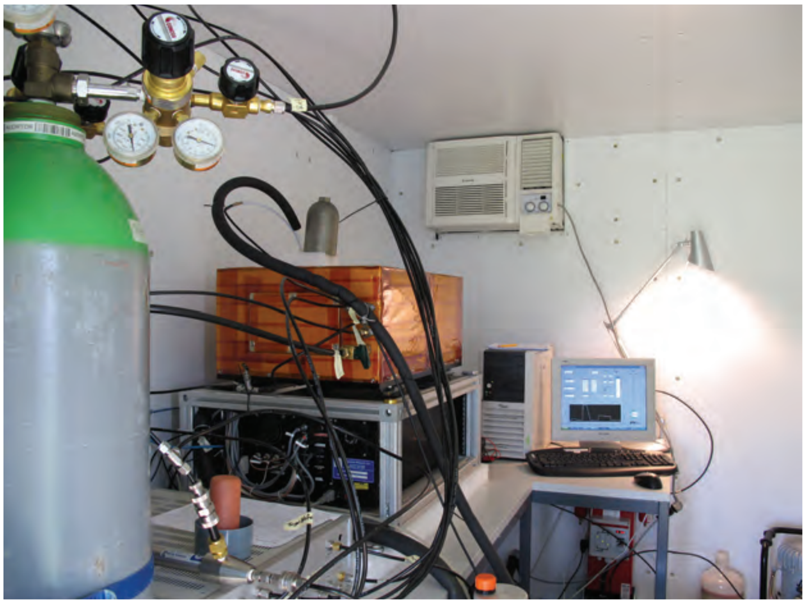
Simulation experiments allow us to address questions of how the duration, intensity and timing of an extreme event affect various carbon cycle processes simultaneously. The responses obtained by these experiments are not only insightful in themselves, they also provide useful input parameters for ecosystem models.

Extreme events are difficult to predict, which is why, under natural conditions, ecosystems are rarely sufficiently well instrumented to monitor and understand the detailed responses of ecosystem processes to weather extremes when they occur. Furthermore, it is difficult to compare different extreme events occurring in different regions with different durations and intensities, and to obtain a general framework for understanding ecosystem responses.

To overcome these limitations, ecosystem manipulation experiments are helpful in that they simulate well-defined extreme conditions and permit a systematic analysis of the effects of extreme events on ecosystems. For example, rainout shelters, which prevent precipitation from entering ecosystem sections (plots) during a defined period, can induce conditions of drought in a temperate grassland or shrubland, and can thereby mimic a situation, which will probably occur in a future climate. Biomass production, ecosystem carbon dioxide fluxes, loss of water through evaporation and transpiration, as well as the total amount of carbon lost or gained by the ecosystem, can be measured in plots subjected to such a drought treatment and compared with plots receiving an amount of precipitation typical for a normal year. Such a standardized approach allows the effect of an extreme event to be quantified and compared both for similar and different types of ecosystems and at different times of the year.

For example, it has been observed that grasslands growing at different elevations and under different rainfall regimes respond very differently to experimental drought, with respect to both their surface temperature (Fig. 7.1) and their productivity (Gilgen and Buchmann 2009).

Using simulation experiments, both in the field and on plant communities grown in containers, it has also been shown that the timing of a drought and of rainfall may cause different responses (Knapp et al. 2002, De Boeck et al. 2011). Furthermore, experiments permit testing effects of the duration and intensity of an extreme event, and to identify to what extent an ecosystem process can resist a defined stress and how fast and how well it can recover from such a stress.



Simulation experiments may also help to identify the relative effect of different aspects of an extreme event. For example, during a heat wave, heat and drought may influence plants and ecosystems to a different degree (Dreesen et al. 2012).

In addition, simulation experiments provide the opportunity to simultaneously monitor the sensitive carbon cycle processes of plants and soils at high time resolution. Stable isotopes can be used to follow the pathway of carbon in an ecosystem, to observe how carbon is transferred from leaves to roots and the soil, and to identify how much of it is stored or respired under extreme conditions. For example, using a carbon isotope tracer, it has been shown that the reduction of photosynthesis under drought causes less carbon being transported to grassland roots, which in consequence decreases the carbon flow to the soil animals feeding on these roots (Seeber et al. 2012). Furthermore, young beech trees have been shown to use the carbon they have assimilated in their leaves during photosynthesis more slowly for belowground respiration under drought (Ruehr et al. 2009).

Top left: Laser spectrometer installed in the field: Soil respiration and its isotopic composition are measured continuously. Photo: Susanne Burri.

Top right: Tracer experiment in the field at ETH research station Chamau: Labelling atmospheric CO_2 with stable carbon isotopes allows to follow carbon through the plant-soil system. Photo: Susanne Burri.

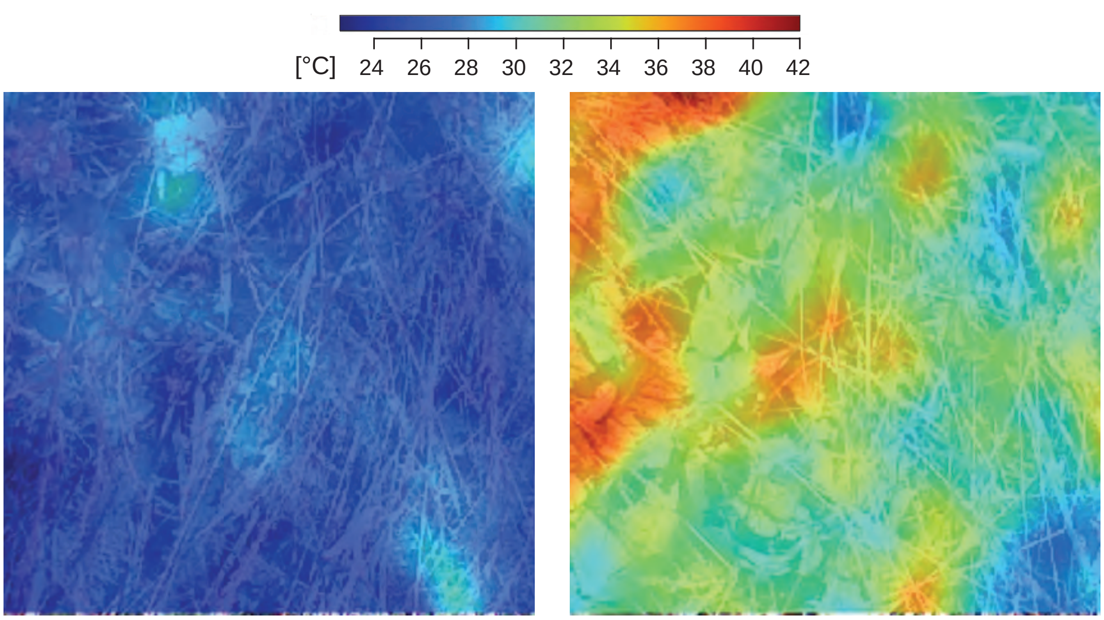
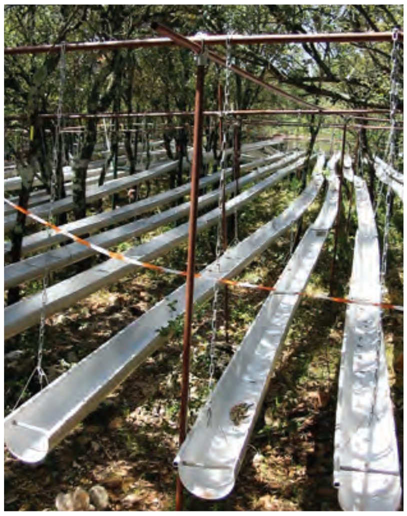


Figure 7.1: Effect of summer drought on vegetation surface temperatures. Lower temperatures (left panel) indicate higher water loss due to cooling of the vegetation by transpiration under control conditions. In contrast, higher temperatures (right panel) indicate lower transpiration rates due to low soil moisture availability under drought conditions. Thermopictures: Dr. Anna K. Gilgen, University Bern, Oeschger Centre for Climate Change Research.

Highlight Chapter 8



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Top left: Rainfall exclusion experimental setup at the Hesse forest, France. Photo: André Granier.

Top two right: Rainfall exclusion experiments, Puechabon, France. Photos: Jean Marc Ourcival.

Observing ecosystem responses to changing environmental conditions at site level is essential for our understanding of ecosystem functioning and our ability to simulate underlying processes. Bringing together models and wide-ranging observations of ecosystem responses to extreme events, provides a unique framework to improve our modeling ability, from year to year variations, and to future impacts of climate variability.

Global simulations of the carbon cycle into the future have shown marked discrepancies between the different models; predictions range between strong sinks and moderate sources of carbon (Friedlingstein et al. 2006). Local observations of ecosystem properties and dynamics are a unique source of information to study mechanisms of ecosystem functioning, and responses to changes in climate, and also to evaluate how models simulate them. Despite the multiplicity of measurements in natural conditions, not many long-term datasets of ecosystem responses to climate, such as observations of ecosystem responses under extreme weather conditions, are available. This is an issue, since models are not always able to describe year to year changes in the carbon and water fluxes between the terrestrial ecosystems and the atmosphere. Model behavior under extreme events has rarely been examined (Fischer and Schär 2010). We rely on detailed comparisons of model results with observations to understand how different measurements can contribute to reduce these uncertainties and to allow model formulations to be improved.

Can the same model setup describe ecosystem responses under normal and extreme weather conditions? To answer this question, experiments where the carbon balance of the ecosystems was studied were carried out in seven European countries. In these experiments, ecosystems were subjected to manipulations that create extreme conditions with a relevant potential of future occurrence, and their impact was followed over several years of study.

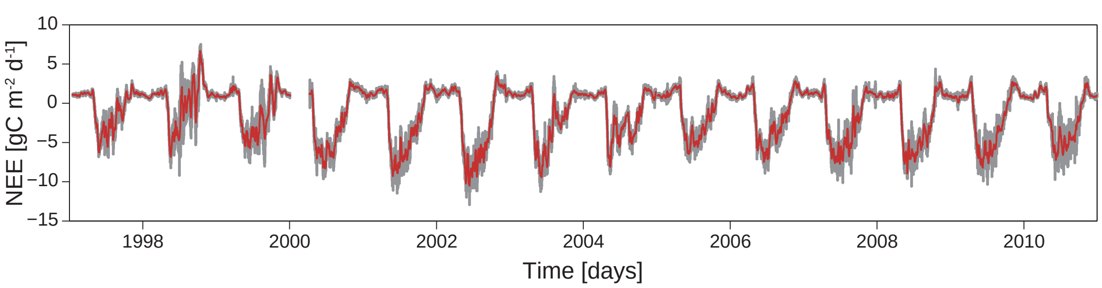

Figure 8.1: Fourteen years of Net Ecosystem Exchange observations (in red, data uncertainties in grey) at the Hesse forest, France.

These experiments include increases in temperature, reductions in precipitation (cf. photos pg. 22) and irrigation, increases in atmospheric CO_2 concentrations; and also human management effects, like increasing nutrient loads (fertilization) and tillage, and thinning activities. The data from these experiments were used to improve the quality of the models. In theory, a comprehensive model should be able to perform equally well under non-manipulated and manipulated conditions using the same setup. However, a need to adjust the ecosystem functional responses between both cases suggests limitations in modeling structures. For example, at the Brandbjerg heathland in Denmark several different treatments are carried out, including increase of atmospheric CO_2 concentration and rain exclusion (photo this page). When a generic vegetation model was optimized for the control condition, it was also shown to well-predict biomass in the increased CO_2 and rain exclusion experiments. However, the results showed that the model had to be calibrated for each of the individual treatments for the appropriate estimation of total ecosystem respiration (Thum et al., in preparation).

Can long term observations of ecosystem processes help to reduce the uncertainty between model predictions under future climate scenarios? Here we rely on detailed measurements of carbon and water exchange between the ecosystem and the atmosphere for long time periods, in excess of twelve years (Fig. 8.1). In addition, estimates of below- and above-ground carbon stocks are also integrated in the analysis, offering a more comprehensive characterization of the ecosystem. A quite diverse set of models was chosen for this modeling experiment, including ecophysiology-based agricultural and forest management models, to models that simulate the land surface in global climate models used to estimate future conditions. The main idea is that by ensuring a superior performance of these models in explaining these long term observations of different ecosystem components, the divergence in future simulations should be reduced (Fig. 8.2). For example, current results have shown that comparing the same model with different types of observations already implies differences in model parameterizations that change future trajectories of ecosystem fluxes of carbon, and that in general, the year-to-year variability of these fluxes also increases. These results highlight the relevance of appropriate representations of ecosystem responses to climate from short to longer temporal scales, where the dynamics of carbon and water in plants and soils conditions in time exert a strong control.

Top: The Brandbjerg experimental setup. Photo: Tea Thum.

Computer models are needed to get insights about the future, while learning from past observations.

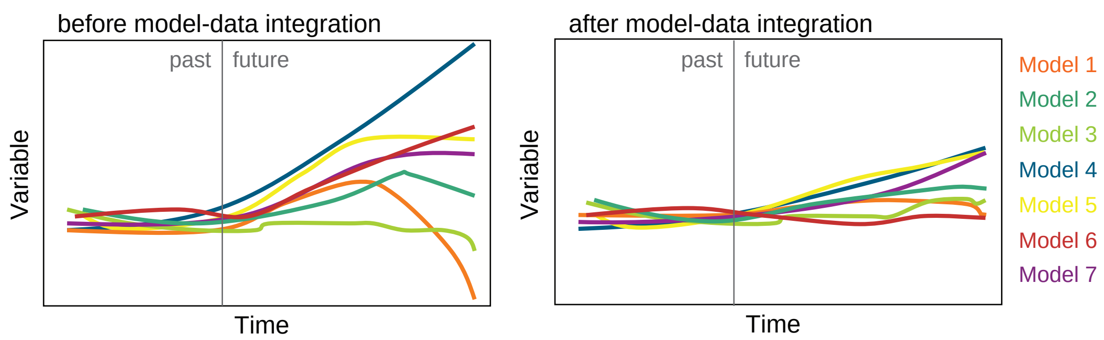

Figure 8.2: Conceptual hypothesis behind the long term model-data integration experiments: model-data integration is expected to decrease our uncertainty of future projections.

Highlight Chapter 9

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Top left: Eddy covariance tower on an alpine grassland during summer, Albula, Switzerland. Photo: Lutz Merbold.

Top right: Primeval beech forest, Falkenstein, Bavarian Forest National Park, Germany. Photo: Martin Thurner.

The future is not observable – hence we need to employ simulations with state-of-the-art models to estimate the effect of changing climate on the terrestrial carbon cycle. Similar to the manipulation experiments above, modeling experiments can be pursued to study specific factors such as climate variability. The application of a multitude of process-based ecosystem models to such experimental climate data, in addition to the normal climate dataset, quantifies the single effect of climate variability and extreme weather conditions on the European carbon balance during 1960-2100.

Regional climate projections until 2100 show increasing variability and frequency of extreme events of meteorological variables in Europe at different scales (Fischer and Schär 2010), in addition to e.g. a gradual increase in air temperature. The effects of such changing variability on ecosystem functions, such as productivity, carbon, nutrient and water availability, or greenhouse gas balances remain unclear. Day-to-day variability of weather condition and the frequency of extreme events might affect ecosystem state and functions more than a gradual increase in the mean climate condition. We contribute to this question from a theoretical point of view by forcing prognostic terrestrial ecosystem models with an artificial climate dataset (REDVAR) which shows reduced climate variability in conjunction with conserved long-term means compared to the control climate data (CNTL).

Step 1a: Bias-correction of several ENSEMBLES (http://ensembles-eu.metoffice.com/) regional climate model outputs (A1B scenario) against WATCH forcing data (http://www.eu-watch.org/) for period 2010-2100 for deriving one consistent time series during 1901-2100.

Step 1b: Transform meteorological variables such that day-to-day and year-to-year variability is reduced but long-term annual and seasonal means are kept the same.

Step 2: Application of several process-based generic and sectorial ecosystem models (cf. Box 'Ecosystem models') to these climate datasets in a factorial experiment where a) constant versus changing climate and b) constant versus changing atmospheric carbon dioxide concentration are varied.

Ecosystem models

To cover a wide range of modeling approaches and domains we utilize several process-based terrestrial ecosystem models that simulate carbon dynamics for specific sectors. DailyDayCent (University of Aberdeen) and EPIC (IIASA) are used for the agricultural sector, PASIM (INRA) simulates grasslands and pastures while BASFOR (CEH) and CASTANEA (CNRS) are specialized on forest ecosystems. Generic models describe all three ecosystem types at once as fractions of a grid cell. Therefore, generic model results for each grid cell can be understood as the aggregation of processes that influence the atmosphere. ORCHIDEE (LSCE), LPJmL (PIK) and JSBACH (MPI-BGC) are such generic ecosystem models used in CARBO-Extreme.

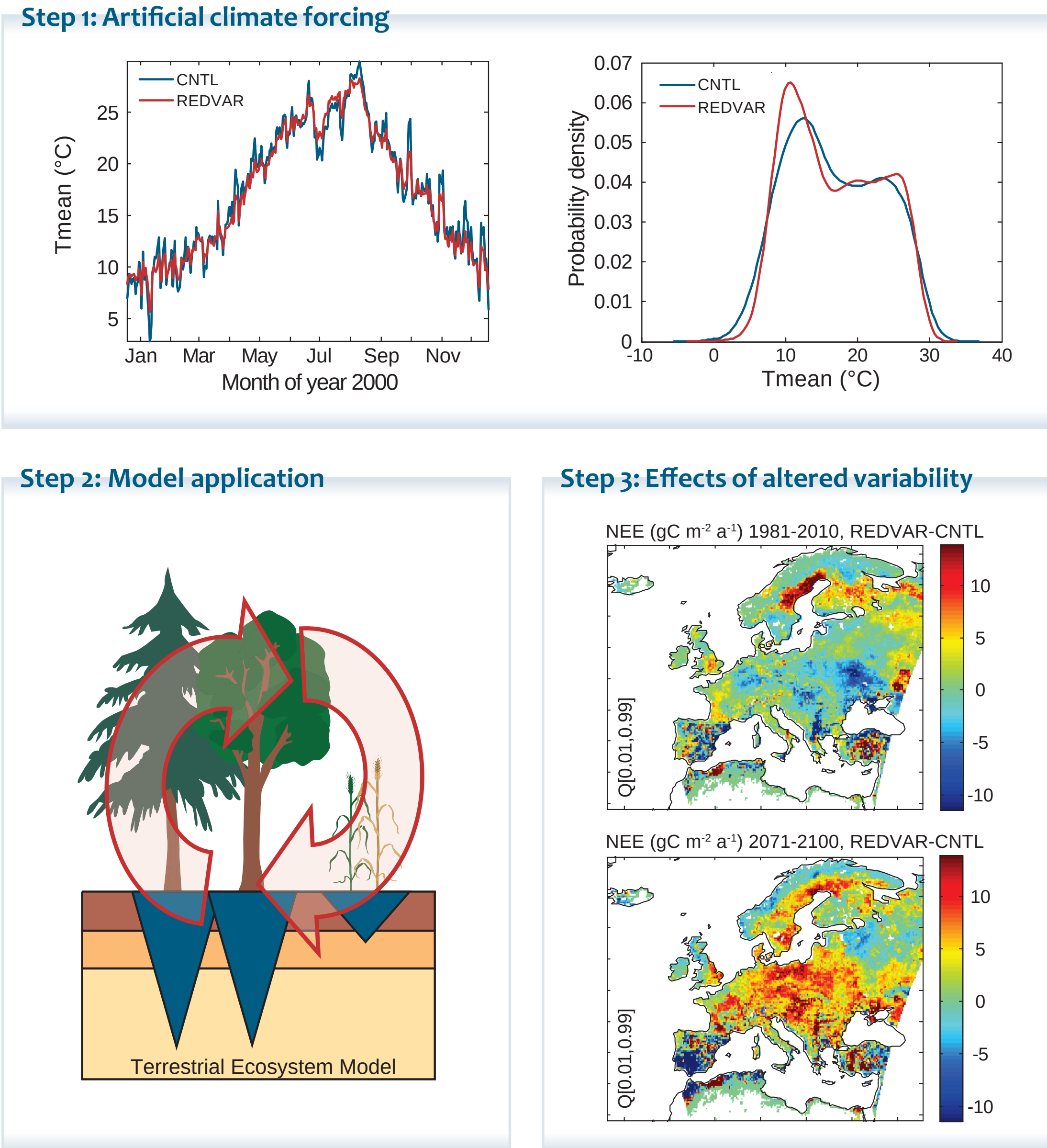

Figure 9.1: Factorial model experimental approach in CARBO-Extreme: Climate data with artificially reduced variability but conserved long-term mean is applied to prognostic ecosystem models to quantify the continental-wide impact of variability and extreme events of meteorological drivers on the carbon balance.

Step 3: Analyze differences of long-term means of land-atmosphere carbon and water exchanges among factorial experiments using either REDVAR or CNTL climate forcing data.

As shown in Fig. 9.1, climate variability has potential effects on the net exchange of carbon dioxide between the land surface and atmosphere. There are clear spatial patterns of this effect which are different in recent times (1981-2010) compared to the end of the century (2071-2100). During 1981-2010, the JSBACH model suggests small effects in Central Europe and larger effects in parts of the Scandinavian boreal forests and in opposite direction in the Ukraine and Spain. However, during 2071-2100 net ecosystem exchange is projected to be much higher under reduced climate variability over most of the continent except the Mediterranean, Norway, Scotland, and Baltic countries. In contrast to grasslands and forests, management has the highest impact on the carbon balance in agricultural systems. Tillage, fertilizer applications, crop rotation and irrigation strongly affect the carbon dynamics and may compensate the impacts of extreme weather events. Analyzing results from further factorial model experiments will help identifying underlying mechanisms to explain these spatial pattern. The continental-scale modeling results will also be used to estimate vulnerability and susceptibility in work package 7.

Enhanced climate variability is projected to having opposite effects on the future carbon balance depending on the location in Europe.

Highlight Chapter 10

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Forests are susceptible to all kind of weather extremes, resulting in direct and lagged impacts on tree growth and mortality in the year(s) after the extreme event.

Top left: Drought, caused by low summer precipitation at the Island of Simi, Greece. Photo: Marcel van Oijen.

Top right: Pinus sylvestris die-off in Sierra de Los Filabres, Andalusia, Spain. Photo: Raúl Sánchez-Salguero.

All land use types are vulnerable to climate extremes. With both their large carbon stocks and their carbon uptake from the atmosphere being affected by weather extremes, forests are expected to experience large net impacts on their carbon balance. In croplands and grasslands, however, despite significant impacts of extreme events, many can be mitigated through management, either within the same year or through longer term adaptation.

All land use types in Europe (largely comprising croplands, grasslands and forests) are vulnerable to climate extremes to some degree. However, given their different characteristics in terms of carbon storage and the frequency with which they are replanted, some are more vulnerable than others. For example, forests and peatlands store large quantities of carbon and are vulnerable to large losses through fire, and adaptive management is difficult due to the longevity of trees and the slow accumulation rate of peat. On the other hand, croplands and grasslands contain less carbon and, are more suitable to adaptive management, since they are typically replanted more often as part of their regular management.

One of the difficulties in dealing with climate extremes is that ecosystems sometimes respond to extremes with a time-lag which means then they may not be recognized as linked to this event. Table 1 summarizes the impact of extremes on different ecosystems, indicates any lagged effects and shows the potential size of the impact.

Forests (including native woodlands as well as managed forests) grow in a wide range of climatic zones from the boreal zone to the tropics. Their longevity, low migration rate (compared to short-lived species) and their high carbon stock makes them very vulnerable to extremes that cause long-term changes in tree growth and forest mortality. Agricultural land (croplands and grasslands) covers a large portion of Europe's area. Extreme weather can result in reduced productivity or even total crop failure (Table 1). Successful farming requires that farmers adapt to climate variability. Extreme weather events can impact crops via both negative impacts on plant physiological processes and direct physical damage, as well as by affecting the timing and conditions of field operations.

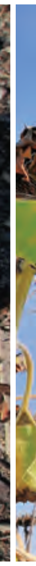
Drought strongly affects the water and carbon fluxes in forests and in agricultural land. Severe and recurrent droughts have been identified as a major contributing factor in recently accelerated rates of tree decline and mortality (Allen et al. 2010). In agriculture, crop failure can be addressed by replanting but in the longer term, the introduction of drought resistant crops is an important adaptation strategy.

Extremes and their impact on agriculture & forestry

Table 1: Impacts of climate extremes on agriculture and forests

	Affected ecosystem	Impact mechanism	Indirect and/or lagged effects	Potential impact size
Drought	Croplands, grasslands and forests	• changes in where the carbon occurs in the plant (allocation) via water flux impacts on plant physiology and phenology (annual growth cycle)	a) increased fire risk b) increased susceptibility to pathogen outbreaks c) increased soil erosion (drought plus wind) d) lagged impacts on plant growth & mortality in long-lived species e) shifts in vegetation composition towards drought stress resistant plants	• large spatial extent • long-lasting effects
Heat wave	Croplands, grasslands and forests	• (warming) may increase plant growth in temperature-limited regions • reduced photosynthesis (by extremely high temperatures if >40°C) • shifts in phenological phases (e.g. reduced grain filling) • reduced pollination success • positive feedbacks with drought	a) impact if the heat wave leads to drought - see entry for drought (above)	• large spatial extent • long-lasting effects
Extreme frost	Croplands	• formation of ice crystals leading to damage of leaves and flowers • stem and roots reduction in C uptake and retention	a) complete crop failure or b) reduced growth	• local to regional • seasonal lag effects
Heavy precipitation	Croplands	• physical damage to crops via water logging impact on carbon & water fluxes and plant physiology	a) erosion/ landslides; lateral transport of soil organic matter (SOM) out of the system b) degradation (losses in SOM, soil nutrients, water retention capacity) and lower productivity c) complete crop failure or reduced growth	• local to regional
Heavy storms	Forests and croplands	• trees and crops blown over (windthrow in trees and lodging in crops) leading to tree mortality and crop failure	a) windthrow leading to accumulated dry dead wood increases fire risk, and risk of pest & pathogen outbreaks b) complete crop failure or reduced growth c) erosion if sparse vegetation cover (e.g. crop fallow)	• local to large spatial extent • long-lasting effects
Fire	Forests and grasslands incl. savannah	• biomass loss • sudden release of large quantities of accumulated carbon • increased tree mortality	a) degradation b) species composition shifts c) desertification & erosion d) loss of water supply function (especially in non-fire-adapted systems and if under additional pressure e.g. overgrazing)	• local to large spatial extent
Pest & pathogens	Forests and croplands	• plant health reduction • plant mortality	a) reduced or delayed crop emergence b) complete crop failure or reduced forest and crop growth	• local to regional

Highlight Chapter 10



The 2003 heat wave in parts of Europe reduced crop yields by 20% compared to the mean for 1991-1999.

Fuhrer et al. 2006

Top left: High meadow (German: 'Schachten'), Bavarian Forest National Park, Germany. Photos: Martin Thurner.

Top right: Bark beetle damage, Bavarian Forest National Park, Germany. Photo: Martin Thurner.

Bottom: Storm 'Klaus' in January 2009 in a maritime pine forest near Bordeaux, France. Photo: Marie Guillot.

Heavy storms and tropical cyclones can cause trees to be blown over (called wind throw by foresters) and can lead to severe damage and mortality of trees, animals and humans. Often, forest damage occurs when trees are planted outside of their natural range. Wind throw may lead to subsequent insect outbreaks or massive fires due to large amounts of dry dead wood, with long-term consequences for the carbon balance, especially where decomposition rates are slow.

In agriculture, crops can also be blown over (called lodging by farmers), resulting in crop damage or total loss. Shorter crop varieties have made cereals less prone to lodging. However, also extreme rainfall can cause damage, particularly by soil erosion in croplands.

Forest insects, and diseases caused by **pathogens**, lead to major disturbances that damage millions of hectares of forests annually, and extreme events impact on their occurrence and outbreak: drought extremes may increase the vulnerability of trees to forest insect and pathogens (e.g. via reduced plant health), less frequent extreme cold periods can reduce the cold-associated mortality of insect pests, whereas insect outbreaks are widespread after heavy storms causing wind throw e.g. in spruce forests. In agriculture, damp conditions after extreme wet periods favour pest and disease development, increasing lodging, and reducing grain quality.

Fires are very relevant in forests, because the carbon stored in the living biomass, the litter and sometimes the soil pool is lost to the atmosphere, but the potential for future sequestration (primary productivity) is also lost. For the loss of carbon stocks in soils and roots, the intensity of the fire, and whether or not it reaches the humus layer of the soil, are important factors. Depending on the severity of the burning, the recovery of these forests depends on their ability to regenerate after fire, but also on the sensitivity of the vegetation to fire. In a moderate-intense burned area, patches of less-damaged trees act as recovery cells

for the next generation to establish. If the seed pool is heavily damaged this might take decades, as will the re-sequestration of the carbon lost in fires.

Whilst the increasing CO_2 content of the atmosphere and warmer temperatures are expected to benefit plant growth in cold-temperature limited regions like northern Europe, increasing drought and disturbance risks may dampen these positive effects on forest growth. More frequent and longer lasting droughts as well as an increased fire risk will probably cause a decline in forest productivity in the Mediterranean and Southern Europe (e.g. Lindner et al. 2010). Current climate-change projections for Europe show, that biomass consumed by fires could increase in temperate and boreal regions. The Mediterranean on the contrary might get into the situation, where fires are increasing at the beginning of the 21st century, but further increase in drought conditions might limit vegetation productivity in such a way that there might not be enough dead biomass available to allow fires to spread. This might lead to less biomass actually being burned in wildfires by the end of the 21st century, despite increasing climatic fire risks.

Forests will need to adapt to the future increased weather variability with greater risk of extreme weather events, but the complex interactions and dynamics of forest ecosystems make it difficult to predict the impacts of extreme events on the forest carbon cycle. Peatlands also suffer under heat waves and drought, losing large amounts of their stored carbon. While croplands and grasslands are exposed to the same range of extremes as other ecosystems, many of the negative impacts can be mitigated through management, either within the same year (e.g. irrigation, replanting of a failed crop), or through longer term adaptation (e.g. changed rotations, drought/heat resistant cultivars). The response of croplands and grasslands to extreme climatic events is, therefore, strongly coupled to the management actions taken during, or in response to, an extreme event.

Increased temperatures and wetness are thought to spread pests and pathogens beyond their current range in croplands, to introduce alien species, and to increase the multiplication rates of pests and pathogens.

Gregory et al. 2009

Top left: Sunflowers burned due to drought in summer, Italy.

Top right: Maize damaged by hail.

Bottom: Winter time in Scots pine forests with decline in Andalusia. Photo: Raúl Sánchez-Salguero.

Highlight Chapter 11

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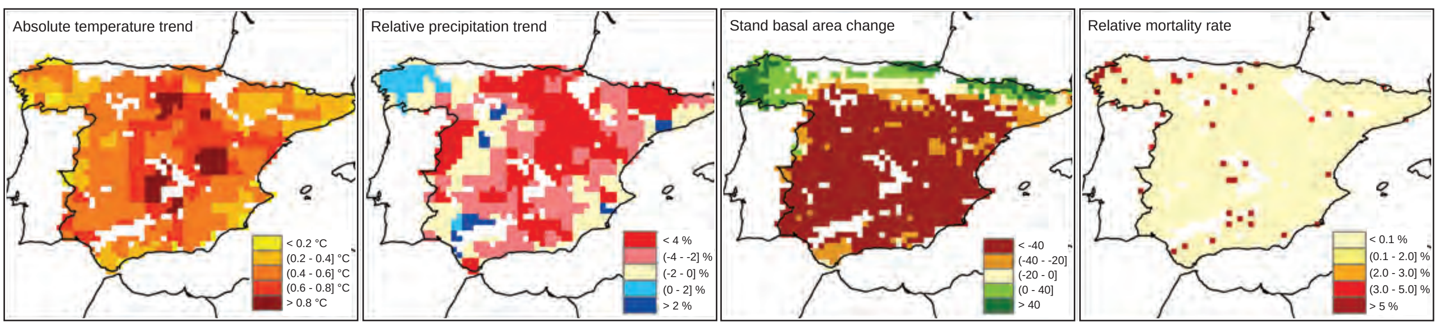
Top: Forest decay in inland dunes of Central Spain at the end of the 20th century. Photos: Jaime Madrigal-González.

Mediterranean forests may undergo important changes with climate warming. Among the most important forest functions, productivity and carbon storage could dramatically diminish as a consequence of increasing water deficits and recurrent extreme drought events. Management of forest stand structure and age distributions can be efficient practices to maintain principal forest functions under climate change.

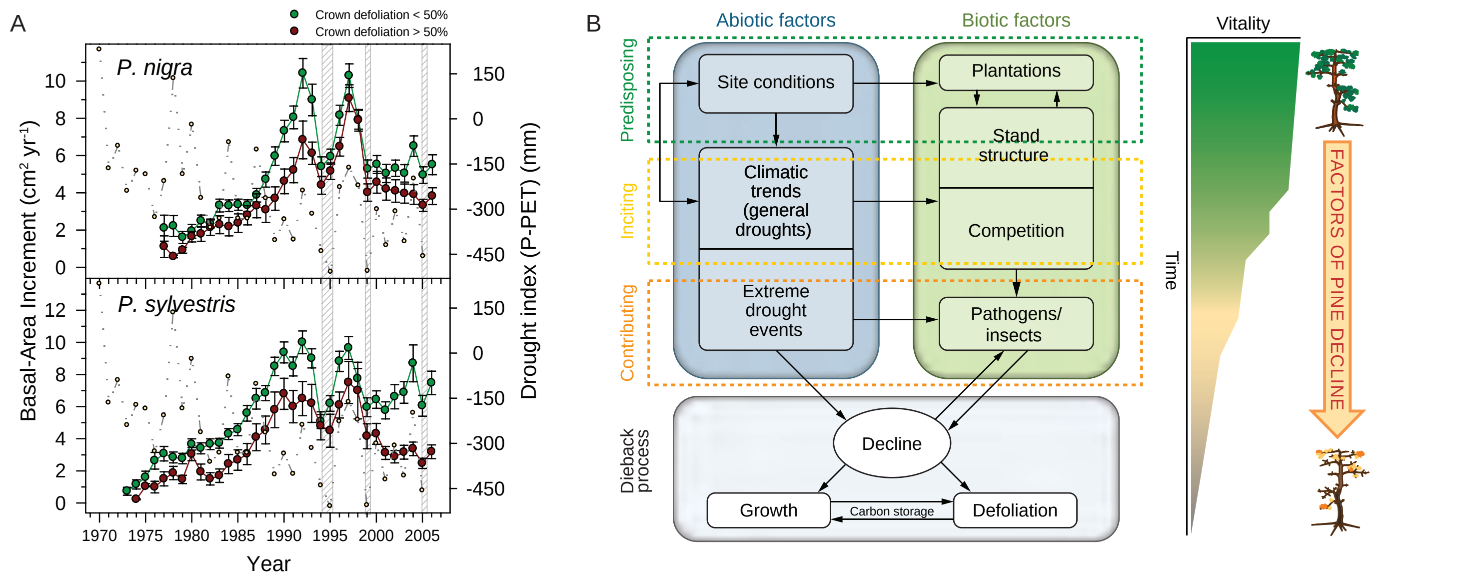
Mediterranean Europe is currently considered a hotspot of climate change as future warming conditions will dramatically aggravate the chronic summer drought that limits productivity and other important ecosystem functions (Lindner et al. 2010). Mediterranean forests have a medium carbon sink potential compared to other European temperate forests, with a neutral-negative biomass balance at the end of the 20th century (Fig. 11.1, Ruiz-Benito et al. 2013 in review). The combination of warming conditions and lower precipitations may have resulted in significant losses in forest biomass pointing to extreme droughts as major hazards diminishing the mitigation capacity of forests under rising concentration of atmospheric carbon. Understanding these patterns and designing adaptive practices to counteract climate change effects will require a thorough understanding of the mechanisms underlying carbon sink dynamics.

Along with tree species well adapted to aridity, some key species have their distribution margins in Southern Europe and are considered particularly vulnerable to climate change (Hampe and Petit 2005). Accordingly, Scots pine and European Black pine forest plantations in Southern Spain, were found to experience severe declines (i.e. extensive tree dieback) in response to unusually extended droughts occurring at

Figure 11.1: Recent temperature and precipitation trends suggest that the Mediterranean region is a climate change hotspot which has been exposed to unusually severe droughts at the end of the 20th century (data provided by NOAA/OAR/ESRL, PSD, Boulder, Colorado, USA, http://www.esrl.noaa.gov/psd/; Matsuura and Willmott 2011). As a consequence, forests are losing their carbon sink capability due to increasing tree mortality and growth suppression (Ruiz-Benito et al., data from Spanish Forest Inventory, MAGRAMA).



Mediterranean hotspot: climate change impacts on forests at the edge



the end of the 20th century (Sánchez-Salguero et al. 2012). Forest decline, however, seemed the result of a long, complex chain of events triggered by episodic droughts (Fig. 11.2). Similarly, species well adapted to aridity such as maritime pine, showed an exponential growth decline in response to increasing drought frequency along the 20th century (Madrigal-González and Zavala 2013 in review). Interestingly, increasing drought frequency rather than drought severity, was a key driver of tree growth suppression in this drought-avoiding species. In both cases, forest stand structure (e.g. size, competition and crown status) as well as tree age, revealed as crucial factors that modulate tree responses to drought. Evidence from dendrochronology and historical inventories suggested that young suppressed trees were considerably more sensitive to aridity than older trees (Fig. 11.3). Also, planted populations at the rear edge of species distribution resulted more sensitive than natural forests in similar areas. Hence, shortening rotation cycles for short term biomass use, with forest rejuvenation may not be a proper measure to adapt these forests to climate change. Instead, maintaining a heterogeneous structure combined with selective thinning practices (i.e. thinning for below or shelterwoods) may be a more suitable measure to enhance forest resilience under increasing aridity.

Figure 11.2: A) Recent growth trends of Scots pine (Pinus sylvestris) and European black pine (P. nigra) at the rear edge of their Iberian distribution suggest a strong relationship between extreme climatic events and likelihood of forest decline. In both species, marked growth declines were observed associated with unusally dry periods (highlighted grey).

B) Sequential decline hypothesis with multiple factors involved in a complex process adapted from Manion (1981) for pine plantations (by R. Sánchez-Salguero).

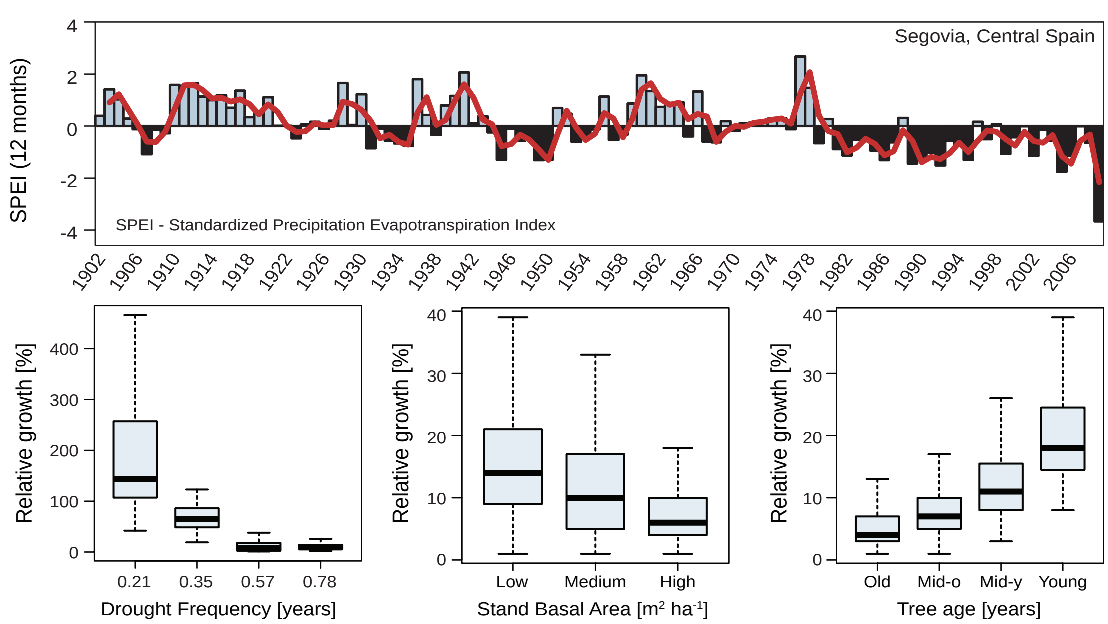
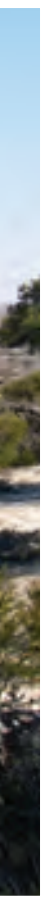


Figure 11.3: Periods of increasing drought frequency along the 20th century may have driven an exponential growth decline in maritime pine. However, growth decline in response to increasing drought frequency varied with tree age and forest stand density.



Highlight Chapter 12

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Changing climate variability and an increasing number of weather extremes will increase the vulnerability of terrestrial carbon sinks. We apply a probabilistic risk assessment method to evaluate the vulnerability of European ecosystems to heat waves and extreme drought. We find that under current conditions, 40% of European ecosystems are vulnerable to drought which may increase to 50% at the end of the century, corresponding to an increase of carbon loss from 823 Tg of carbon (Tg C = 10^9 g C) to 1374 Tg C.

Severe droughts, i.e. combined low precipitation and heat wave, increase vulnerability of carbon sinks in southern Europe.

The vulnerability of the carbon cycle (cf. Box 'Vulnerability concepts') is assumed to increase with increasing climatic variability. For example, with more frequent extremes such as drought periods or heat waves forest mortality may increase and lead to high amounts of carbon emissions and thus changes the carbon cycle. The assessment of this vulnerability is an important task to identify regions across Europe in which the carbon cycle is particularly sensitive or vulnerable to such heat waves and drought periods.

We developed a novel probabilistic framework for quantifying the vulnerability and risks to the carbon balance (Van Oijen et al. 2013 in review, Rolinski et al. 2013 in review). In this framework, risks associated with specific environmental conditions are calculated as the product of two terms: the probability of the hazardous conditions times the vulnerability of the ecosystem to them. Our assessment shows that ~40% of the European ecosystems are currently vulnerable to drought events which in the future may increase to up to ~50% (Table 2).

Vulnerability concepts

The Millenium Ecosystem Assessment defines vulnerability as "Exposure to contingencies and stress, and the difficulty in coping with them. Three major dimensions of vulnerability are involved: exposure to stresses, perturbations, and shocks; the sensitivity of people, places, ecosystems, and species to the stress or perturbation, including their capacity to anticipate and cope with the stress; and the resilience of the exposed people, places, ecosystems, and species in terms of their capacity to absorb shocks and perturbations while maintaining function."

Hassan et al. 2005

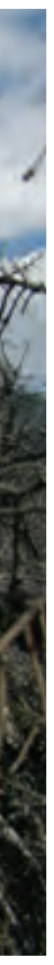
A more general definition of vulnerability is given in the IPCC 2007: "The degree to which a system is susceptible to, or unable to cope with, adverse the effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity."

In our study, we focus mainly on the aspect of potential carbon losses and ecosystem damages under extreme climatic events. A further step to improve our vulnerability analysis will be to include the adaptive capacity of ecosystems in our assessment.

Top left: Burnt slope, Andros, Greece. Photos: Marcel can Oijen.

Top right: Wind throw in the High Tatras, Slovakia. Photo: Annett Börner.

Carbon vulnerability assessment for Europe



	Vulnerability of ecosystems (in Tg C)		Proportion of vulnerable area (%)	
	1981-2010	2071-2100	1981-2010	2071-2100
Precipitation	245	523	8.1	19.3
Precipitation & temperature index (SPEI[1])	823	1374	39.5	49.6

[1] SPEI is the Standardized Precipitation Index accounts for the influence of temperature on the potential evapotranspiration (Vicente-Serrano et al. 2010; SPEI values are regarded as indicator of severe drought below -1.5).

Table 2: Vulnerability of European ecosystems to drought as simulated by LPJmL (in Tg C) and proportion of vulnerable area (%).

Drought events in these vulnerable areas could lead to a potential loss of 1374 Tg of carbon in the future. We defined 'drought' as annual rainfall less than the local 5% quantile for the time period 1971-2000. By that definition, the probability of drought was 0.05 everywhere in Europe during that period. Because of climate change, drought probability is expected to decrease in northern Europe and increase to up to 25% in southern Europe (Fig. 12.1) under future conditions (2071-2100).

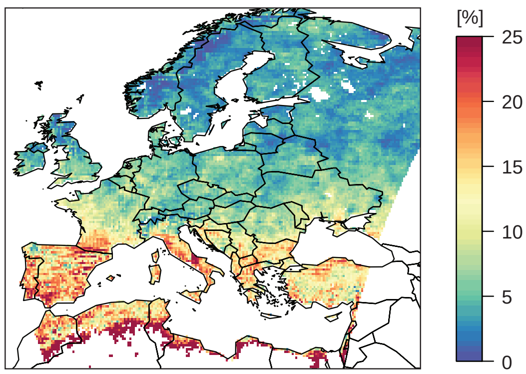


Figure 12.1: The probability of drought years in the period 2071-2100. Drought years are defined as local annual rainfall below the 5% quantile in 1971-2000.

During 1971-2000, vulnerability for European ecosystems to drought is highest in the Mediterranean and central western Europe (Fig. 12.2A), as estimated by the ecosystem model LPJmL. The risk map (Fig. 12.2B) is just a rescaling of the vulnerability map, as risks are proportional to vulnerability in this period. We repeated the risk analysis for the years 2071-2100 (Fig. 12.2), but kept the threshold for hazardousness as the 25% quantile for 1971-2000. Drought vulnerability is expected to increase in Southern Europe but decrease further north (Fig. 12.2A) and drought probability is highest in the Mediterranean (Fig. 12.1), leading to high risk for carbon loss in Spain and throughout the Mediterranean (Fig. 12.2B).

The vulnerability and risk analysis is applied to further simulation results. We are investigating the impact of extreme weather conditions on carbon fluxes of diverse ecosystem types across Europe, for different scenarios of environmental change, and using a range of ecosystem-specific and generic models.

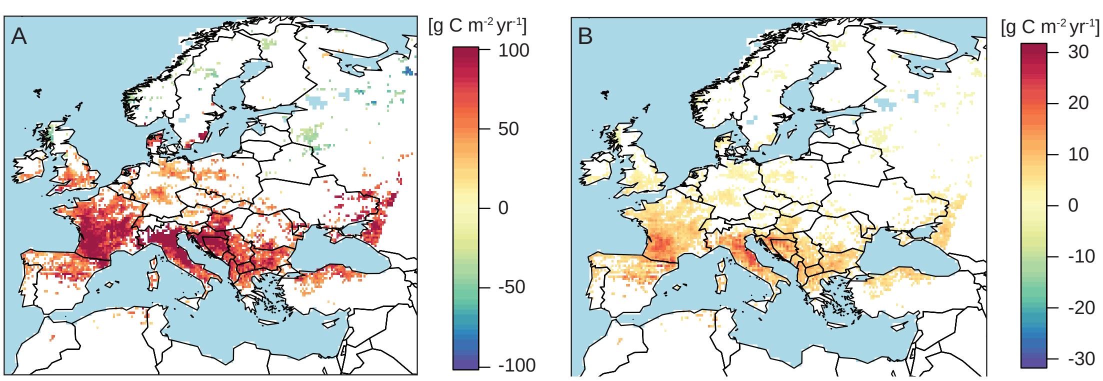


Figure 12.2: A) Vulnerability and B) risk for drought causing NPP losses (positive values, in g C m^{-2} yr^{-1}) in European ecosystems. Shown are only significant vulnerability and risk values for 2071-2100.

Outlook & open scientific questions



OUTLOOK

Climate extremes trigger anomalous fluctuations in the carbon cycle. Under specific conditions, the intensity of these alterations of the terrestrial carbon cycle can be so strong that long periods of carbon sequestration are neutralized and additional CO_2 is released to the atmosphere. These undesired fluctuations vary regionally but latest research indicates that they add up to quantities of global relevance. Hence, one of the crucial research questions is, to what extent does the feedback between climate extremes and the carbon cycle induce a significant acceleration of climate change. Today's observational evidence and state-of-the-art modeling efforts are still insufficient to provide any definite answer, but various lines of evidence suggest that this we are confronted with a critical feedback mechanism in the dependency of climate on the carbon cycle .

Observational records of climate impacts on ecosystems and the carbon cycle are often still too short and not widespread enough. FLUXNET currently simultaneously observes climate and carbon-water-energy cycle variations together at more than 500 sites globally, but only few of those sites have run for more than ten years. The continuation of such networks, as well as space based Earth Observation missions, which give a global picture, is crucial for confidently diagnosing the impact of climate extremes on the terrestrial carbon cycle.

Although progress has been made, climate models are still not realistic enough with respect to the simulation of climate extremes. A finer process representation of atmospheric dynamics, in particular convective processes and cloud formation will be required. Given that water cycle extremes, in particular droughts, appear to be one dominant triggers for carbon cycle extremes, it will be crucial to focus on precipitation in climate models. While recent emphasis has been on building Earth System Models (integrating climate and biogeochemical cycles), a new emphasis on higher resolution modeling and improved physics is expected to yield the basis for better projections of such climate extremes in the future.

At the same time, biosphere models need to resolve ecosystem physiological processes which are triggered by extreme events. These processes occur at different organizational levels from molecular-cellular level (e.g. gene expression and subsequent metabolic changes), to organismic

level (e.g. water transport through plants) and whole-ecosystem level (e.g. changes in soil physical properties, nutrient levels, or plant and microbial species composition). They interact, operate on different time scales and comprise physical, chemical and biological mechanisms. The scientific challenge lies in identify and quantify the most important interactions and feedbacks in such complex (eco-)system.

Here, experiments are the most important tool for improved process understanding. For substantial improvements in knowledge and understanding in the future, we need longer-term experiments, which allow memory effects, adaptation etc. to be tested, and experiments which cover important but under-represented biomes (e.g. savannas, tropical forests). Experiments should be designed to be comparable, and to push the systems towards (or beyond) the tipping point in order to identify important thresholds. Besides thresholds and tipping points, biological adaptation and biodiversity also remain particularly unclear and are not at all well considered in state-of-the-art Earth System Models. Plants may change their growth, dispersal, and allocation under the pressure of climate extremes; plant and microbial communities may be transformed in terms of composition. We expect adaptation and functional biodiversity to dampen the effect of climate extremes on the carbon cycle. Yet, the importance and global validity of this expectation needs to be tested in experimental and modeling studies.

If these lines of research are strongly supported in the near future, and eventually integrated by frameworks evolving e.g. from CARBO-Extreme, we can expect major progress in understanding, quantifying and projecting climate extremes and their role on ecosystems and the carbon cycle. Until then, as a precaution all efforts should be undertaken to minimize emissions that ultimately drive climate change and climate extremes.

Top from left to right:

Grassland fire.

Bark beetle damage, Großer Rachel, Bavarian Forest National Park, Germany. Photo: Martin Thurner.

Partial rainfall exclusion experiment at the experimental site in Puechabon, France. Photo: Jean Marc Ourcival.

Shrubland after fire, Levkas, Greece. Photo: Marcel van Oijen.

Meteorological tower in the Dischma valley near Davos, Switzerland. Photo: Lutz Merbold.

Setup of rainout shelters in order to simulate reduced summer precipitation to a typical swiss grassland. Photo: Lutz Merbold.

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Terms and concepts, abbreviations

Carbon (C)	
Carbon dioxide (**CO_2**)	Most important anthropogenic greenhouse gas
Carbon **flux**	Rate of import/export of carbon per unit time and unit ground area
Carbon **stock**	Total amount of carbon per unit ground area
CGCM	Coupled General Circulation Model
Climate Extreme (extreme weather or climate event)	Occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable which the ecosystem has experienced within a climate reference period. The appropriate length and time of the climate reference period depends on how fast the system under study adapts to the climate. For simplicity we take today's climate (i.e. last 30 years) as a reference period and, both extreme weather events and extreme climate events are referred to collectively as 'climate extremes. (see e.g. IPCC 2012: Summary for Policymakers)
CNTL	Control climate dataset for Europe spanning 1901-2100
EMEs	Ecosystem Manipulation Experiment site
fAPAR	Fraction of Absorbed Photosynthetically Active Radiation derived from spectral measurements from satellite
GCM ensemble	Collection of several global climate model simulations, supposed to span a range of uncertainties
Greenhouse gases (**GHG**)	Greenhouse gases are (natural and anthropogenic) gases in the atmosphere that can absorb and re-emit radiation within the spectrum of thermal infrared radiation emitted by the Earth's surface (indirect longwave radiation), and by clouds. The most important anthropogenic greenhouse gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O).
Gross Primary Productivity (**GPP**)	Total amount of carbon assimilated by plant photosynthesis per unit ground area within a certain time; often used unit is mass of carbon per unit area per year (g C m^{-2} yr^{-1})
IPCC	Intergovernmental Panel on Climate Change (http://www.ipcc.ch/)
IPCC SREX	IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (http://www.ipcc-wg2.gov/SREX/)
Lagged effects	Indirect effects of climate extremes typically occurring weeks to years after an extreme event, triggered by a causal process chain. Example are pest and pathogen outbreaks following heavy storm caused windthrow or, occurring the year after a drought, when the vegetation has been weakened due to drought stress reduced plant health (e.g. less carbohydrate reserves stored) or due to less frequent cold extremes in presently cold regions.
Net ecosystem productivity (**NEP**)	Net balance of carbon assimilation (by photosynthesis) and carbon loss (by respiration)
Net primary productivity (**NPP**)	GPP minus the autotrophic respiration by plants
Photosynthesis	Process by which plants convert light energy captured from the sun into chemical energy building up sugars from water and carbon dioxide (CO_2)
RCM ensemble	Collection of several regional climate model simulations, supposed to span a range of uncertainties
REDVAR	Climate dataset with artificially reduced variability and conserved mean
Respiration (R)	Metabolic process providing energy for maintenance and growth, which sets free CO_2 and consumes oxygen (O_2)
SPEI	Standardized Precipitation-Evapotranspiration Index is a metric which can be used to quantify and monitor drought
SRES	IPCC Special Report on Emission Scenarios; provided for calculation of climate change scenarios, both of which were applied in climate change impact assessments, as described in the 4^{t}h IPCC Assessment Report. In this project the A1B scenario was applied.

Impress

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Print Druckhaus Gera GmbH, Gera, Germany

Acknowledgements

We would like to thank Martin Thurner, Marcel van Oijen, Jaime Madrigal-González for providing front cover photos and Silvana Schott for seamless administrative support.

Disclaimer

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 226701 (CARBO-Extreme). However, the content and views expressed in this document are those of the authors and may not in any circumstances be regarded as an official position of the European Commission. Please note that the studies presented in this publication are mainly based on peer reviewed scientific studies, but cannot be regard or cited as peer-reviewed scientific contributions in their own right.

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GA N° 226701 (FP7/2007-2013)