CARBO-Extreme

The terrestrial Carbon cycle under Climate Variability and Extremes – a Pan-European Synthesis

FP7-CP-FP

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Executive Summary

Climate strongly influences terrestrial ecosystems, their carbon cycle and thus their ability to act as a carbon sink (depending on climate and land-use). Climate change is expected to lead not only to rising mean temperatures across Europe with decreasing precipitation in southern regions and increasing rainfall and snow in northern regions, but also to changes in the magnitude and frequency of extreme weather events. The future fate of European terrestrial biosphere´s acting as a net carbon sink is highly uncertain. So far only gradual climate and land-use change (e.g. slow warming) has been seriously considered in predictive carbon cycle studies. Climate variability and extremes will play an important role, but have not been sufficiently accounted for in modelling and experimental studies, thus leading to a critical knowledge gap.

CARBO-Extreme´s overall objective is to obtain a better and more predictive understanding of European terrestrial carbon cycle responses to climate variability and extreme weather events. Therefore 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. A consistent harmonized multi-source database on the European carbon cycle components for studying climate variability and extreme events was built and a Bayesian model calibration and comparison performed, to improve terrestrial carbon cycle predictions and their uncertainties in scenario analyses.

CARBO-Extreme results confirm that climate extremes strongly influence terrestrial ecosystems and their carbon cycle. Changing climate variability and an increasing number of weather extremes will increase the vulnerability of terrestrial carbon sinks, e.g. climate variability may accelerate fire along biome boundaries and the two factors together decrease tree abundance and productivity to an extent, where the tree-line between steppe and temperate forests is likely to be shifted northwards. In summary, all land use types in Europe (largely comprising croplands, grasslands and forests) are vulnerable to climate extremes to some degree. Multiple strands of evidence indicate that water-cycle extremes, in particular droughts, are a dominant threat to carbon cycle related ecosystem services. Climate variability will be most likely the factor, which will limit the capacity of the investigated ecosystem types to adapt to climate change. Taken together, 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. In addition biome boundary shifts (e.g. forest to grassland) are possible with more extreme climate variability and induced fire occurrence as evidenced with a simulation experiment with a global vegetation model. In addition lateral export of dissolved organic carbon into rivers becomes an important carbon fluxes under heavy precipitation. A data-driven analysis in CARBO-Extreme shows that the global effect of carbon cycle extremes triggered by climate anomalies is on the order of the current mean terrestrial carbon sink. Hence, the consequences of extreme events can largely offset the positive effects of carbon fertilization in an enriched CO_2 atmosphere.

Although progress has been made, climate models are still not realistic enough with respect to the simulation of climate extremes, e.g. the analysis of soil respiration measurements from 52 precipitation manipulation experiments revealed that current moisture relations for soil respiration used typically in models cannot be trusted for predicting soil respiration when rainfall patterns alter. At the same time, biosphere models need to resolve ecosystem physiological processes triggered by extreme events occurring at different organizational levels from molecular-cellular, to organismic and whole-ecosystem level. The scientific challenge will be the identification and quantification of the most important interactions and feedbacks in such complex (eco-)system comprising physical, chemical and biological mechanisms operating on different time scales.

1) Summary description of project context and objectives

It is beyond scientific doubt that climate change is occurring and that it is being driven by human activity. Climate strongly influences our terrestrial biosphere, the functioning of terrestrial ecosystems and therefore their carbon cycling and carbon sequestration potential. 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. There is general concern that climate change will have fundamental impacts on our ecosystems, and the future fate of European terrestrial biosphere´s acting as a net carbon sink is highly uncertain.

So far only gradual climate (e.g. slow warming) and land-use changes have been seriously considered in predictive carbon cycle studies. Climate variability and extremes will play an important role, but have not been sufficiently accounted for in modelling and experimental studies, thus leading to a critical knowledge gap.

By definition, climatic extremes occur infrequently. Since extreme events are rare, there are less data available on their impacts, which mean it is more challenging to identify long-term changes for extreme events than for gradually changing climate variables (e.g. rising temperature).

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 plethora of complex interactions. Extremes have the potential to cause rapid losses from accumulated carbon stocks, as well as long-lasting impacts on the carbon cycle of the terrestrial biosphere. The impact depends on the severity, duration and timing of the extreme event. Direct and lagged effects on plant growth and mortality, and subsequent potential land cover change, often go beyond the duration of the extreme event. While there is little 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.

The disproportionate impacts of extreme climatic events on terrestrial ecosystems, their huge consequences on societal and economic well-being, evidence from observations that there has already been a change in the occurrence and frequency of some extremes and the projected increases in intensity and/or frequency of environmental extremes are all reasons for concern.

Therefore **CARBO-Extreme´s overall objective is to obtain a better and more predictive understanding of European terrestrial carbon cycle responses to climate variability and extreme weather events**.

In CARBO-Extreme, scientists from different fields work together 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.

We used an integrative approach (Figure 1_1) combining soil process studies, network of ecosystem manipulation experiments, long-term observation data sets (observation component), model development, model-data integration, model experiments and scenario analysis (modelling component), with carbon vulnerability analysis, dissemination and policy interaction (assessment component).

While Greenhouse gas fluxes into and out of ecosystems can be directly measured by the eddy covariance technique, 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. For example 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. While satellite data enable us to detect extreme anomalies in vegetation activity across the globe, 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, but they also provide useful input parameters for ecosystem models.

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 and 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.

Another project objective was to give advice to the European Commission and other stakeholders with regard to carbon cycle impacts of extreme weather events. This was realized via different dissemination activities, workshops and conferences.

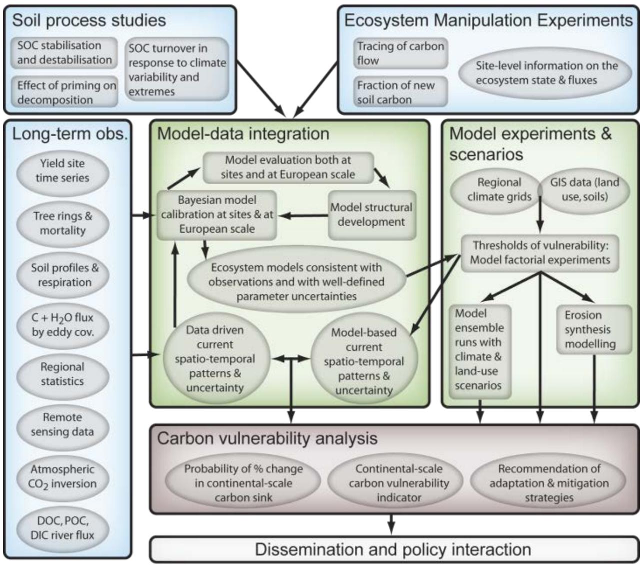

Figure 1_1: CARBO-Extreme work structure with observation component (blue), modelling component (green) and assessment component (brown).

2) Description of the main S&T results/foregrounds

2.1. WP1 Process study synthesis Lead: UA

Task 1.1 Assessing the role of soil mineralogy in the stabilization of SOC and the sensitivity to temperature and soil moisture extremes Lead: LUH

G.Guggenberger (Task leader), M.O. Göbel [LUH]

Soils were sampled at a permafrost study site at Cherskii with the aim to investigate whether, in addition to the soil environmental conditions (partly permafrost; low redox potential in the active layer and low temperatures in the lower part), the organic matter is also stabilized by mineral-organic associations. We observed that in all horizons 70-80% of the organic matter in these soils was associated with minerals, including cryoturbated horizons and soil from the permafrost itself. The chemical composition of the organic matter indicated that the mineral-bound soil organic matter was quite altered (i.e. formation of carboxylic groups and microbial components on the mineral surfaces). These observations pointed to the fact that here is a possibility of a stabilization of organic matter by formation of mineral-organic associations also in permafrost soils. The ^{14}C-age of both mineral associated organic matter and particulate organic matter in these soils varied, but in general suggested that both these fractions were pretty old (Figure 2.1_1).

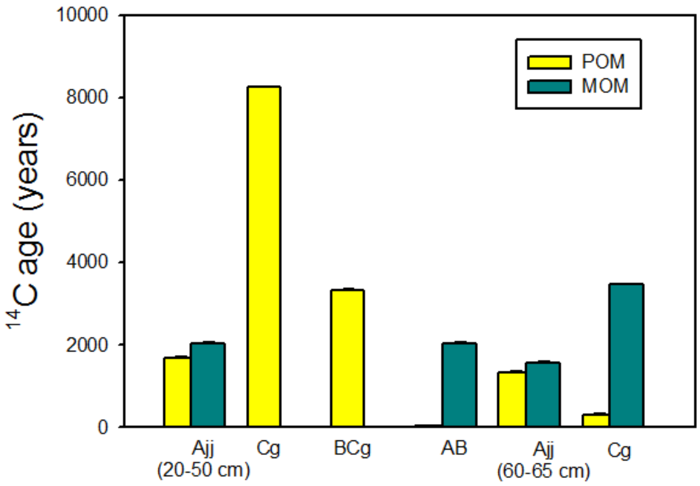

Figure 2.1_1: ^{14}C ages of mineral associated organic matter (MOM) and particulate organic matter (POM) in the different layers of the permafrost soil; horizons where bars are missing have not been analyzed yet.

This confirms indeed that the environmental conditions are important in the stabilization of organic matter in these permafrost soils. In the Cg and BCg horizons the temperature was pretty cold even in August (ca. 4°C) and the soils were reduced (unfortunately, no redox potential measured). When these different fractions were incubated (and expressed relative to the mineralization rate of the O-horizon material), it became obvious that the organic matter from each horizon and from both the particulate and mineral-associated fractions is in fact easily decomposable. Thus, in the case of permafrost soils with pre-dominantly low-activity clays, formation of mineral-organic associations does not infer an additional stabilization of the organic matter.

The knowledge gained in Task 1.1 is therefore that: a) the soil environmental conditions are decisive for organic matter decay in permafrost soils; and b) at improved environmental conditions due to permafrost thaw and associated increasing temperature and decreasing soil moisture, also mineral-associated organic matter is easily decomposable by soil microorganisms. Thus permafrost soils may be particularly sensitive to temperature extremes when they cross the thawing threshold.

Task 1.2 Assessing the potential of priming to reactivate sub-surface soil carbon Lead: INRA

S.Fontaine (task leader) [INRA]

80 cm-long intact soil cores were sampled from an upland grassland in central France (Theix, 45°43'N, 03°01'E). Four of these were sown with *Festuca arundinacea* at a density of 2000 seeds

m^{-2} and four were kept bare for comparison. Plants received a double labelling (^{13}C & ^{14}C) for the whole duration of experiment (511 days). Living plants significantly accelerated the mineralization of SOM as compared to bare soil, and this throughout the duration of the experiment (*p*-value < 0.05). The cumulative *priming effect* almost trippled the SOM mineralization rate in the bare soil. There was a significant interaction between planting and soil depth (*p*-value < 0.01). The ^{14}C contents and calculated ages of the soil C released as CO_2 from upper (10-33 cm) and deep soil horizons (56-80 cm) were quite surprising. For the upper horizon of the bare soil cores, mean age of released soil C was 1,174 (±165) years BP. The presence of plants significantly decreased the ^{14}C content of released CO_2 indicating that the rhizosphere priming mobilized very old soil C. The calculations indicated that the pool of soil C mineralized by *priming* in the upper soil horizon was 6004 (±1021) years BP old. The mean age of C released from bare soil increased with depth from 1,174 (±165) to 1,810 (±210) years. Also here, priming decreased the ^{14}C content of the C released as CO_2. The mean age of soil C released by priming in the deep soil horizon was estimated to be 15,612 (±2489) years BP.

The outcome of Task 1.2 is thus that deep rooted plants are indeed capable of accelerating the mineralization of deep SOM. The rhizosphere priming effect induced by deep roots mobilized soil organic C that was stabilized for more than 15,000 years. Our results thus support the hypothesis of Fontaine et al. (2007) that the stability of deep soil C is due to the energy limitation of microbes. With climate extremes, transport of carbon into deeper layers or increased rooting depth can thus lead to mobilization of old carbon.

Task 1.3 Evaluating SOC turnover under different climate variability Lead: UA

I. Janssens (Task leader) and S. Vicca [UA]

The Arrhenius equation is commonly used to describe the relationship of the velocity of a reaction with temperature. This equation predicts an increase in organic matter mineralization with increasing temperature. It also predicts that the temperature response of organic matter mineralization increases with its recalcitrance. These predictions are supported by short term enzyme assays and by soil incubations, which show a positive relationship between temperatures, enzymatic activities and soil respiration up to an optimum temperature. However, soil warming field experiments have shown that the temperature-induced acceleration in soil respiration only occurs for few years, suggesting that mineralization of the large pool of recalcitrant C may not be accelerated by warming. To reconcile these differences, an alternative theory to explain the effect of temperature on velocity of enzymatic reactions and recalcitrant organic matter mineralization was developed by the INRA partner, based on results from focused experiments. In this alternative theory, we take into account two key processes which are often overlooked while modeling the effect of temperature on enzymatic activities and organic matter mineralization: 1) Energy limitation of microbial decomposers: the availability of fresh energy-rich substrates supplied by autotrophs is low and limiting for decomposer community growth. Moreover, recalcitrant organic matter is too poor in available energy to sustain biological activity. Decomposers degrade recalcitrant organic matter through co-metabolism with fresh energy-rich substrates. This energy limitation of decomposers must be taken into account to predict the effect of temperature on enzymatic reactions. 2) Temperature-dependent inactivation of enzymes: enzymes undergo inactivation along the course of time due to loss of their three dimensional structure induced by Brownian movement. Temperature increases accelerate Brownian movement and thereby also the inactivation of enzymes. Ageing of enzymes is not considered when explaining the response of ecosystems to temperature changes.

The theory was tested in soil cores with and without grassland vegetation. As predicted by our theory, in non-steady-state systems the mineralization of recalcitrant soil C in bare soils increased with temperature. When the increase in fresh C flux with temperature is not taken into account, also the mineralization of recalcitrant soil C significantly increases with temperature in the soil cores with plants (p-value < 0.001). However, after normalization for fresh C inputs, we found that temperature negatively affected the mineralization of recalcitrant soil C. This negative effect of temperature on recalcitrant soil C mineralization was observed in 7 different grassland species.
These findings show that, when the temperature-dependent inactivation of enzymes and the energy limitation of microbial decomposers are considered explicitly in models, the effect of temperature on soil C mineralization is not as simple as suggested by the Arrhenius equation that was developed for single biochemical reactions and not for complex soil microbial communities. In contrast to the prediction of the Arrhenius equation, our results show that temperature negatively affects the mineralization rate of recalcitrant soil C when the flux of fresh C supplying soil microbes with energy is taken into account. The model indicates that this negative temperature effect arises from an intensification of enzyme inactivation when temperature increases.

2.2. WP2 Network of Ecosystem Manipulation Experiments Lead: ETH

Task 2.1 EME Access and Networking Lead: CNR-IBIMET

F. Miglietta (Task leader) [CNR-IBIMET] and the 12 PIs with associated staff of the individual EMEs

The aim of this task was to coordinate and access a network of 13 research sites with experimental manipulations across Europe. Twelve of the 13 sites had been continuing the prescribed measurements and data collection. One site was destroyed by a wind storm in 2009 and was discontinued (D. Loustau, INRA, France). The remaining sites comprised important land use types (agriculture, forest, heathland, peatland), were run by the respective PIs since quite some years and had been continued, typically with external funding. For each site and for each treatment, time-series of carbon pools and fluxes (soil, vegetation), environmental (meteorology, soil water and temperature) and ecosystem variables (LAI, standing biomass, species composition etc.) had been collected, old as well as new data were submitted to the central database and made available to modellers, particularly for model-data fusion exercises for selected model-site combination. Significant interactions were also developed between the CARBO-Extreme EME sites and the infrastructure Project EXPEER (7 FP-EU).

The long-term datasets revealed both, stable responses of ecosystems to environmental stress such as drought, but also inter-annual variability in the magnitudes of the responses of different biogeochemical processes. The following stress impacts were studied:

- Soil warming/cooling on heterotrophic respiration and net primary production of crops,
- Drought/Water reduction on growth, C dynamics, species composition and water uptake of lowland and mountain grasslands,
- Warming, drought and elevated CO_2 affecting a heathland ecosystem,
- Water deficits in a Mediterranean forest, and
- Precipitation changes in a Mediterranean woodland.

Carbon uptake as well as loss rates were affected differently in different ecosystem types, requiring models to account for these ecosystem-type/land use type and environmental settings. The results have been in many papers or will be published soon. Thus, being able to draw on a large number of long-term experimental studies was highly advantageous.

Task 2.2 Cross-cutting activity carbon tracing **Lead: ETH Zurich**

N. Buchmann (Task leader) and S. Burri [ETH Zurich]; A Knohl [U. Göttingen]; M. Bahn and M. Schmitt [UIBK]

In this task, several pulse-labelling experiments with $^{13}CO_2$ had been carried out at two grassland sites in Switzerland and Austria in 2010 and 2011 to investigate the transfer of newly assimilated carbon from above-ground to below-ground processes in response to summer drought, thus providing detailed info about the short-term responses to drought of the carbon cycle in agroecosystems at two altitudes (Fig. 2.2_1). In addition, a methodology has been developed to trace carbon flow using mobile laser spectrometry. Allocation speed from the sward to belowground differed among the sites. Drought reduced the incorporation of recently fixed carbon into shoots and increased carbon allocation below-ground relative to total tracer uptake (Burri et al., submitted). Contrary to our hypothesis, we did not find a change in allocation speed in response to drought, although drought clearly reduced soil CO_2 efflux rates. 19 days after pulse labeling, only about 60% of total tracer uptake was lost via soil CO_2 efflux under drought compared to about 75% under control conditions. Predisposition of grassland by spring drought lead to different responses to summer drought in 2011 compared to 2010, suggesting increased sensitivity of grassland to consecutive drought events as predicted under future climate change (Burri et al., submitted). A paper on drought effects on the transfer of recently assimilated C from plants to the mesofauna has been published (Seeber et al. 2012). Insights about methodological advancements on how to identify physical back-diffusion producing a non-biological $\delta^{13}C$ signal will be submitted soon (Burri et al.), similar to the results of the respective labelling experiments (Burri et al. submitted, Schmitt et al., Hasibeder et al.). A synthesis manuscript is planned as soon as these manuscripts are in review.

Fig. 2.2_1: Top left: Rain out shelters at the Chamau site (CH); top right: steady-state-flow-through chambers measuring soil respiration. Bottom left: Labelling chamber at Chamau (CH); bottom right: Set-up at Stubai, (AT).

Task 2.3 Cross-site meta-analysis from EMEs Lead: UA

I.Janssens (Task leader) and S. Vicca [UA] and the 12 PIs with associated staff of the individual EMEs

In order to reach the objectives of this task, all empirical data from the 12 manipulation experiments had been used. In addition, a large database from 65 additional experimental sites with climate manipulation experiments had been compiled and altogether used for meta-analysis. This data base contains (among others) measurements of biomass production, leaf physiology, vegetation characteristics, foliar and soil chemistry and soil respiration, as well as ancillary data such as soil moisture, soil texture and meteorological data for characterization of the climate. Because all manipulation experiments differed in climatic conditions, species composition, soil properties, et cetera, effects of climate manipulations (e.g. withholding 50% of summer precipitation) could not be analyzed in a conventional way. Instead, all experiments needed to be made comparable before being analyzed. We focused specifically on the following processes:

1. Effects of climate extremes on ecosystem carbon inputs,
2. Effects of climate extremes on soil C respiration,
3. Effects of climate extremes on net ecosystem productivity and soil carbon pools, and
4. Effects of climate extremes on crop yields and harvestable products.

Several workshops took place to work on specific hypotheses and to prepare joint synthesis papers. The first one, addressing the conceptual framework (Vicca et al. 2012, New Phytologist) discusses problems that arise when comparing precipitation manipulation experiments. The need for a reliable quantification of the actual manipulation (which depends not only on precipitation inputs, but also largely on factors such as soil texture and rooting depth) is illustrated. The measurements to do so are indicated with an example and contrasted with the data that are currently available.

Together with US colleagues (lead: Lindsey Rustad), a meta-analysis is currently being performed on drought experiments. First analyses revealed a reduction of plant growth, soil respiration and foliar N concentrations in response to drying, and for plant growth, the response was larger in grasslands than in forests.

A synthesis paper based on soil respiration measurements from 52 precipitation manipulation experiments revealed that current moisture relations for soil respiration used typically in models cannot be trusted for predicting soil respiration when rainfall patterns alter (Vicca et al., in review). Structural and/or functional changes following precipitation manipulation can lead to substantial over- or underestimations. Thus, model parameterization need to be improved to adequately represent these changes.

2.3 WP3 Long term Carbon Measurements and Climate Lead: CEA

Task 3.1 Tree ring data Lead: WSL

D. Frank (Task leader) and F. Babst [WSL]; T. Kun, B. Poulter, P. Ciais [LSCE]; O.Bouriaud [ICAS]

The goal of this task was to analyze long-term records of annually-resolved radial growth to quantify the variability and sensitivity of key carbon cycle parameters to climate change. Additionally tree-ring data were employed to test, validate and improve carbon cycle models. As the basis for empirical analysis, efforts were directed at both harmonizing existing tree ring data and performing a targeted sampling at selected eddy-covariance sites throughout Europe.

Specific proposed tasks included:

- Extract a dataset of tree ring chronologies (quality, species, harmonization) from existing databases that can be used for carbon applications
- Organize a specific coring programme at eddy-covariance stations to obtain information about recent droughts and ecosystem processes, and relate them to the process monitored on those sites at fine temporal scale
- Derive estimates of stand level and regional woody NPP from tree ring data
- Evaluate how tree ring data compare with eddy-covariance GPP, biometric, remote sensing measurements
- Help to develop modules of tree growth into generic carbon models ; Carbon models evaluation and improvements using tree ring data

These tasks were largely accomplished in the CARBO-Extremes project not only improving quantification of the terrestrial carbon cycle, but also opening new research avenues in using tree-ring data to reduce uncertainties in future projections of the coupled carbon cycle climate system. In the remainder of this section, we will outline scientific advances roughly grouped as i) climate sensitivity of forest growth across Europe ii) tree-ring and eddy-covariance estimates of carbon uptake and allocation and iii) testing and improving dynamic global vegetation models with tree-ring data.

Climate sensitivity of forest growth across Europe

Investigations on the climate sensitivity of radial tree growth across Europe were accomplished by compiling and harmonizing a network of existing tree-ring chronologies across the European domain, and subsequently quantifying the climatic constraints on inter-annual growth. In total, datasets from 992 sites representing 36 different tree species across Europe were aggregated and analysed. All tree-ring datasets met certain quality thresholds (e.g., coverage of the 1920-1970 period, a minimum of 5 tree-ring series during this time period, etc.) prior to consistently removing the biological age-trend. Analysis with down-scaled climatology revealed i) broad biogeographic patterns in the climate controls on growth such as the temperature limitations in Scandinavia and near tree-line zones in Central to Southern Europe, ii) a high species-specific component in determining radial growth responses to climate variation and iii) the importance of lagged effects of climate on radial growth (currently not considered in state-of-the-art dynamic global vegetation models). In addition to the climate sensitivity, extreme growth anomalies across Europe during the past 500 years were catalogued based upon this network showing the occurrence of spatially extensive reductions in radial growth during certain years such as 1976, providing insights into terrestrial carbon uptake prior to periods covered by satellite, eddy-covariance, and even instrumental climate data. This network proved suitable to evaluate dynamic global vegetation models (see third point below) *(Babst et al. 2013 Glob. Ecol. and Biogeog.; Babst et al. 2012 Environ. Res. Lett.)*

Tree-ring and eddy-covariance estimates of carbon uptake and allocation

While certain aspects of the of the carbon cycle response to climate change and extremes were able to be quantified with existing data, most site locations were not representative for eddy-covariance stations and also did not allow the absolute quantities of carbon uptake to be estimated due to the lack of appropriate metadata (e.g., stand density, representativeness of sampled trees). Accordingly, CARBO-Extreme efforts in this task were directed at devising and testing a protocol suitable for biomass estimation and more importantly applying this sampling scheme at eddy-covariance stations to link changes in above ground biomass estimated from tree-rings with alternative measures of ecosystem productivity. Sampling of all trees within plots of fixed size was conducted at 5 eddy-covariance sites throughout Europe balancing species diversity and geographical range with available project resources. For comparison with eddy covariance data and quantification of carbon uptake, tree-ring data were used to reconstruct historical tree diameters which were subsequently up-scaled to site level above ground woody biomass increments (Fig. 2.3_1) using allometric equations and stand measurements. Uncertainties in quantification were estimated due to a variety of factors such as the number of sampled cores per tree, the number of sample plots, and the range of arguably suitable allometric equations. Furthermore measurements of inter-annual variability in ring density were performed at all sites providing insights into the allocation dynamics once radial growth is largely complete but while cells still are undergoing secondary cell wall development and lignification. Correlation analyses between biometric and eddy-covariance based estimates of ecosystem carbon uptake during the past decade revealed reasonably strong relationships at seasonal time scales, especially in the absence of forest management practices. Wood density appears to be particularly linked to late-summer eddy-fluxes indicating that photosynthates during the second half of the growing season may be largely used for cell-wall thickening processes and likely storage.

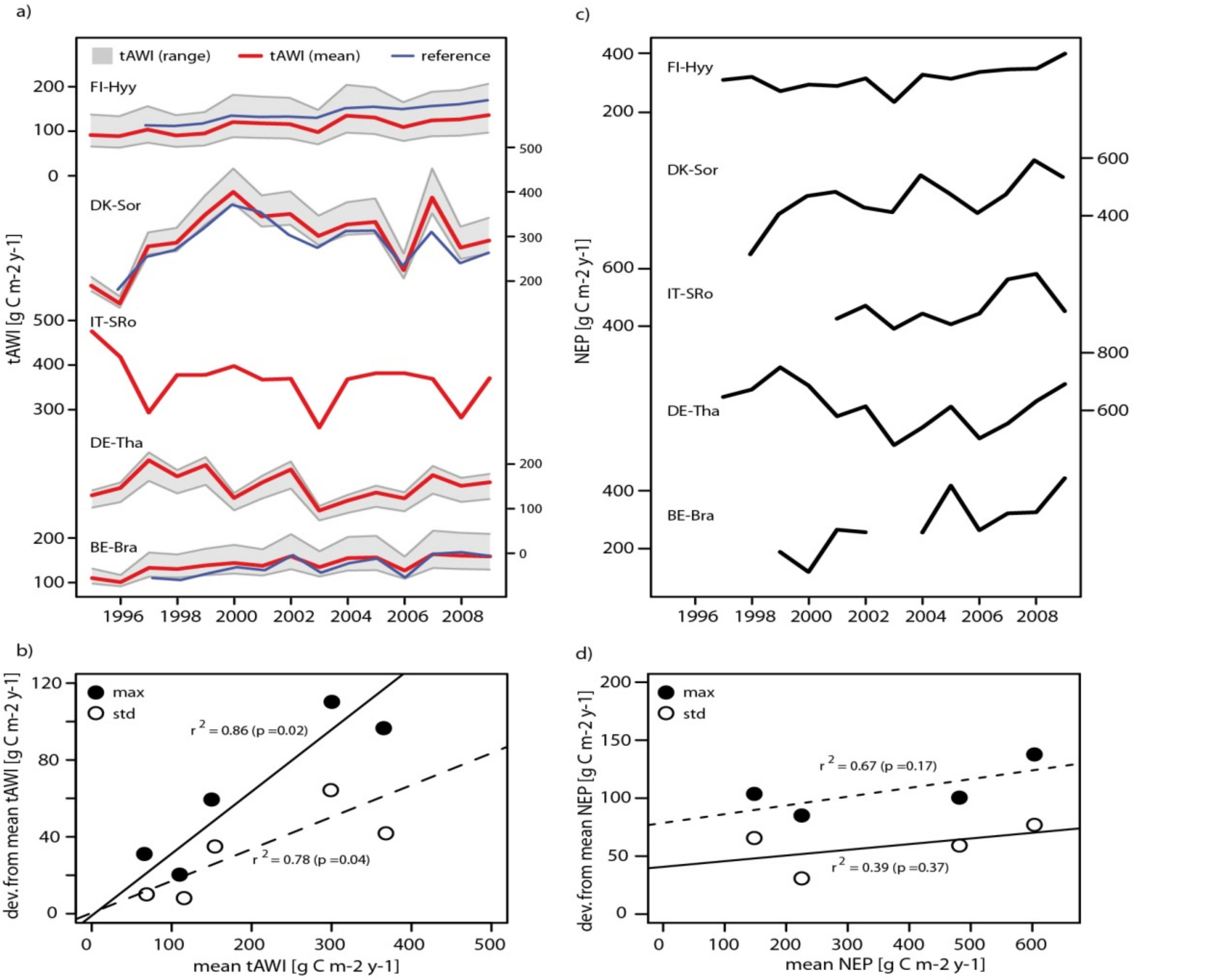

Figure 2.3_1: Interannual variability of a) tree-ring derived total above ground woody biomass increment (tAWI) at five European flux-tower sites and c) corresponding EC based NEP measurements. Uncertainty ranges around tAWI result from multiple biomass functions (means shown in red) and site-specific reference data are shown in blue (where available). Additionally, the relationships between (b) mean tAWI and (d) mean NEP with their respective standard and maximum deviations during the flux-tower period are presented. Please note that values obtained at the BE-Bra site are not shown in panel (d) since an EC data gap in the climatically extraordinary year 2003 hampered the calculation of robust standard and maximum deviations. (Ref. *Babst et al., in review New Phytol*.)

Furthermore, results indicated that depending on the site, 30-80% of the sequestered carbon (i.e. annual NEE) is allocated to above ground woody tissues. The above efforts provide a conceptual framework for future studies combining biometric with eddy-covariance measurements and contribute to improved understanding of carbon allocation to different storage pools in boreal, temperate and Mediterranean forest ecosystems. *(Babst et al. in review Dendrochronologia; Babst et al. in review New Phytol.; Ibrom et al. in prep.)*

Testing and improving dynamic global vegetation models with tree-ring data.

The empirical tree-ring data provide insights into ecosystems processes and rates of relevance for current generation dynamic global vegetation models (DGVM's) and thus future predictions. In task 3.1 we focused on using tree-ring data to test, validate, and improve the LPJ and ORCHIDEE-FM DGVMs representation of NPP sensitivity to temperature and precipitation (Fig. 2.3_2).

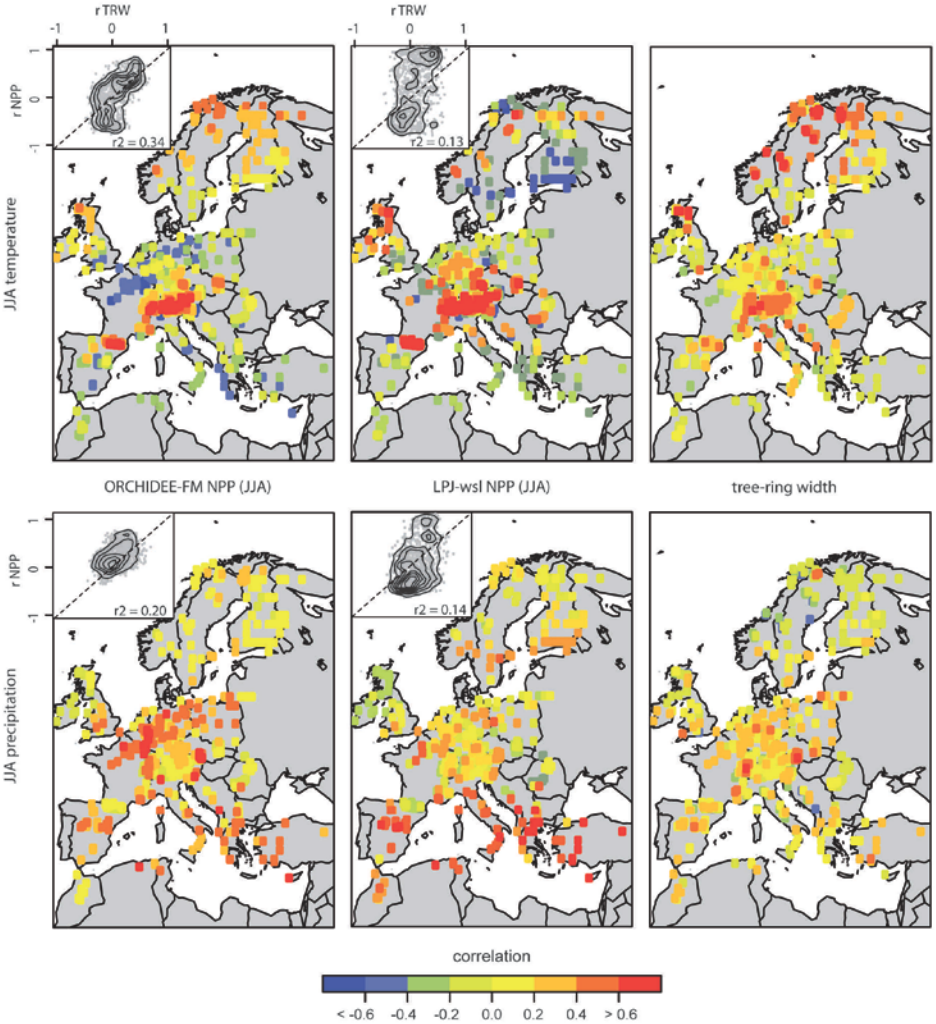

Fig. 2.3_2: Comparison of the June-August climate responses of empirical tree-ring data and simulated net primary productivity (NPP) derived from two dynamic global vegetation models. Correlations with temperature (top) and precipitation (bottom) are shown for NPP from ORCHIDEE-FM (left), LPJ-wsl (middle), and tree-ring width (right). NPP was estimated using FAO soil input data. The contour plot insets show direct comparisons and linear regression coefficients between the climate sensitivity of tree-ring width (horizontal axis) and modeled NPP (vertical axis) with the dashed line representing the one-to-one (target) relationship. Map area: 20-70°N, 10°W-40°E. (Ref. Babst et al. 2013 Glob. Ecol. and Biogeog)

We could for example determine that both models tend to underestimate the summer season temperature sensitivity of NPP in Northern Europe, whilst overestimating the precipitation sensitivity in Central and Southern Europe. Attribution of model characteristics and structure contributing to model-data disagreement included the threshold temperature for carbon allocation, with subsequent adjustments to model parameters yielding improvements in the modelled representation of plant responses to climate variation. Additional efforts used long-term tree-ring and ice-core data to provide a probabilistic quantification of the positive temperature feedback on the global carbon cycle; results suggested that coupled carbon cycle climate models tend to overstate the strength of this feedback in the past. *(Babst et al. 2013 Glob. Ecol. and Biogeog. ; Tan et al. in review Environ. Res. Lett.; Frank et al. 2010 Nature).*

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Task 3.2 Tree growth and mortality — Lead: UAH

M. A. Zavala (task leader), J. Madrigal-González, P. Ruiz-Benit [UAH];
C. Wirth, S. Rattclife [U Leipzig]; G. Kändler [Forest research Inst. Freiburg];
D. Coomes [U Cambridge]; A. Lehtonen [METLA]

This task has focused on the role of demographic processes -chiefly growth and mortality- on biomass changes at several scales. For this purpose we have compiled and harmonized forest inventory analyses and combine them with forest management records and dendro studies in some localities. We have also use process-based model (ORCHIDEE) for performing experiments to disentangle confounding factors. Specifically : 1) At an European scale we have investigated how recent climatic changes interact with stand-level processes to modulate decadal biomass changes in the three main biomes (Boreal, Temperate and Mediterranean forests); 2) at a regional scale we have examined drivers of tree mortality along environmental and competition gradients in Iberian forests; 3) at a more local scale we have investigated drivers of forest decay in pine species at the rear edge of their distribution and specifically if carbon fertilization effects can counteract the detrimental effects of increasingly more pronounced droughts.

Recent climatic changes in Boreal, Temperate and Mediterranean forests

European forests have a prominent role in the global carbon cycle and an increase in carbon storage has been consistently reported during the 20th century. Further increase in forest productivity due to increases in temperature and CO_2 concentrations, however, could be overwhelmed by increased climatic variability and climatic extremes. Research using plot-level forest inventory data was conducted to identify the relative importance of structural (stand basal area and mean d.b.h.) and environmental factors including mean climate (water availability and minimum temperatures) and recent climatic trends (temperature and precipitation trends in the last 20th century decade) on basal area change (proxy of biomass change). We focused on National Forest Inventories of Spain, Germany and Finland as they are representative of the principal biomes in Europe (e.g. Mediterranean, Temperate, Boreal). Using linear mixed-effects models we observed that stand structure, climate and recent climatic change strongly interact to modulate basal area change. We found highest basal area increments in forests with medium stand basal area and small to medium sized trees. Furthermore, low biomass change correlated with decreased water availability and this decline was exacerbated in warm areas. Basal area change increased with recent climatic warming but this increase was offset by water availability. In short, forests at developing stages, due to legacy land use effects, may have the highest carbon sink potential under warming conditions, yet could be strongly constrained by concomitant decreasing water availability.

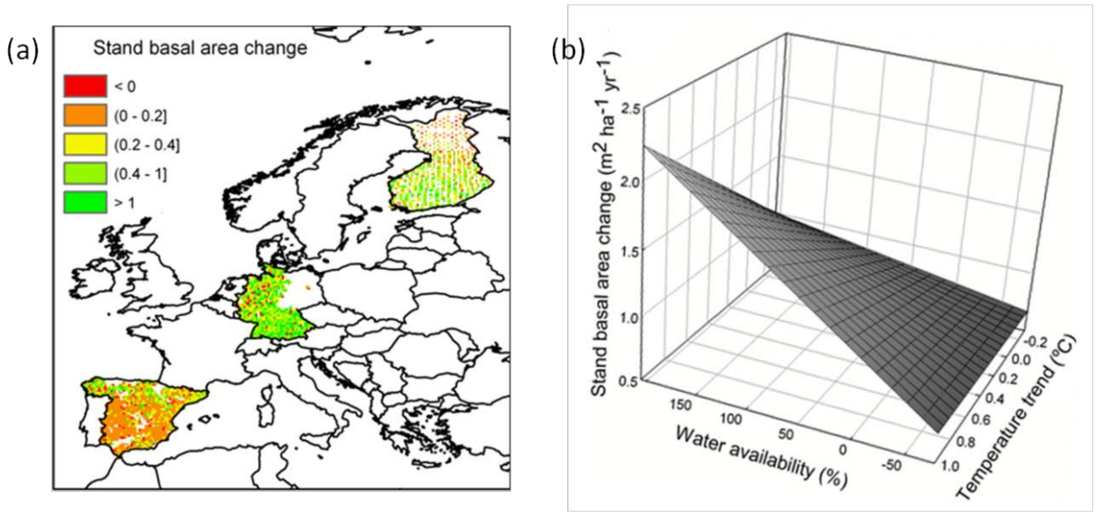

Figure 2.3_3: (a) Spatial distribution of observed stand basal area change (m^2 ha^{-1} yr^{-1}); (b) Stand Basal Area Change as function of interactive effects of water availability and recent temperature trends

Patterns and drivers of tree mortality along competition and environmental gradients: implications for modeling changes in forest biomass.

Tree mortality is a key process driving stand dynamics and thus carbon storage dynamics. Hence, understanding major drivers of tree mortality might help us to model more realistically forest carbon dynamics particularly under climate change. Using repeat-measure information from c. 400,000 trees from the Spanish Forest Inventory, we quantified the relative importance of tree size, competition, climate and edaphic conditions on tree mortality of 11 species, and explored the combined effect of climate and competition. Tree mortality was affected by all of these multiple drivers, especially tree size and asymmetric competition, and strong interactions between climate and competition were found. All species showed L-shaped mortality patterns (i.e. showed decreasing mortality with tree size), but pines were more sensitive to asymmetric competition than broadleaved species. Among climatic variables, the negative effect of temperature on tree mortality was much larger than the effect of precipitation. Moreover, the effect of climate (mean annual temperature and annual precipitation) on tree mortality was aggravated at high competition levels for all species, but especially for broadleaved species. The significant interaction between climate and competition on tree mortality indicated that global change in Mediterranean regions, causing hotter and drier conditions and denser stands, could lead to profound effects on forest structure and composition. Therefore, evaluation of potential climatic change on tree mortality ought to consider stand structure, since two systems of similar composition but different structure could radically differ in their response to climate.

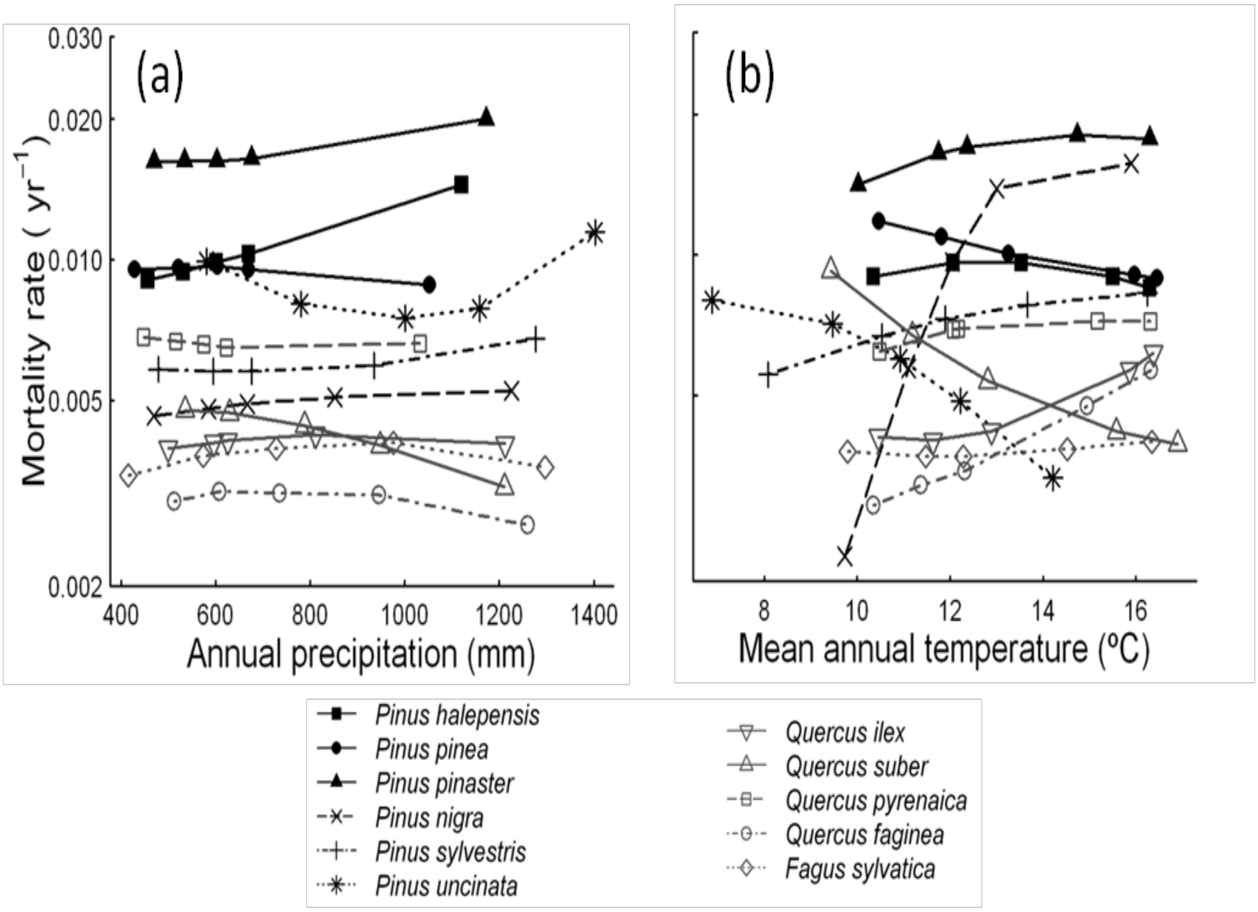

Figure 2.3_4: Predicted mortality rates (yr^{-1}, log scale) in relation to annual precipitation and mean annual temperature for the 11 most abundant species in Iberian forests

Competition and tree age modulated last century pine growth decline in response to high frequency of dry years in a water limited forest ecosystem

Extreme drought over mean temperature or precipitation trends a key factor of climate change affecting forest functions. In a study conducted in inland-dune pinelands in the Iberian Peninsula we examined last century growth trends using decadal direct measurements of wood volume increments recorded in harvested trees belonging to a chronosequence of forest stands. As relevant climatic predictors we considered mean temperature, mean precipitation and three drought indices based on the Standardized Precipitation and Evapotranspiration Index (SPEI) (i.e. mean water balance, frequency of dry years and the most severe drought event in the decade). Results supported that the final outcome of climate change on forest productivity would critically depend more on unusually high frequency of dry years than mean temperature, precipitation or water balance. However this trend can greatly vary with population-level structural factors such as population age distribution and competition, i.e. negative impacts of increasing drought frequency are disproportionally higher in younger trees under high competition.

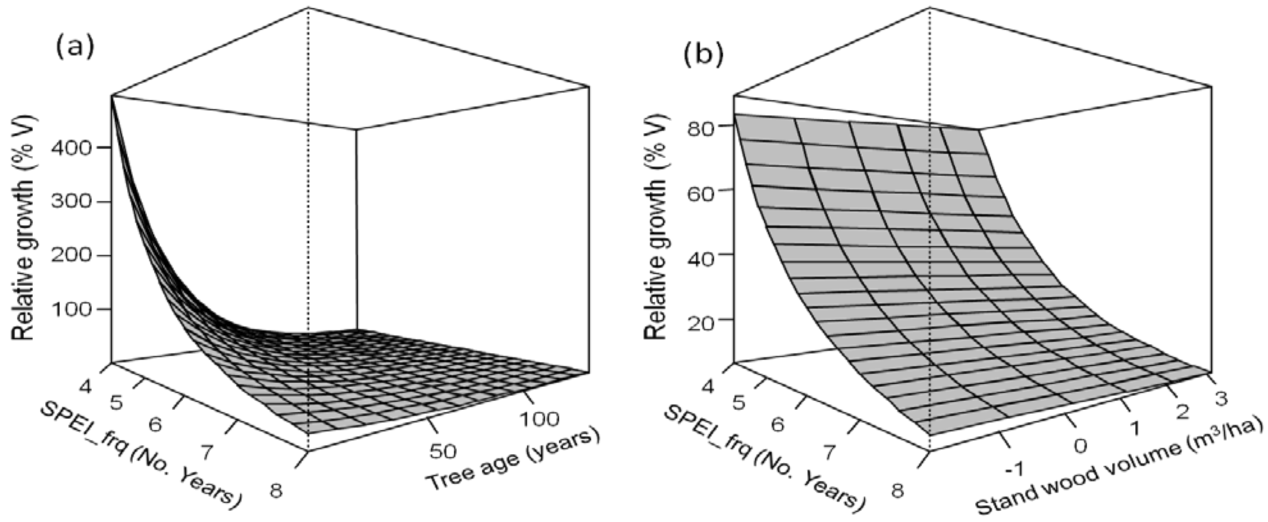

Figure 2.3_5: 3-D plots showing the supported model: (a) Relative tree growth under interactive effects of tree age and the frequency of dry years (SPEI_frq); (b) relative growth under interactive effects of stand wood volume (competition) and the SPEI_frq

Disentangling the role of carbon fertilization in water-limited forest ecosystems: confronting long-term observational data and process-based model outputs (ORCHIDEE)

The benefits of living in an enriched CO_2 atmosphere can counterbalance the negative impacts of drought and climate change. In particular it is unclear whether the benefits of carbon fertilization in an enriched CO_2 atmosphere can offset the costs associated with increasing water stress. Rising concentration of atmospheric carbon might, to a certain extent, reverse the negative impacts of altered water deficits on tree growth by means of enhanced water use efficiency. Long-term observations are scarce in long lived forests species and experiments are hampered by the number of processes involved. In this study we examine the main drivers underlying last century carbon storage in a water-limited Mediterranean ecosystem.

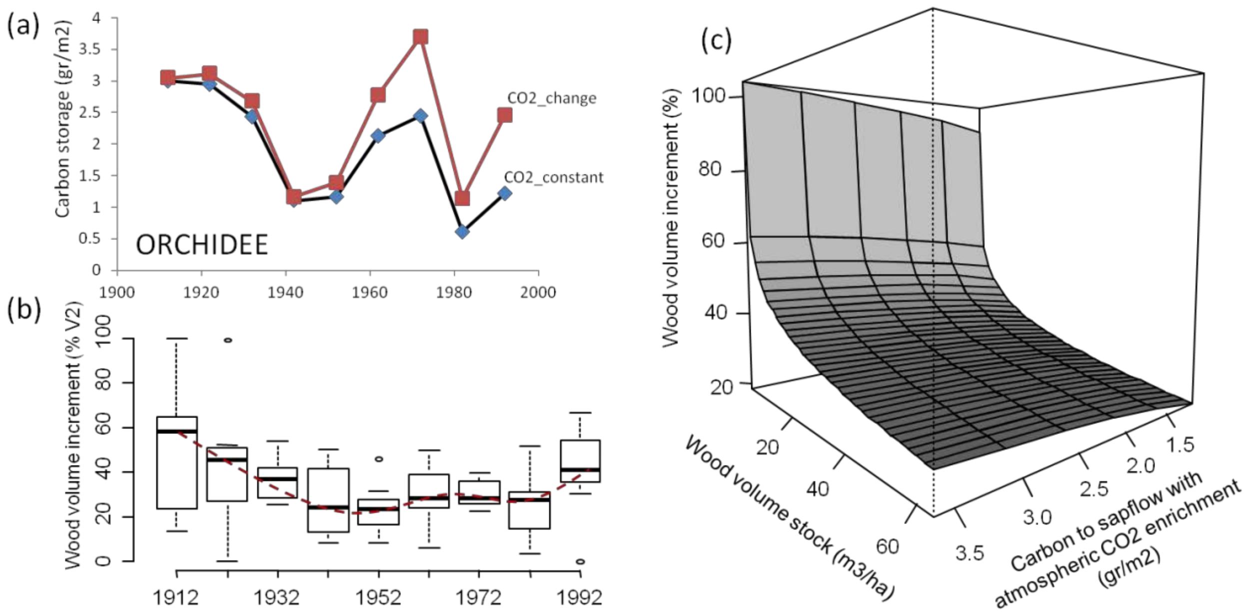

Figure 2.3_6: (a) Simulated carbon to sapwood using climatic data (e.g. temperature, precipitation) under constant and enriched carbon conditions along the 20th century; (b) Relative wood volume increment since at each decade since 1992 to 2002; (c) Relative wood volume increment as function of forest wood stock and carbon to sapwod in enriched CO_2 conditions.

A processes based model (ORCHIDEE) was used to examine the relative role of carbon fertilization on long term carbon storage dynamics. We found that the carbon fertilization associated effects result in more realistic predictions -with higher rates of carbon storage- than simulations not accounting for this effect. Although significant, the effect of carbon fertilization was however insufficient to counterbalance the last century carbon storage decline associated with high frequency of dry years.

In summary, Extreme events will have a key role affecting forest functions and ultimately limiting the mitigation capacity of forests. Moreover, consequences of extreme events can largely offset the positive effects of carbon fertilization in an enriched CO_2 atmosphere. Therefore, predicting future patters of extreme events more than mean climatic conditions might be helpful for a more realistic forecast of forest functioning and structure under climate change.

Extreme droughts and forest decay in pine species at the rear edge of their distribution

For Eurosiberian pine species -at the rear edge of their distribution- these detrimental effects can be more patent and extreme droughts can trigger a sequence of chained events leading to forest decay. These processes can be aggravated in high density forest plantations in which thinning processes have not been implemented. We used combined dendro measurements and forest inventory data to examine the relative role of structural and environmental gradients in replanted pine forests in a drought prone area of Southern Spain. As hypothesized, extreme droughts in terms of intensity and length interact with tree density to trigger a forest decay process in these plantations.

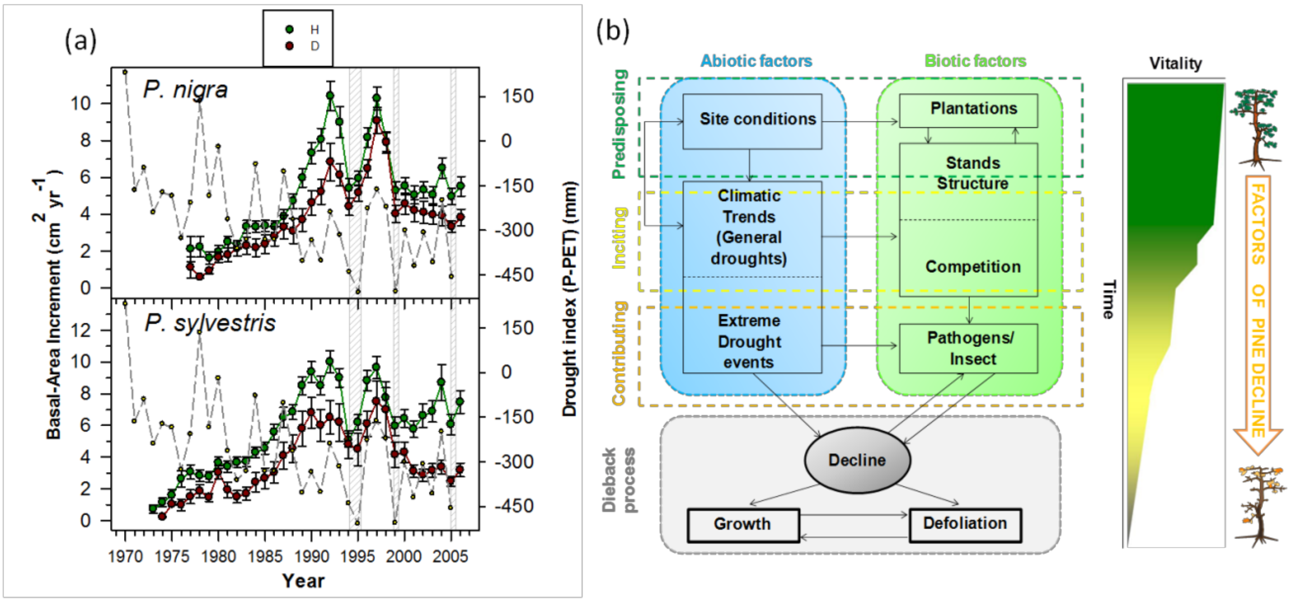

Figure 2.3_7: (a) Recent trends in basal area growth (BAI) of two pine species (i.e. Pinus sylvestris and Pinus nigra) at the rear edge of their Iberian distribution suggest a strong relationship between extreme climatic events and likelihood of forest decline. Highlighted grey periods denote unusual droughts. In both species, marked growth declines were observed associated with these dry periods which may trigger the decline process. (b) Sequential decline hypothesis with multiple factors involved in a complex process adapted from Manion (1981) for pine plantations at the rear edge (by R. Sánchez-Salguero).

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Ruiz-Benito P, Madrigal-González J, Ratcliffe S, Coomes D, Kändler G, Lehtonen A, Wirth C & MA Zavala Recent climatic changes interacts with stand structure modulating biomass changes Boreal, Temperate and Mediterranean forests (submitted Biogeosciences)

Madrigal-González J, Hantson S. , Yue, C., Zavala, M., & P. Ciais Disentangling the role of carbon fertilization in water-limited forest ecosystems: confronting long-term observational data and process-based model outputs (ORCHIDEE) (to be submitted to Biogeosciences).

Ruiz-Benito P., Lines E.R., Gómez-Aparicio L., Zavala, M.A. & D. Coomes (2013) Patterns and drivers of tree mortality in Iberian forests: Climatic effects are modified by competition. Plos ONE 8(2): e56843.

Sánchez-Salguero R, Navarro-Cerrillo RM, Swetnam TW, Zavala MA (2012). Is drought the main decline factor at the rear edge of Europe? The case of southern Iberian pine plantations. Forest Ecology and Management 271: 158-169.

Madrigal-González J & MA Zavala Competition and tree age modulated last century pine growth decline in response to high frequency of dry years in a water limited forest ecosystem (submitted Agriculture and Forest Meteorology)

Task 3.3 Crop yield variations and climate **Lead: UNIABDN**

M. Wattenbach, P. Smith [UNIABDN]; X. Wu, M. Mahecha, M. Reichstein [MPI BGC Jena]

This task focused on yield as records of the impact of climate variability and extremes on cultivated ecosystems. The yield and quality of food crops is central to the well-being of humans and is directly affected by climate and weather. Early studies of climate change on crops mainly focussed on effects of increased carbon dioxide (CO_2) level and/or global mean temperature and/or rainfall and nutrition on crop production. However, crops can respond nonlinearly to changes in their growing conditions, exhibit threshold responses and are subject to combinations of stress factors that affect their growth, development and consequently yield. In this context climate variability and changes in the frequency of extreme events are especially important (Porter and Semenov 2008).

Disaggregate national (FAO) and regional (EUROSTAT-NUTS3) yield statistics over the past 30 yrs to produce maps of yield anomalies

In a first step we analysed the response of crops to changes in climatic conditions using a bioclimatic envelope approach to identify potential limitations for a particular crop (Tuck et al., 2006). In the analysis we used the bioclimatic approach in combination with crop yield statistics from Eurostat (EUROSTAT 2010) in order to distinguish between weather- and climate-driven changes in crop yield from management effects. We identified events around 2003, 2006, 1980 and 1959 to be crop yield anomalies that could also be captured by a simple bioclimatic envelope approach identifying them as climatically driven, rather than a result of changes in management caused by, for example, agricultural production subsidies. In contrast, trends in crop yield seem to be mainly driven by improvements in production methods, as the trend could not be captured by the bioclimatic envelope. Identifying the year 2003 as an anomaly for the two central European countries, Germany and France, and not for Spain and Denmark corresponds well with the findings of Ciais et al. (2005). Even though this is only a preliminary analysis, it already identifies other potentially important time periods for a more detailed analysis. The comparison between ORCHIDEE-STICS, the yield statistical data and the bioclimatic envelope models show only very limited agreement. However, there are a number of additional sources of variance in the model beside the climate drivers, like management activities, land cover distribution etc. Only a more detailed analysis examining these sources in more detail will lead to an understanding of the non-converging patterns.

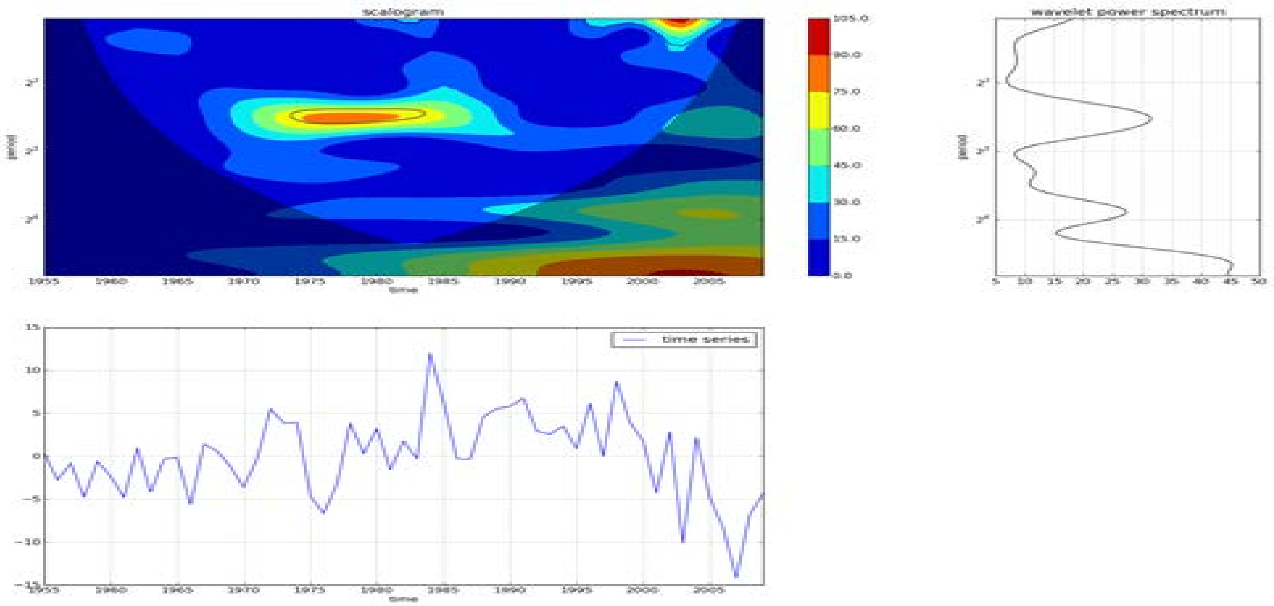

Figure 2.3_8: Example of Eurostat yield data for wheat in France. The wavelet analysis shows two significant events in 2003, 2005-2006 and another around the year 1976-1980 in detrended yield data.

Compare patterns of regional yield anomalies with remote sensing fields

In the follow on activities these data where used to constructed the gridded (0.5 × 0.5 degree) average crop yield data for Barley, Wheat, Grain maize and Potatoes for the period 1975-2009. (CX Eurostat data). Data were compared monthly GIMMS NDVI and up-scaling GPP (0.5 × 0.5 degree) during 1982-2008. Trends in gridded crop yield, NDVI and GPP are subtracted by fitting a cubic smoothing spline.

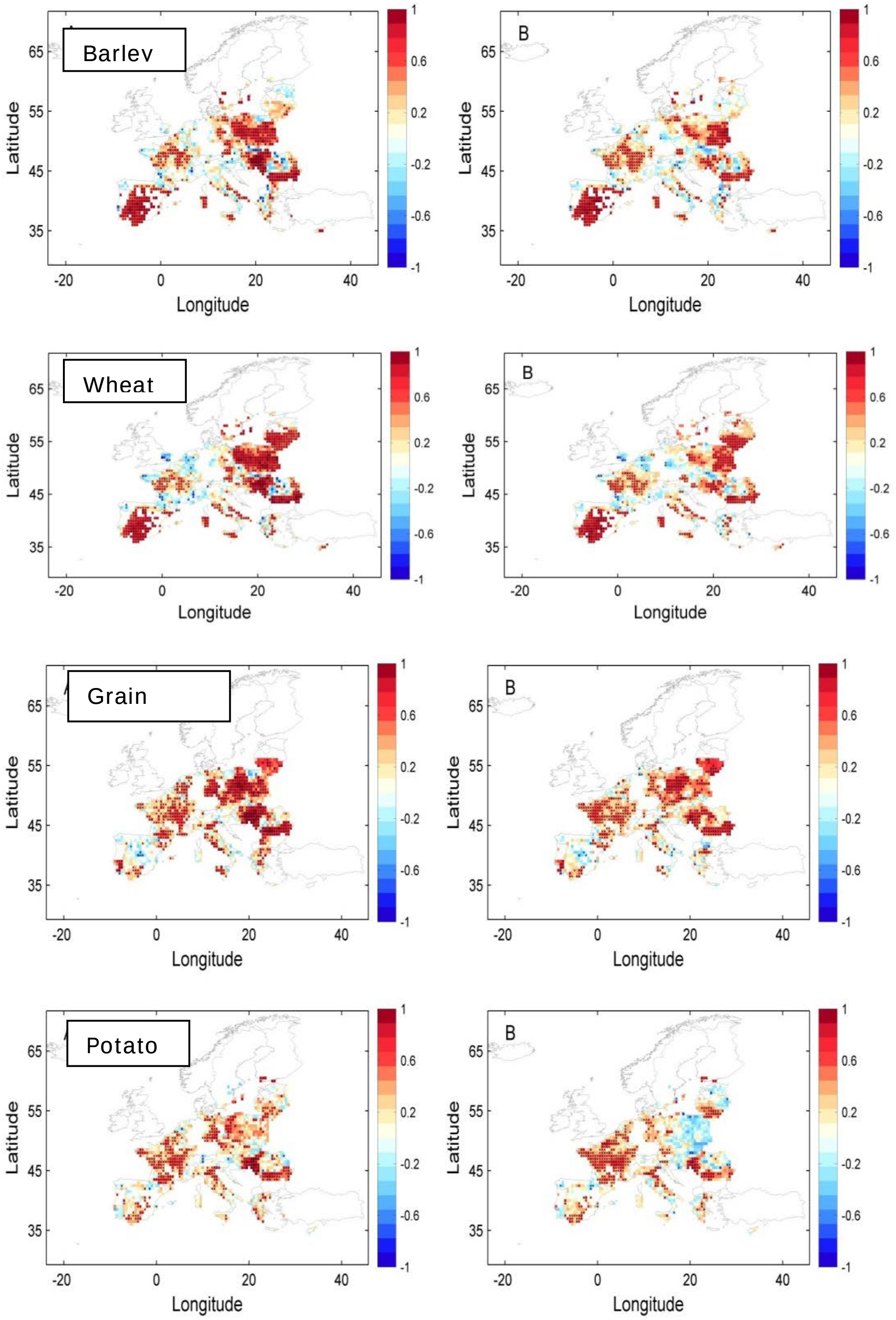

Figure 2.3_9: Correlation coefficients between the crop production and (A) the growing season summed up-scaling GPP and (B) growing season summed NDVI for Barley, Wheat, Grain maize and Potatoes. All variables used in this kind of analysis are de-trended using the same method based on cubic smoothing spline. Growing season is different for different kinds of crops. Blank grids indicate that there is no crop data or with very low (< 5%) fraction of cropland in these grids. Labelled black points indicate statistically significant ($p < 0.05$).

There are general good matches between the interannual variations of crop yield, GPP and NDVI in most of regions for all the four kinds of crops, despite of the weak correlations in some regions for different crops (Figure 2.3_10) and relative low correlations for Potatoes. Weak correlations in these relationships generally occurred in regions with complex geophysical structure (i.e. Alps Mountains).

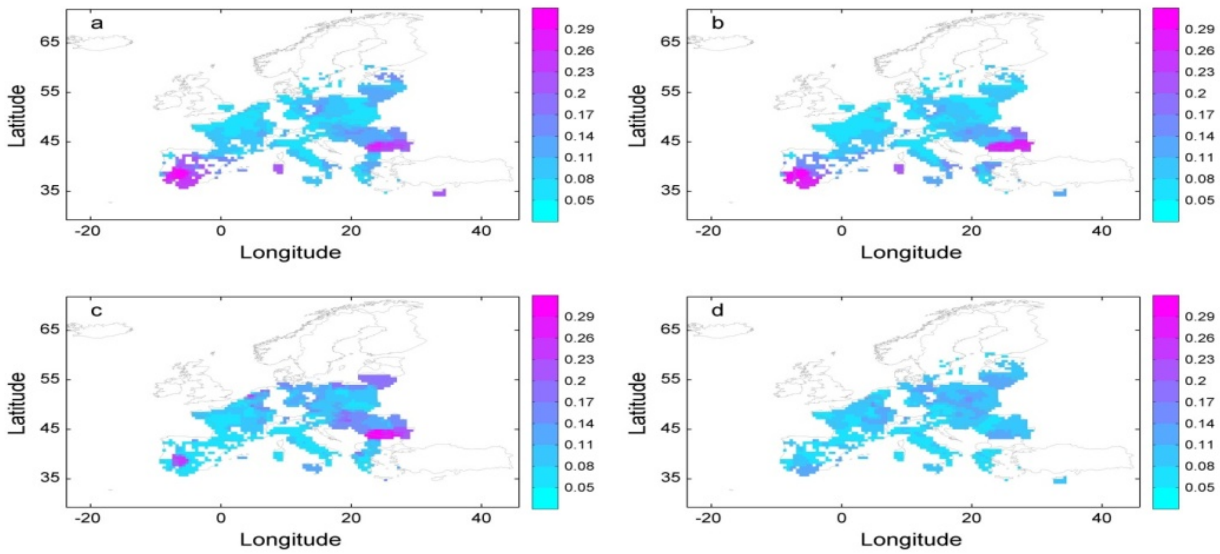

Figure 2.3_10: Spatial pattern of the coefficients of variation of the detrended crop yield data during 1975-2009 for Barley (a), Wheat (b), Grain maize (c) and Potatoes (d). Blank grids indicate that there is no crop data or with very low (< 5%) fraction of cropland in these grids.

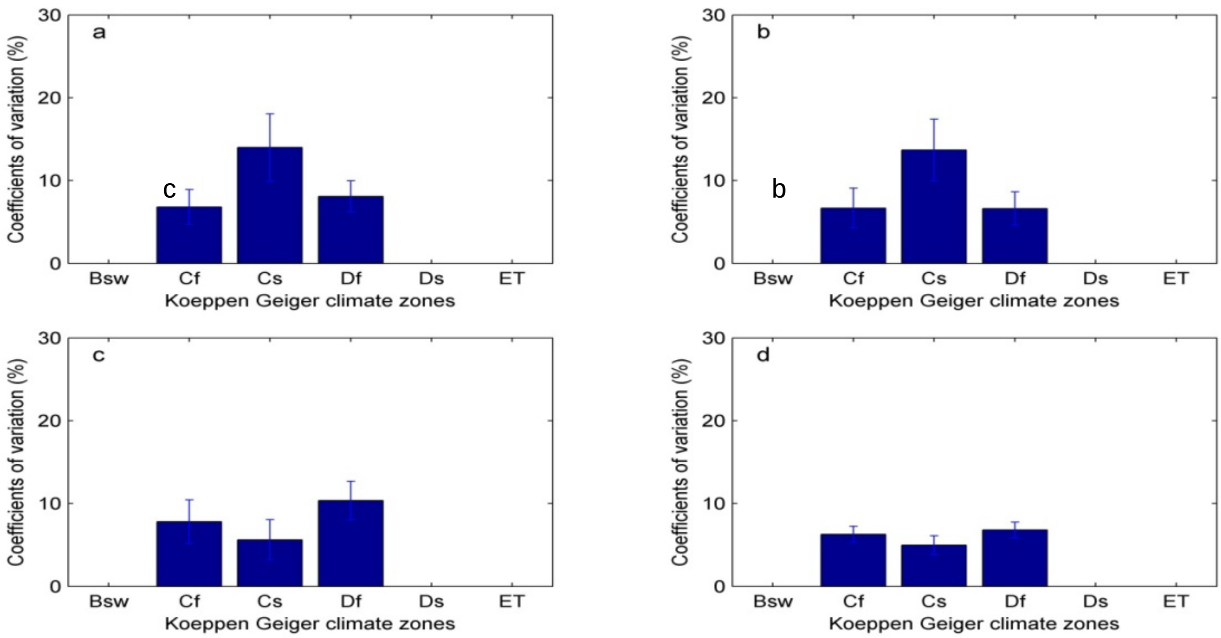

Figure 2.3_11: Mean values (bars) and standard deviations (error bars) of coefficients of variation of the crop production during 1975-2009 in different climate zones for Barley (a), Wheat (b), Grain maize (c) and Potatoes (d). Different letters in the figure indicate significant differences ($p < 0.05$) determined by the Tukey-Kramer test.

The coefficients of variation of the interannual variability (IAV) in the crop production are generally much larger in the dry region (i.e. Koeppen Geiger Cs region) than that in the humid regions for Barley and Wheat (Figure 2.3_10 and Figure 2.3_11). In contrast, the IAV of Grain maize and Potatoes yields tend to be higher in humid regions than that in the arid region (Figure 2.3_10 and Figure 2.3_11). Investigations of the changing temporal variability in crop production showed that overall there seems to be an increase in IAV in crop production especially in southern

Europe for crops under investigation. The increasing interannual variability in crop production is not determined by the arbitrary selection of the sliding window length. Notably, the interannual variability of NDVI and GPP also shows an increasing trend in southern Europe, especially in Iberia peninsula. Interestingly, we did not find any evidence of increasing interannual variability in TRIANO which could be a hint to a higher inertia.

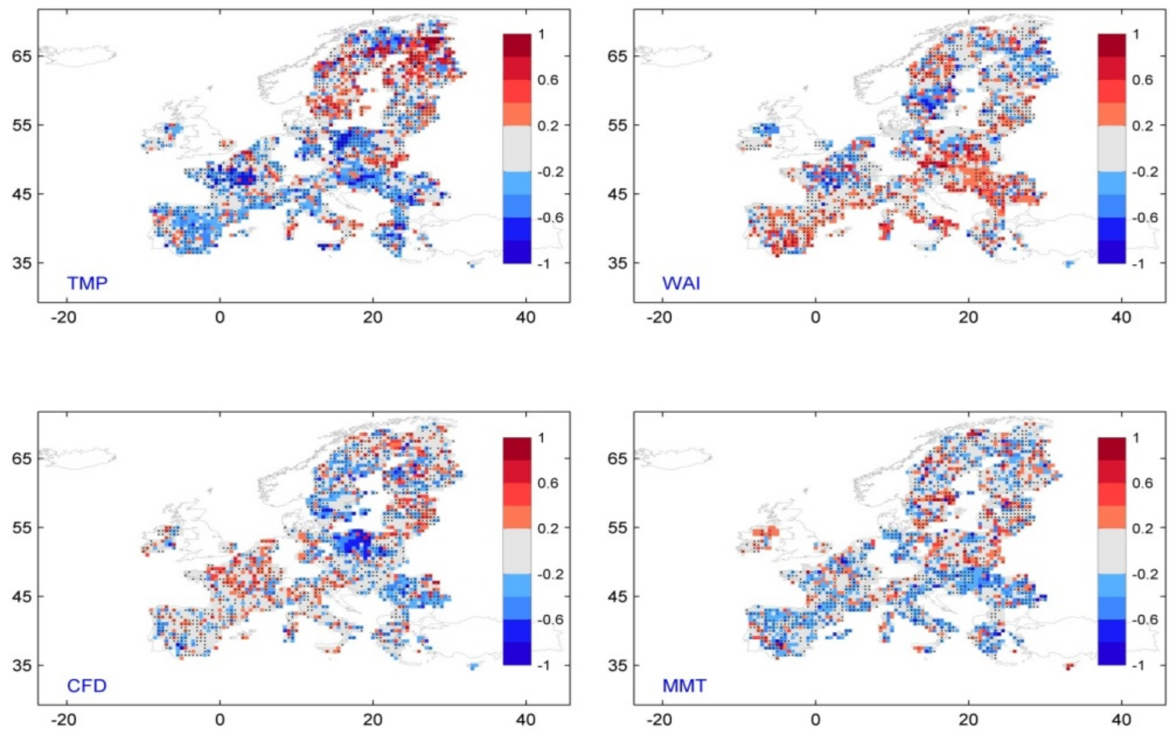

Figure 2.3_12. Response function coefficients between Barley yield and mean growing season temperature (TMP), total growing season water availability index (WAI), spring consecutive frost days (CFD) and spring maximum of daily maximum temperature (MMT). Growing seasons for Barley were fixed to March-June. Labeled black points indicate statistically significant ($p < 0.1$).

Crop production of the four kinds of crops in the northern part of Europe (> 60N) shows significant positive response to mean growing season temperature during 1975-2009, while crop production in most of the central and southern Europe is generally limited by the water supply as illustrated by the positive response coefficients between crop production and water availability index (Figure 2.3_12). However, we did not observe such clear pattern in TRIANO data. TRIANO tends to show positive correlations to mean growing season temperature and negative correlations to total growing season WAI in mountain regions (Figure 2.3_13).

The effects of spring consecutive frost days (CFD) on the crop production did not show clear spatial patterns but instead are crop-specific and spatially heterogeneous. Spring CFD tends to show negative correlation to tree growth in mountain regions (Figure 2.3_13). Notably, the MMT during the active growing season tends to limit crop production in the southern Europe (Figure 2.3_12)

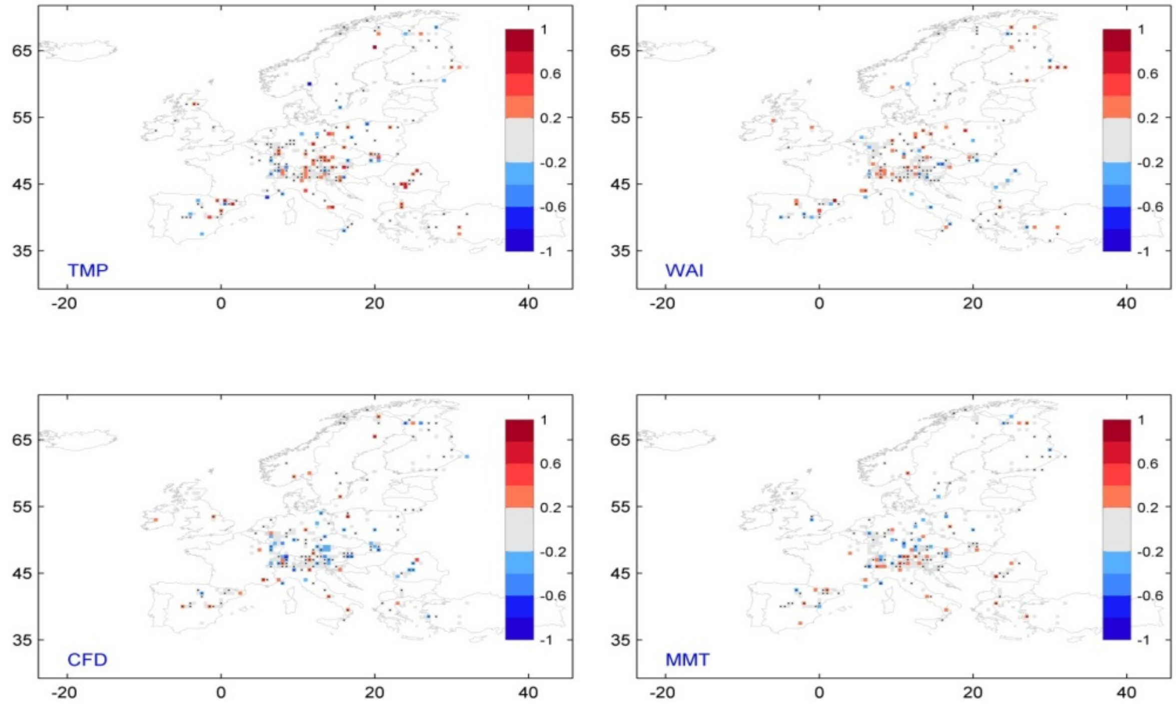

Figure 2.3_13. Response function coefficients between tree ring anomalies and mean growing season (March-September) temperature (A), total growing season water availability index (B), spring consecutive frost days (C) and summer half maximum of daily maximum temperature (D). Labeled black points indicate statistically significant ($p < 0.05$).

Test crop models against these data

In this sub-task, we compared the yield and bioclimatic envelope data to the biogeochemical process model simulation such as ORCHIDEE-STICS for the European scale allows us to evaluate if the model is able to capture the dynamics of climate driven yield fluctuations and anomalies. ORCHIDEE-STICS is a coupled (De Noblet-Ducoudré et al., 2004; Gervois et al., 2008) consisting of a dynamic global vegetation model ORCHIDEE (Krinner et al., 2005), and a process-oriented crop model STICS (Brisson et al., 2003). In the conclusion the pattern seen in the wavelets when comparing ORCHIDEE-STICS with yield and bioclimatic envelope in France show few similarities. However, there is a pattern in the period of 1985-1995 in ORCHIDEE and yields that are overlapping. There is no common pattern for between the model and the bioclimatic envelope. The same holds for the comparison of wheat yield, bioclimatic envelope and ORCHIDEE-STICS.

Beside the European wide comparison we also analysed the site scale comparison using the CARBUEUROPE-IP crop site network (Wattenbach et al., 2010). Details for the comparison can be found in detail in Wattenbach et al. (2010) and are not further elaborated in this report.

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Task 3.4 Analysis of long term ecosystem CO_2 fluxes **Lead: UNITUS**

D. Papale (Task leader) [UNITUS]

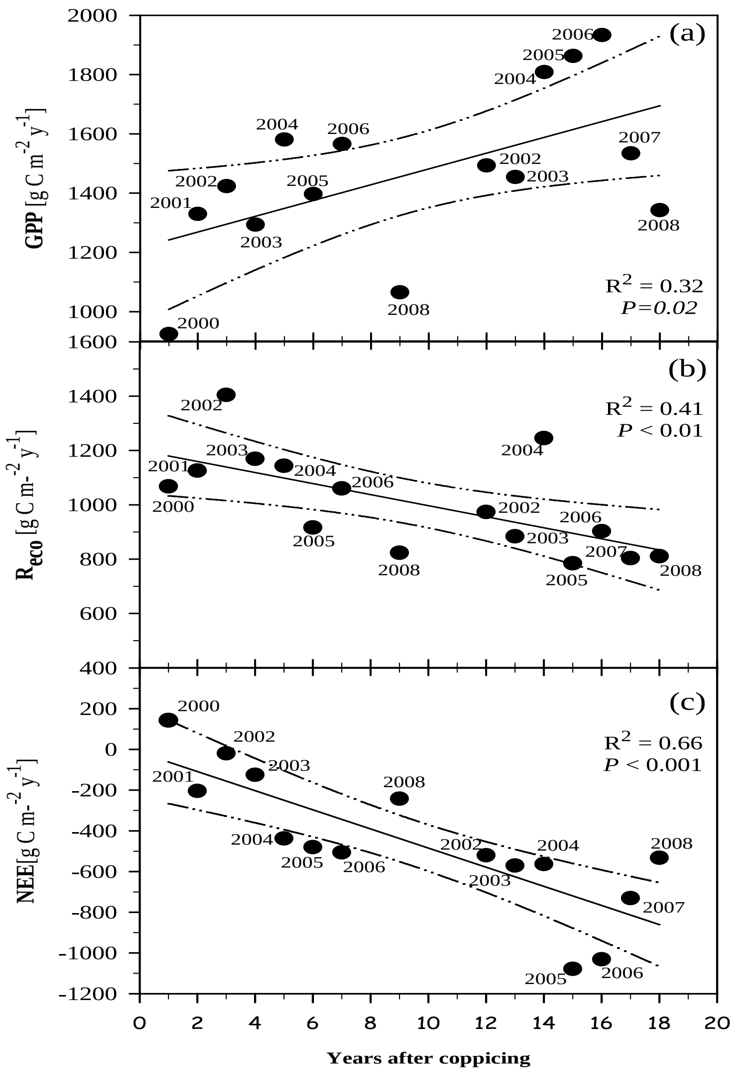
The objective of this task consisted in the analysis of ecosystem level carbon fluxes and major pools of European sites being operative for at least 7 years among the CarboEurope eddy covariance sites network. In particular the task addressed 1) the evaluation of the response of CO_2 fluxes to climate anomalies and extremes including lag effects and 2) the generalization of the response of fluxes to climate anomalies for different ecosystem types and climate regions which can serve as a ground for modeling evaluation and parameterization.

Evaluation of the response of CO_2 fluxes to climate anomalies and extremes including lag effects

Sites being part of the Carbo-Europe IP database were firstly ranked by the length of the available records. The “long record” sites initiated eddy covariance flux monitoring in 1996 and have been thus continuously operative and delivering data for more than 16 years. A second criterion applied was the existence of ancillary information and finally the representativeness of the sites for different climate and vegetation types. Only sites located in forest ecosystems were selected, since the eddy covariance towers measuring in non-forest ecosystems have been generally installed only in more recent years (table 2.3_1). The data have been processed according with the standard methodologies and additional tools developed in the context of WP4 in order to make the data comparable and uncertainty estimated. The data have been then analyzed in order to identify effect of climate extremes on fluxes. The first result obtained has been the finding that others processes, in particular ecosystem disturbances, management practices and others confounding factors can have an effect of the fluxes higher than the climate extremes in particular in a relatively short time period like the one analyzed. This examples in particular have been presented and studied: first the effect of geological CO_2 sources that can add strong biases on the flux measurements by eddy covariance. This has been found and presented in Rey at al. 2012 using data acquired in a dry site in South Spain, selected as example of limit environmental condition.

Table 2.3_1: list of sites involved in the analysis and made available to the others CARBO-Extreme activities.

Country	Site	Start of EC measurements	Records in database (years)	Vegetation/climate type (IGBP/Koppen) classification	Tair (°C)	Precip. (mm)
FI	Hyttiala	1996	13	ENF/boreal (Dfc)	3.8	709
SE	Norunda	1996	12	ENF/boreal (Dfc)	6.1	527
DE	Hainich	2000	8	DBF/cool tembperate (Cfb)	6.8	750
DK	Soroe	1996	14	DBF/cool temperate (Cfb)	8.3	730
FR	Hesse	1997	12	DBF/cool temperate (Cfb)	9.9	875
IT	Collelongo	1996	14	DBF/cool temperate (Cfb)	7.5	1148
BE	Brasschat	1997	11	Mixed/ cool temperate (Cfb)	9.8	750
DE	Tharandt	1996	14	ENF/cool temperate (Cfb)	7.7	820
FR	Le Bray	1996	13	ENF/ cool temperate (Cfb)	13.2	972
IT	Roccarespampani 1	2000	9	DBF/ warm temperate (Csa)	15.1	876
IT	Roccarespampani 2	2002	7	DBF/ warm temperate (Csa)	15.1	876
ES	Las Majadas	2004	6	SAV/warm temperate (Csa)	15.9	854
FR	Puechabon	2000	9	EBF/ warm temperate (Csa)	13.5	872
IT	Castelporziano	1997	12	EBF/warm temperate (Csa)	15.6	767
IT	San Rossore	1999	12	ENF/warm temperate (Csa)	15	794



The management role has been instead analyzed using the data from the two Roccarespampani towers. The two eddy covariance systems monitored two stands with different age that are part of a coppice forest divided in sub-areas harvested every 20 years. The data acquired by the two towers allowed an analysis of the net ecosystem production of the forest at different age after the harvesting and this highlighted the role of age as main driving factor of the carbon exchange (Figure 2.3_14). The analysis also showed how the increasing NEE with age is due to an increase of photosynthetic capacity (GPP) and a decrease of the ecosystem respiration (confirmed by chambers measurements, not shown here).

Figure 2.3_14: NEE, GPP and Reco as function of the age (years after harvesting) in the coppice Roccarespampani forest.

Generalization of the response of fluxes to climate anomalies for different ecosystem types and climate regions

Analyzing the role of the main drivers we focused on the impact of air temperature (Tair) and water deficit anomalies on the variability of flux at daily resolution as well as the changes in physiological parameters of photosynthesis and ecosystem respiration (α-quantum yield; β-max. photosynthetic capacity; rb-basal respiration at 15°C) retrieved by a semi-empirical model parameterized at site level. The variability of daily CO_2 flux (NEE, GPP, Reco) has been analyzed in respect with drivers anomalies for different seasons and different Plant Functional Types. In particular the data have been binned into 2.5 percentile classes of the driver anomaly respect to the mean long term average (1989-2010 reconstruction from ECMWF) and regressive analysis performed respect to the anomalies in the three fluxes components. Results have been presented at the final CARBO-Extreme conference and here below is reported one example. In table 2.3_2 are presented the slope and correlation coefficients between the anomalies in air temperature and the anomalies in GPP, for the different sites analyzed and the different season. It is possible to see how in general a positive anomaly of the air temperature in March-May has a positive effect on GPP (increase of GPP) at all the sites except for the Mediterranean sites where there is no clear correlation. Anomalies in air temperature occurring in summer have instead a different effect according with climate areas, stimulating GPP in Boreal-Continental ecosystem and limiting it in the Mediterranean forests. For Reco (not shown) the effect of the anomalies in air temperature has been found to be always positive (stimulating increase of respiration).

Table 2.3_2: slope and correlation coefficient (in parenthesis) between the anomalies in air temperature and the anomalies in GPP for the different forest sites involved in the study. Red indicate positive relation, blue negative. The correlations are reported for different seasons. Together with the site code also the climate (B = boreal, Ct = continental, Wt = Warm) and the Plant Functional Type are reported.

	DJF	MAM	JJA	SON
FIHyy (B - ENF)	**0.011 (r2 = 0.581)*** **	**0.124 (r2 = 0.315)*** **	0.051 (r2 = 0.081)	-0.043 (r2 = 0.045)
SENor (B - ENF)	**0.061 (r2 = 0.323)*** **	**0.224 (r2 = 0.257)*** **	**-0.255 (r2 = 0.253)*** **	-0.037 (r2 = 0.018)
DEHai (Ct - DBF)	**0.026 (r2 = 0.680)*** **	**0.187 (r2 = 0.206)** **	**0.173 (r2 = 0.352)*** **	-0.066 (r2 = 0.019)
DKSor (Ct - DBF)	**0.048 (r2 = 0.633)*** **	**0.549 (r2 = 0.339)*** **	**0.361 (r2 = 0.315)*** **	0.109 (r2 = 0.046)
FRHes (Ct - DBF)	**0.015 (r2 = 0.527)*** **	**0.317 (r2 = 0.261)*** **	**0.103 (r2 = 0.158)* **	**0.193 (r2 = 0.172)** **
ITCol (Ct - DBF)	**0.034 (r2 = 0.545)*** **	**0.502 (r2 = 0.339)*** **	0.099 (r2 = 0.084)	-0.108 (r2 = 0.034)
BEBra (Ct - ENF)	-0.022 (r2 = 0.087)	**0.162 (r2 = 0.323)*** **	**0.233 (r2 = 0.531)*** **	0.027 (r2 = 0.011)
DETha (Ct - ENF)	**0.120 (r2 = 0.909)*** **	**0.414 (r2 = 0.578)*** **	0.009 (r2 = 0.002)	**0.117 (r2 = 0.145)* **
FRLBr (Ct - ENF)	0.014 (r2 = 0.016)	**0.078 (r2 = 0.093)**	**-0.135 (r2 = 0.196)** **	**0.098 (r2 = 0.251)*** **
ITRo1 (Wt - DBF)	0.014 (r2 = 0.029)	0.181 (r2 = 0.043)	-0.145 (r2 = 0.080)	-0.075 (r2 = 0.093)
ITRo2 (Wt - DBF)	**-0.035 (r2 = 0.207)** **	**0.605 (r2 = 0.167)** **	0.093 (r2 = 0.018)	0.081 (r2 = 0.029)
ESLMa (Wt - EBF)	0.020 (r2 = 0.017)	-0.001 (r2 = 0.000)	**-0.056 (r2 = 0.159)* **	-0.028 (r2 = 0.032)
FRPue (Wt - EBF)	**0.094 (r2 = 0.518)*** **	**0.148 (r2 = 0.336)*** **	**-0.150 (r2 = 0.139)* **	-0.052 (r2 = 0.032)
ITCpz (Wt - EBF)	0.043 (r2 = 0.059)	0.066 (r2 = 0.071)	**-0.136 (r2 = 0.191)** **	0.007 (r2 = 0.001)
ITSRo (Wt - ENF)	**-0.078 (r2 = 0.208)** **	**0.365 (r2 = 0.539)*** **	-0.098 (r2 = 0.051)	-0.041 (r2 = 0.022)

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Task 3.5 Long term remote sensing analysis — Lead: VUA

R. de Jeu (task leader) [VUA]; F. Maignan, F.M. Bréon [LSCE]

Long term soil moisture dataset from passive and active microwave observations

A methodology to develop a long term consistent soil moisture database from multisensor satellite observations has been developed. The data is now free available at (http://www.esa-soilmoisture-cci.org). The complete methodology is described by Liu et al., (2011, 2012). The data was released in June 2012 and downloaded by more than 600 different organizations within one year. Figure 2.3_15 gives an overview of the long term soil moisture trend as derived from this long term record.

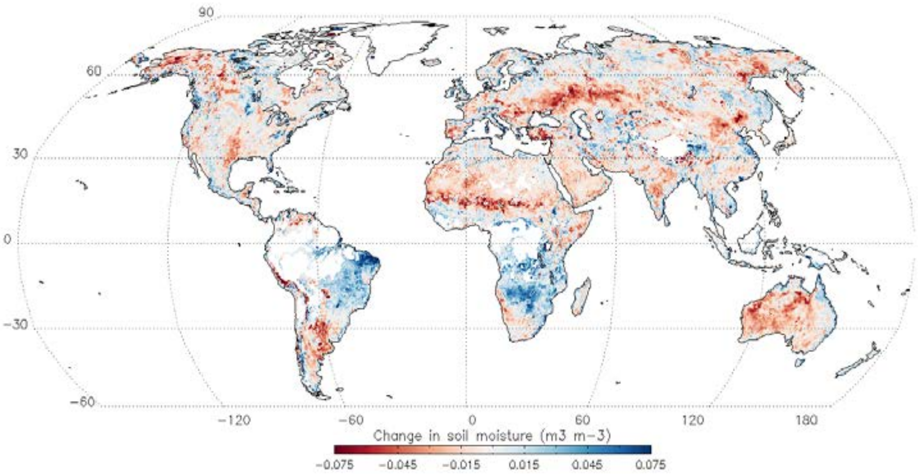

Figure 2.3_15: Trends in annual average satellite soil moisture (in m3m-3 per year) from 1979 to 2010. These values were derived from the harmonized soil moisture dataset; a 30+ year harmonized satellite soil moisture data record based on (historical) passive and active microwave observations (De Jeu et al., 2012).

Available passive and active microwave satellite-based soil moisture products are used to make one long term (1979-2010) consistent global dataset. The combining approach developed in this study is used to generate a long term soil moisture dataset from a series of microwave satellite sensors. Accordingly, a long term global soil moisture dataset is yielded and will be extended in the near future using data from new and upcoming satellites including ESAs Soil Moisture and Ocean Salinity and SMAP.

Comparison with a global carbon model

The satellite derived soil moisture datasets were compared to soil moisture from the process-based vegetation model ORCHIDEE during the period 2003–2004. We found that the soil moisture products from the satellite and ORCHIDEE correlate well, in particular when considering the root zone soil moisture of ORCHIDEE. However, the root zone soil moisture in ORCHIDEE consistently overestimated the temporal autocorrelation relative to the satellite and in situ measurements. This may be due to the different vertical depth of the two products, to the uncertainty in precipitation forcing in ORCHIDEE, and to the fact that the structure of ORCHIDEE consisting of a single-layer deep soil, does not allow simulation of the proper cascade of time scales that characterize soil drying after each rain event. We concluded that assimilating soil moisture in ORCHIDEE using AMSR-E with the current hydrological model may significantly improve the soil moisture dynamics in ORCHIDEE. The results from this study are published in Rebel et al., 2012.

Soil moisture and vegetation dynamics

The impact of water availability on vegetation was assessed. Two studies were conducted. One analyzed the relationship between the drought index (SPEI) and Net Primary Production (NPP) at a global scale. The other study analyzed the spatiotemporal relationship between the NDVI and satellite soil moisture for Continental Australia.

In the first study we found spatially variations in the relationship between SPEI and NPP. For the regions driven by water availability (mostly the semi arid regions) we found positive correlations between NPP and SPEI. For the regions driven by temperature and radiation (especially the northern Boreal regions) we found negative correlations between SPEI and NPP. These results are published in Chen et al., 2013a.

In the study on soil moisture and NDVI dynamics over Continental Australia we found a strong positive relationship between soil moisture and NDVI, which had a typical time scale where soil moisture is one month ahead of the NDVI. The correlation was strongest during the dry years in Australia. In addition, we analyzed the long term trends for soil moisture and NDVI using piecewise regression and discovered similar turning points for both NDVI and soil moisture. This study demonstrated the strong relationship between soil moisture and vegetation over different spatial and temporal scales and the results from this study could be used as a benchmark for global vegetation models. This study is currently in review (Chen et al., 2013b)

MODIS and AVHRR NDVI products

We provided netcdf files over Europe, both maps and time series.

MODIS NDVI

We provided directionally corrected NDVI MODIS/Terra daily data, at the Climate Modeling Grid resolution (CMG, 5 km, 0.05°), for the 2000-2008 period. The correction follows the algorithm described in Vermote et al. (2009). Over the European PFTs the noise is estimated to be less than 0.02.

AVHRR NDVI

We used the Land Long Term Data Record LTDR version 3, which includes BRDF effects correction, cloud mask improvement and a better orbital drift correction, for the 1981-2000 period. The data are given on the same CMG grid as MODIS products. We also provided the Quality Assessment field delivered in the LTDR files (see details in http://ltdr.nascom.nasa.gov/ltdr/docs/LTDRDataFormatDescriptions_03_2010_30.pdf).

NDVI data have been filtered against:

QA bit number 1: Pixel is cloudy

QA bit number 2: Pixel contains cloud shadow

QA bit number 3: Pixel is over water

QA bit number 6: Pixel is at night (high solar zenith angle)

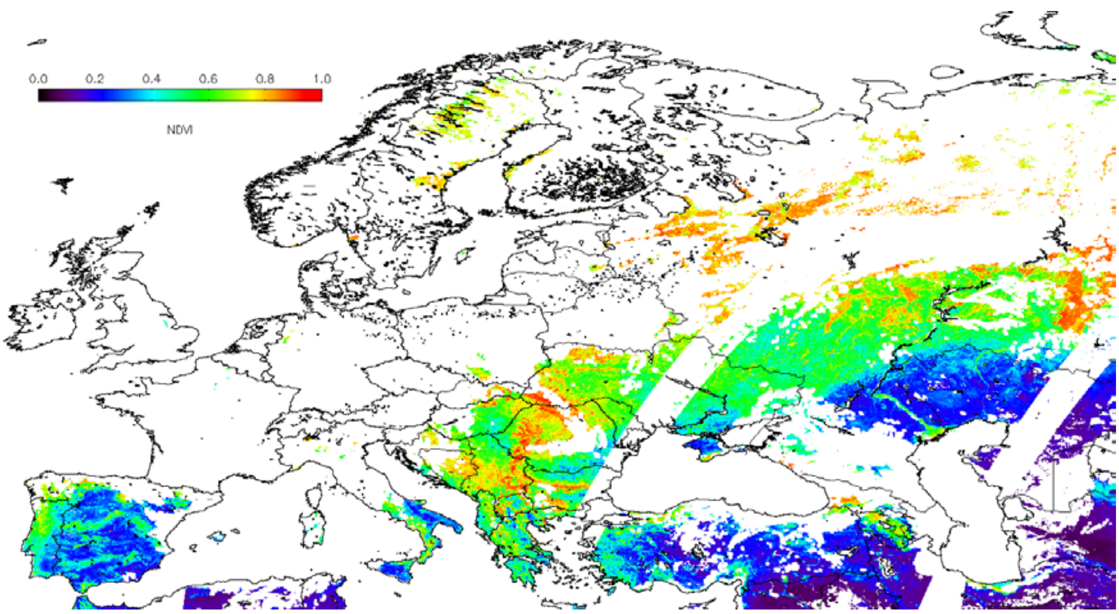

Figure 2.3_16: MODIS map for 15th August 2000

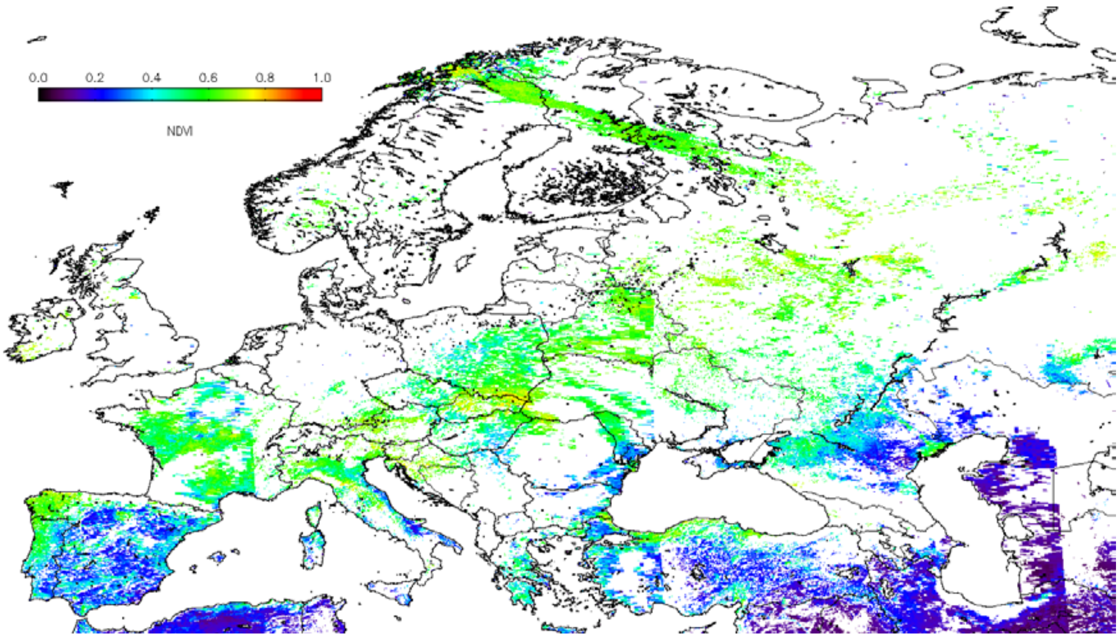

Figure 2.3_17: AVHRR LTDR map for 15th August 2000

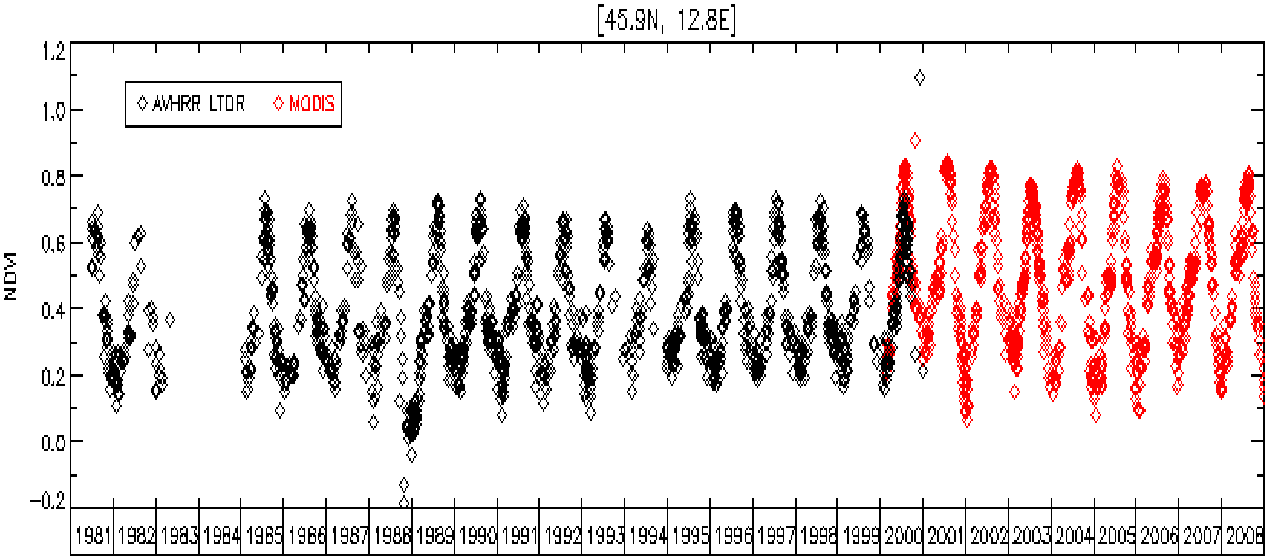

Figure 2.3_18: NDVI time series for a north Italian pixel

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A merged surface soil moisture dataset for the period 1979-2010. free available at http://www.esa-soilmoisture-cci.org

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Task 3.6 Soil carbon regional datasets **Lead: CU**

G. Kirk, P Bellamy [CU]; B. Guenet, F. Moyano, P. Ciais [LSCE]

The main objective of this task was to understand the contribution of climate change and variability versus other drivers on the long term soil C decrease measured by the gridded soil carbon inventory of England and Wales

Modelling the contribution of climate change and variability to the observed long term soil C decrease over England and Wales

Widespread decreases in soil carbon were observed in England and Wales between 1980 and 2000 in the National Soil Inventory (NSI) (Bellamy et al., 2005). Subsequent studies with a simple single pool soil organic matter (SOM) model, which quantified changes in carbon inputs to the soil and rates of decomposition, showed that the changes were largely due to changes in land use or management (Kirk & Bellamy, 2010). In work in Task 3.6, we used the DAYCENT model, initialised in various ways, to study the contribution of climate variation to the observed soil carbon dynamics in England and Wales (Foereid et al., 2012).

The initialization methods were: (1) a steady state ‘spin-up’; (2) the SOM pool distributions predicted at steady-state but with the true, initial soil C content; and (3) by fitting the initial pool distribution to the rates of change in soil C observed in the NSI. We ran the model for the main soil types on arable land and managed grassland in England and Wales, identified by taking the top five soil–land use combinations in 50 km grid squares across the area, giving 376 ‘sites’. We found the model predicted losses of carbon overall, and the losses varied with different climate scenarios applied over the NSI survey period. The predicted differences between climate scenarios were less sensitive to the initialisation method than to the soil carbon content (Figure 2.3_19).

In further work (Guenet et al., 2013), we used three versions of the coupled soil-vegetation model ORCHIDEE to separate the effect of trends in SOM input and decomposition induced by climate trends over 1978-2003. The first version of the model (ORCHIDEE-AR5) used for IPCC-AR5 CMIP5 Earth System simulations, is based on three soil carbon pools defined with first order decomposition kinetics, as in the CENTURY model. The second version (ORCHIDEE-AR5-PRIM), built for this study, includes a relationship between litter carbon and decomposition rates, to reproduce a priming effect on decomposition. The third version (O-CN) takes into account N limitations to SOM decomposition. We performed regional gridded simulations with these three versions of the ORCHIDEE model over England and Wales. None of the three model versions was able to reproduce the observed NSI soil carbon trend. This suggests that either climate change is not the main driver for the observed soil carbon losses, in agreement with our earlier modeling studies, or that the ORCHIDEE model even with priming or N-effects on decomposition lacks the basic mechanisms to explain soil carbon change in response to climate, which would raise a caution flag about the ability of this type of model to project soil carbon changes in response to future warming.

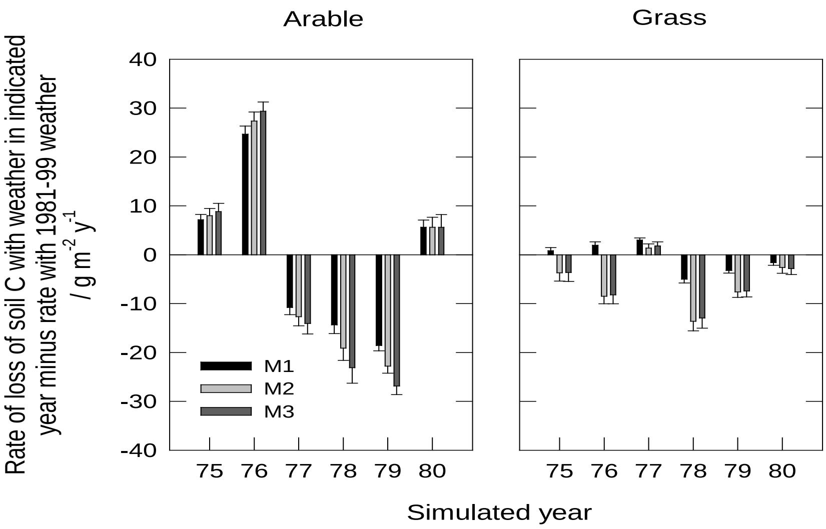

Figure 2.3_19. Differences between rates of SOM loss from the soils of England and Wales predicted with the weather in the indicated individual years repeated for 18 years and that predicted with the actual weather over 1981–99 averaged over the period. M1, M2, M3 indicate the three model initialisation methods (see text). The values are averages across individual soils and grid squares for each land use category weighted in proportion to the total area represented. Bars indicate 95% confidence intervals.

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Task 3.7. DOC export by streams caused by extreme rainfall events in Scotland and Sweden

Lead: CEH

K. Dinsmore, M. Billett [task leader, NERC, CEH Edinburgh], N. Avrosiadi, T. Grabs, K. Bishop [SLU]

Multisite analysis of the role of high flow extremes on aquatic DOC export.

Over the last 12 months we have combined UK and Swedish datasets to carry out a multisite analysis of the role of high flow extremes on aquatic DOC export. This involved 7 UK and 6 Swedish catchments (Figure 2.3_20) with weekly (UK) or fortnightly (Sweden) DOC concentration data and either continuous (UK) or daily (Sweden) measurements of discharge. Measurement periods range from 5-29 years. Catchments cover a range of runoff regimes and include the presence/absence of spring flood due to snow melt (Figure 2.3_21).

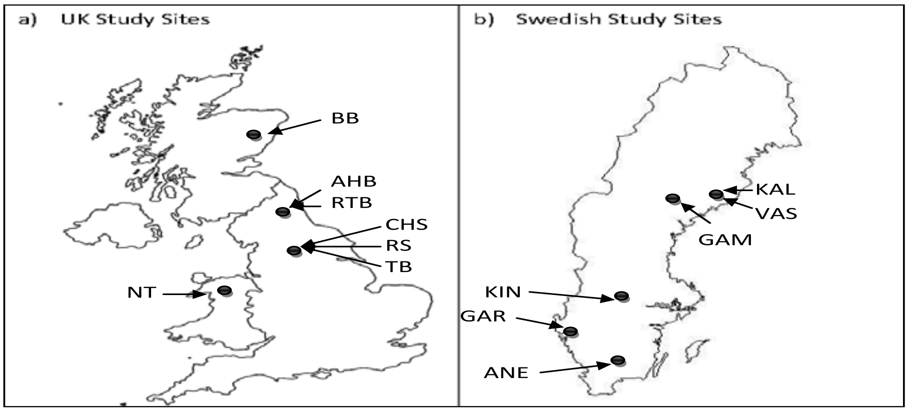

Figure 2.3_20: Location of the 13 study catchments used to study DOC export during high flow extremes

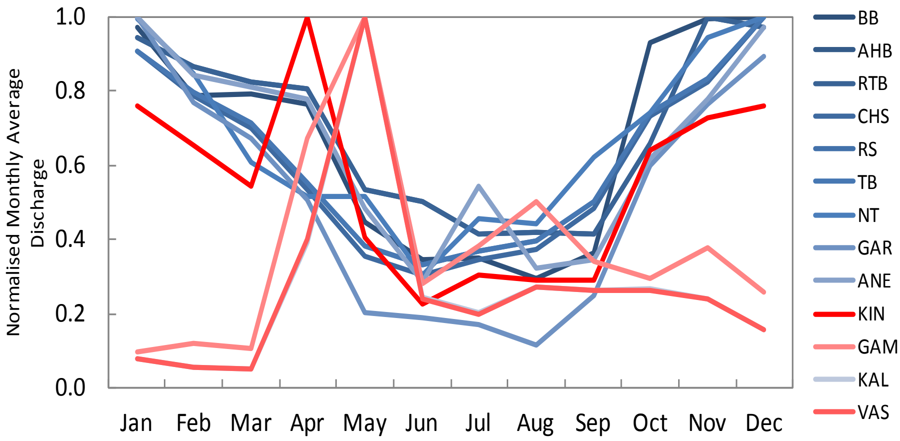

Figure 2.3_21: Mean monthly discharge at the study catchments. Red lines highlight the 3 catchments which show significant spring flood events.

In 8 of the 13 streams, greatest DOC export was recorded in autumn when high concentrations coincided with high discharge. Three of the Swedish catchments (GAM, KAL and VAS) all had highest exports in spring coinciding with the spring snowmelt event. Results show that during high flow extremes (defined as flow greater than monthly Q5), which equates to approximately 5% of year, between 17-32% of annual runoff occurs and 19-46% of total annual DOC is exported. When seasons are considered individually, ‘event’ flow produced the greatest proportional DOC export during summer. Hence increases in extreme flows during the summer will have a greater impact on total annual export than a similar increase in extreme flows if they occurred during the winter. Enhanced DOC export either occurs by increased transport (runoff) or change from a low to a high DOC source. Our analysis showed that in the highly organic peatland catchments the large volume of runoff during events was the primary cause of the high contribution of events to total DOC export. However, runoff alone could not explain the event contribution from the non-peatland catchments indicating that source concentration, particularly in summer/autumn (linked to enhanced primary productivity), was also an important cause of the high event contribution to DOC export. The degree to which source concentrations contributed to the event export was linked to the organic content of the catchments. We suggest this corresponds to the level of DOC stratification within the soil profile, hence an increase in extreme events will have a greater influence on catchments where SOM horizonation exists.

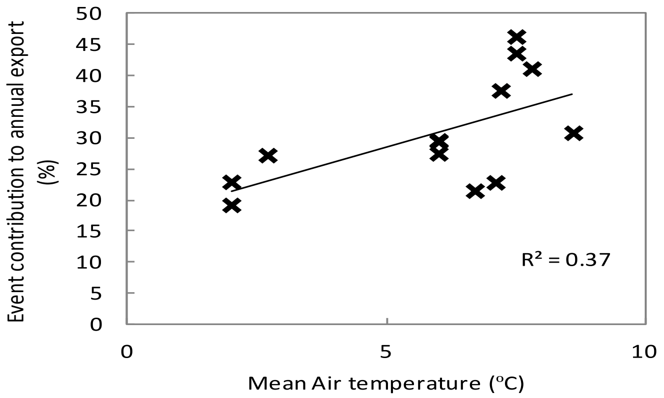

Figure 2.3_22: The relationship between event contribution to DOC export and mean annual air temperature

In relation to climate, DOC export in warmer catchments (where high productivity leads to higher DOC concentrations in the near-surface soil layers) was more sensitive to an increase in 'extremes' as both increased runoff and a change in the dominant flowpath effect total export (Figure 2.3_22). In summary, the following results have been found in the CARBO-Extreme project. 1) High flows are disproportionally important to total annual DOC export with up to 46% of annual export occuring during extreme events (approximately 5% of time). 2) An increase in 'extreme' events is likely to lead to greater DOC export than would occur due to a comparable increase in mean flow, 3) In highly organic catchments where little DOC horizonation exists within the soil profile, the increase in export will be due almost exclusively to the increase in the transport pathway (runoff), 4) In warmer, drier catchments total annual DOC export will be more sensitive to an increase in 'extremes' as both the increase in the transport pathway and the change in dominant flowpath will effect total export, and 5) an increase in high flow extremes during the summer is likely to have a greater impact than an increase in extreme events in other seasons.

Task 3.8 Synthesis of multiple gridded datasets and model results at continental scale
Lead: LSCE
T. Kato, P. Peylin, P. Ciais [LSCE]; M. Jung, C. Beer, M. Mahecha [MPI-Jena]

The goal of the synthesis task is to organize and synthesize the 'data mining' and data analysis program of the WP, and to interface with the model developments in WP5 for ensuring an optimal use of all data.

Database status

Data developed from each task are available via the Carbo-Extreme database directly or via request. The data exchange portal (mainly hosting large spatiotemporal long-term observations and model results) is also online via the link http://www.bgc-jena.mpg.de/geodb/Carbo-Extreme/Home.php

Synthesis study among models simulated NEE over European continent

We established analysis on consistency between bottom-up and top-down estimates of the CO_2 budget of Europe. Estimation of the regional carbon budget has been an important research topic since atmospheric CO_2 concentration was started to be measured in 1950s (Keeling, 1960). Consequently, in several recent decades, two different types of model have been developed intensively for estimating regional terrestrial CO_2 budgets: Terrestrial Biosphere Model (TBM) and Atmospheric Inversion model (AI), as bottom-up and top-down approaches, respectively.

In addition to the preliminary research till last year, we further conducted the investigation on uncertainty and spatial resolution among modeling approaches over European continent where possesses one of the largest number of simulation performances, by prognostic and diagnostic TBMs and AIs. A comprehensive intercomparison across number of the Terrestrial Biosphere Model (TBM) and Atmospheric Inversion model (AI) is performed in terms of interannual changes in Net Ecosystem Exchange (NEE) between terrestrial biosphere and atmosphere over European region. Analysis is done together with 20 model simulations: 6 models from AI (LSCE_PEYLIN, LSCE_PYVAR, MPI-Jena-s96, MPI-Jena-s99, Transcom3, CarbonTrackerEU), 11 models from TBM Prognostic (NCAR-CLM4, HYLAND, LPJ, LPJ-GUESS, OC-N, ORCHIDEE, SDGVM, TRIFFID, VEGAS, ORCHIDEE-IERA, Biome-BGC), and 3 models from TBM Diagnostic (MTE, ANN, MOD+17). A manuscript will be submitted soon.

We hypothesized that the spatial resolution of each simulation is one of the factors determining the uncertainty of simulated NEE, especially when the simulated flux is compared to observations. Nevertheless, the spatial resolution of model simulations results from the resolution of available input data forcings, e.g. climate, atmospheric transport for AIs. Therefore, we expect that the agreement between model simulations is affected by spatial resolution, and here we investigate the dependency of between-models NEE consistency on spatial resolution. First, the NEE gridded fields were aggregated spatially into 1°x1°, 2°x2°, 3°x3°, 3°x3°, 5°x5°, 10°x10°, 15°x15°, 20°x20°, and 30°x30° resolutions over Europe. Then, we calculate the standard deviation of interannual changes in annual NEE for each grid point in each model. Third, the mean and standard deviation of these maps of temporal standard deviations are calculated among the models for each approach. Fourth, the average of them are plotted against the spatial resolution for each of three approaches (Fig. 2.3_23).

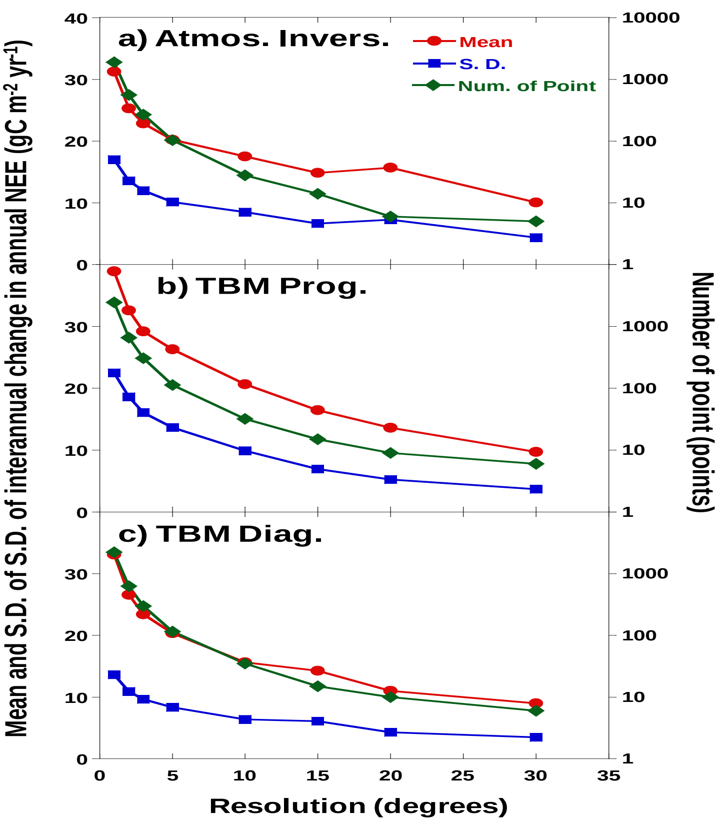

Figure 2.3_23: Multi-models' mean and standard deviation (S.D.) of the standard deviation in interannual change of annual NEE, and number of land points over Europe as a function of spatial resolution, as obtained by aggregation of high resolution NEE model results for a) atmospheric inversions, b) prognostic TBM and c) diagnostic TBM during 2001-2007. For obtaining the mean and S.D. values, first the standard deviation in interannual changes of annual NEE is calculated in each grid. Then the mean and S.D. of that are averaged over the models in each approach. Finally, the spatial distributions of them are averaged over the grids.

There is a gradual decrease in both mean and standard deviation along with coarser spatial resolution, although the process based models show higher values in both variables compared to other two approaches at same resolutions. Moreover, the AIs and Diagnostic models show local maxima in both statistics at 20o and 15o resolutions, respectively (Fig. 2.3_23a and 23c, respectively). Those fluctuations of both mean and standard deviation in AIs and diagnostic TBMs are thought to come from the small number of grid points at coarser resolutions than 15°, (less than 16 grid points over Europe). Because Europe has a complex coastline, spatial averaging produces abrupt change in area-averaged terrestrial biosphere fluxes, which includes former ocean part in a grid when shifting from high resolution to low resolution. Nevertheless, overall decreasing trends in all the three approaches suggest that they contain random errors in the model spatial distribution of grid-point NEE, whose values are thought to decrease by spatial averaging, leading to lower mean and standard deviation values of NEE at coarser resolutions. We think that those potential random errors are coming possibly from the prior flux, or from the input data forcing. Thus, we conclude that, first, all the three approaches contain the random error in their simulations possibly due to the random error in prior flux or input climate forcings, rather than systematic error potentially being thought to keep both statistics constant for spatial resolution variation. Second, prognostic TBM contains larger uncertainty in temporal variation as shown by higher mean and standard deviation over interannual changes in annual NEE (Fig. 2.3_23b), compared to the other two approaches.

Synthesis study on regional hot spots / processes of interannual variability of European carbon balance

We aim to quantify year-to-year changes in the dynamics of CO_2 fluxes (i.e. net ecosystem exchange, NEE and ancillary variables) contributing to a comprehensive description of the variability of the terrestrial carbon cycle over Europe based on observational evidence. The analysis is based on two methodologically independent upscaling products which represent 22 years of quasi–observational GPP (and NEE) estimates over Europe, and a novel concept for evaluating interannual variability developed in CARBO-Extreme the so called “year-to-year differences” (IADs). A manuscript will be submitted.

The main results can be summarized as follows: 1) The IAD depicts some regional hotspots, where in particular the Black Sea i.e. southern Spain, Romania, parts of Bulgaria, and the Ukraine seem to be affected by this high values of IAD; 2) We estimate that on a 20 years horizon, approximately 20% of the land surface experienced a 20-year extreme year; 3) Patterns of IAD in GPP tends to agree with IADs in the water availability; 4) Unexpectedly, we cannot identify relevant trends in the IAD. We also have to emphasize that the role of the identified extreme years is potentially highly relevant on global scales.

Conceptually, the developed strategy for evaluating IADs is expected to provide a perspective for (a) analyzing outputs from terrestrial biosphere models, (b) comparing observed and modeled patterns of IAD, and (c) for investigating if the IAD within observations is higher than the accuracy of model-data comparisons.

Besides, Zscheischler et al. (2013, *Ecological informatics, doi:* ***10.1016/j.ecoinf.2013.03.004***) developed a new technique for identification of extremes in anomalies of spatiotemporal long-term observations relevant to the terrestrial C-cycle variables. Ongoing work suggests that very few though large spatiotemporal extreme events may explain most of the inter-annual variability of land C fluxes.

2.4. WP4 Data infrastructure and model support Lead: UNITUS

D. Papale [UNITUS] and I. Janssens [UA] (Task leaders)]

The database and data processing activity in the project has been focused on the collection, harmonization, processing and distribution of data measured in the context of CARBO-Extreme but also by groups that although not directly involved in the project wanted to share their measurements and data. This aspect highlights the attractiveness of the scientific activities planned and also the maturity of the scientific community. For this reason the first task for the project database has been to propose, discuss and approve a common data sharing and data use policy that has been accepted by all the participants and contributors and that has been used also as example by others projects and initiatives.

The data collection, done also in the context of WP3, has been focused on two data type: long term timeseries of carbon, water and energy fluxes measured by eddy covariance sites and Ecosystem Manipulation Experiment data. The two group of measurements followed different processing procedures because intrinsically different and also because the eddy covariance data are already following a good standardization standard and for this reason easier to handle.

In particular, the long-term dataset has been prepared to be used in the model-data fusion exercise and for this reason a number of new developments in terms of data processing has been tested and applied. The main innovative aspects have been: 1) the uncertainty estimation in the carbon fluxes due to the processing applied, where multiple methods to filter for low quality data are used and the differences quantified and reported with the data, 2) the estimation of the random error component in all the fluxes, particularly important when halfhourly measurements are used, 3) the Energy Balance Closure (in the eddy covariance data the energy balance between net radiation and energy fluxes if often not close) has been forces to be close developing a correction technique that estimates also an uncertainty boundary, 4) key meteorological variables have been downscaled at tower level from ECMWF gridded products in order to reconstruct a 20 years timeseries at each of the sites involved. All these innovations in the processing, after an additional test given by the use of the products by the modelers in CARBO-Extreme, are now under consideration as basis for the future processing in ICOS and FLUXNET and also under discussion with AmeriFlux to be further developed and implemented in these large networks. This is in our opinion a main foreground result of CARBO-Extreme.

For the Ecosystem Manipulation Experiment data, a large database with data from over 70 experimental sites has been compiled. This database contains (among others) measurements of biomass production, leaf physiology, vegetation characteristics, foliar and soil chemistry and soil respiration, as well as ancillary data such as soil moisture, soil texture and meteorological data for characterization of the climate. The dataset is still under processing and analysis and discussion about the ingestion and sharing through the CARBO-Extreme database still under discussion with the different data owners. However it is one of the largest standardized dataset of these type of measurements and this will be also a basis for future scientific activities.

All the CARBO-Extreme data are distributed through a specific project page hosted by the European Fluxes Database Cluster. The page is available at the address www.europe-fluxdata.eu/carboextreme and includes Guidelines, Data Access tools and a PI Area where data owner can submit new measurements, update the site information and check the list of the users that downloaded their data in order to contact them if needed. The CARBO-Extreme page will be kept online and updated for 12 months after the project and then all the data and metadata migrated in a new portal, probably the ICOS ecosystem portal, to ensure their availability in the long term.

2.5. WP5 Model Data Integration Lead: MPG

Task 5.1: Process-model evaluation & structural development Lead: MPG
C.Beer (task leader), N.Carvalhais [MPG]; M. Kuhnert, P. Smith [UNIABDN]; R. Lardy [INRA]; S. Rolinski [PIK]; M. van Oijen [CEH]

In CARBO-Extreme, the one-dimensional sectorial models PaSim (grassland model), Daily DayCent (cropland model) and BASFOR (forest model) as well as the one-dimensional generic models JSBACH, ORCHIDEE and LPJmL have been run using forcing data at site level. The comparison to data from ecosystem manipulation experiments and long-term observations as well as more formal model-data fusion exercises (Task 5.2) allowed a detailed evaluation of the models. This exercise was also attractive and interesting for other modelling groups which led to a very successful additional application of the forest model CASTANEA and the Coup model.
Simulated carbon and water exchanges between the land surface and the atmosphere as well as simulated ecosystem component carbon stocks have been improved due to parameter calibration (cf. Deliverable 5.7). These results were presented during the "CARBO-Extreme workshop on ecosystem model evaluation using model-data-fusion techniques", 24-26 May 2011, Jena and during the 2nd annual project meeting, 26-29 Sept 2011, Montpellier and are available online:

http://www.carbo-extreme.eu/index.php?n=Intra.WP5Workshop
http://www.carbo-extreme.eu/index.php?n=Intra.MontpellierMeeting

The model evaluation also demonstrated structural deficiencies which led to further development of the models. The initial model-data fusion exercise using the LPJmL model and eddy covariance flux measurements at grassland sites led to the implementation of more grassland management options. Since the productivity of plants are influenced by their removal or harvest, for grasslands used for livestock feed the harvest scheme was modified. By introducing different management options, the timing and amount of biomass removal as well as their further fate in the carbon and water fluxes were diversified. The chosen three basic options represent extensive (mowing twice a year), medium (pastoral systems with low animal densities) or intensive (rotation paddocks with high animal densities) management. The model JSBACH initially ran with one soil bucket for the hydrological cycle. This has been improved by a 5-layer scheme in collaboration with Stefan Hagemann from the Max Planck Institute for Meteorology in Hamburg which represents topsoil water dynamics more reliably. The model ORCHIDEE has been advanced by a stand growth and forest management model during the reporting period. Recent developments to DailyDayCent involve a complete rewrite of the N_2O and CH_4 routines. The forest model BASFOR was shown to need a more stable response to environmental perturbations, which could not be achieved by calibration alone and required changes in simulation of foliar dynamics and nitrogen relations. PaSim improvements were made to the animal module, which allow simulating forage production and dry matter intake taking into account selective grazing between vegetation compartments and the effect of high temperatures. For ruminants' performance and enteric CH_4 emissions at grazing new equations were also added to estimate the energetic content of the intake, the livestock system simulated and, with dairy cows, the level of milk production.

Task 5.2 Bayesian model calibration and uncertainty propagation Lead: CEH
M.van Oijen (task leader) [CEH]; N. Carvalhais, C. Beer, M. Mahecha, M. Reichstein, G. Schuermann, S. Zaehle [MPG]; P. Peylin, N. MacBean [LSCE]); T. Thum, [LSCE, now at FMI]; A. Rammig, S. Rolinski [PIK]; D. Papale [UNITUS]; A. Granier, D. Loustau [INRA]; T. Keenan, A. Richardson [(HARVARD]

During the reporting period, extensive model-data fusion exercises have been performed to improve sectorial and generic models. In general, there are two main types of data which have been used successfully: Results from ecosystem manipulation experiments and long-term observations.

Our prior knowledge about the probability of parameter values is adjusted during the Bayesian calibration procedure. Usually, the distributions are getting narrower, the median is shifted and in some cases also their shape is altered (Deliverable 5.7). In addition, the model-data fusion exercises allowed a well-in formed evaluation of the prognostic models at site level (cf. Task 5.1).

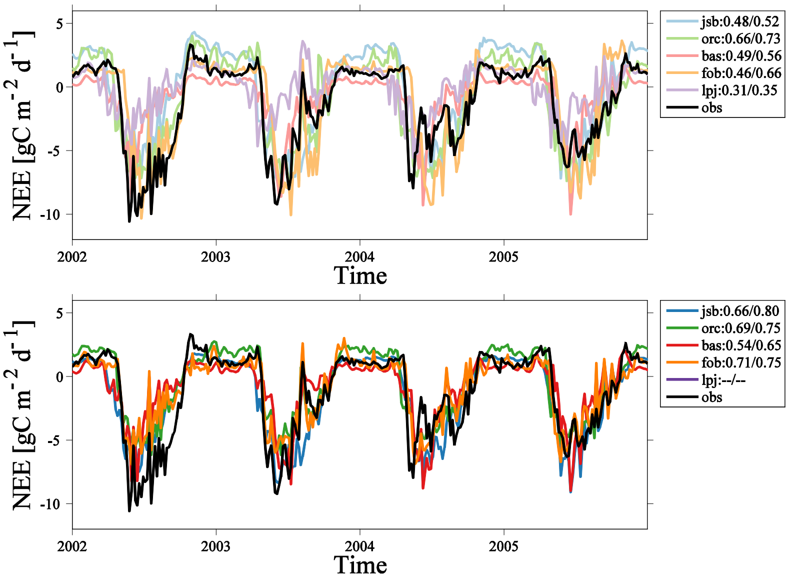

Figure 2.5_1: Simulated NEE fluxes for Hesse for *prior* (top) and *a posteriori* parameter vectors (bottom). Results for the period 2002-2005 out of 1996-2011 are shown for visibility reasons. Results report the model efficiency (MEF) for calibration (left) and evaluation (right) periods.

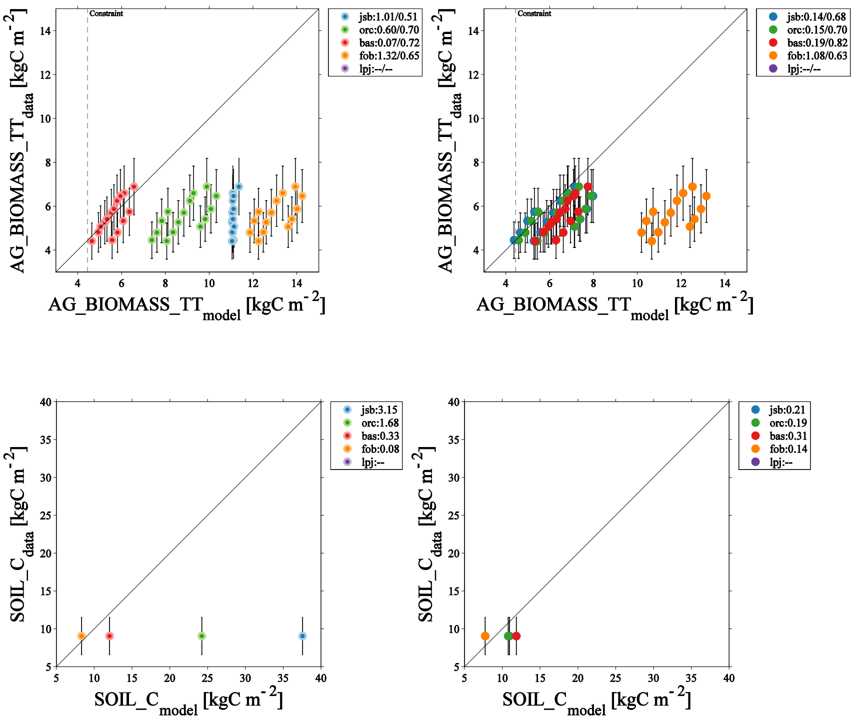

Figure 2.5_2: Comparison of observations with *prior* (left) and *posterior* (right) simulations of above ground biomass (top) and total soil carbon stocks (bottom).

There exist different kinds of observation at different scales about the ecosystem state and function which can be used in a model-data fusion exercise. For example, half-hourly observations of carbon dioxide or energy exchanges between the land surface and the atmosphere using the eddy covariance method or the above-ground wood increment at annual time scale store important information about the short-term and longer-term dynamics of the system. In addition, total vegetation or soil carbon stocks, leaf area index etc. describe the state of the system at daily to annual time scale. In CARBO-Extreme such different types of information has been integrated into one consistent model-data fusion exercise (cf. http://www.carbo-extreme.eu/uploads/Intra/MDFlongterm/LT-InSitu-MDF_protocol_20120420_noTC.pdf). This exercise was successful in improving short-term carbon and water fluxes (Fig. 2.5_1) as well as vegetation and carbon pools (Fig. 2.5_2). The so derived parameter vectors allow a more reliable projection of the future European carbon balance.

Task 5.3 Spatio-temporal multi-scale integration & consistency check Lead: CEA LSCE
P.Peylin (task leader), T. Kato, P.Peylin, P.Ciais [LSCE];

The consistency of bottom-up and top-down estimates of the CO_2 budget of Europe was assessed using several prognostic and diagnostic terrestrial biosphere models (TBM) as well as atmospheric carbon dioxide inversion schemes (AI). The intercomparison was performed in terms of interannual changes in NEE over Europe. (cf. Deliverable 5.8).

To assess the degree of similarity of interannual NEE across the different approaches, the correlation between NEE time series are examined (Fig. 2.5_3). In addition, correlation to climatic factors has been studied. The results demonstrate the overall weak correlation between continental-scale NEE time series based on different approaches which also indicates further need for identifying the relevant processes of interannual variation of NEE.

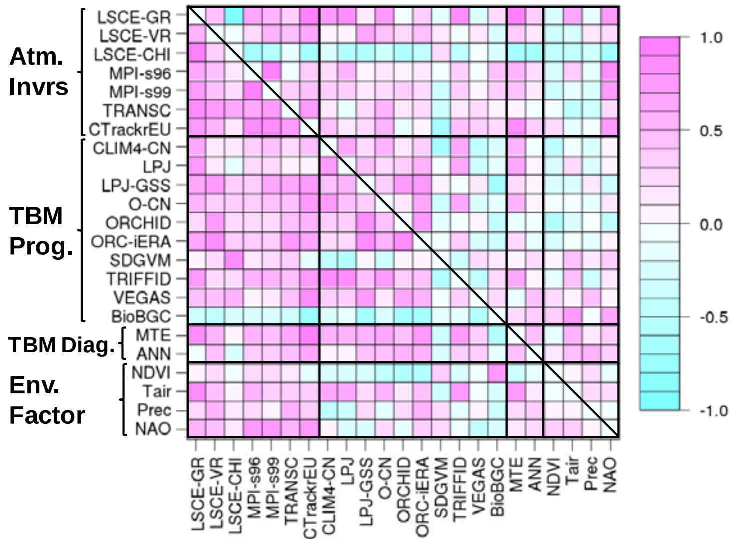

Fig. 2.5_3: Correlation coefficient in interannual change in annual (top right triangle) and JJA (bottom left triangle) NEE among two models or between the model and environmental factor during 1996-2010.

2.6. WP6 Scenario Analysis Lead: UNIABDN

The objective of work package 6 is to provide spatially C flux scenarios based on projections of the European terrestrial carbon cycle and associated uncertainties by applying the improved and calibrated models of WP5 driven by regional climate scenarios, to feed in to the vulnerability synthesis in WP7. Eight different model are used for this approach, the four cross-sectoral models CLM (Community Land Model version 4, Bonan et al. 2003), ORCHIDEE (Krinner et al. 2005), JSBACH (Raddatz et al. 2007), LPJmL (Bondeau et al. 2007) as well as the four sectoral models PaSim (Riedo et al. 1998; Graux et al. 2012), BASFOR (Van Oijen et al. 2005), EPIC (Van der

Velde et al. 2012; Balkovič et al., accepted), DAILYDAYCENT (Parton et al. 1998). The sectoral models consider only one of the three land use categories forest (BASFOR), grassland (PaSim) and cropland (EPIC, DAILYDAYCENT). Parameters of most of these models were optimized using experimental data and long-term observations in work package 5.

Task 6.1: Collation of fundamental spatial data sets including regional climate scenarios
Lead: ETH Zurich
S.I. Seneviratne (task leader) [ETH Zurich]; C.Beer [MPI-Jena]

For the spatial simulations, the models needed spatial distributed input data that were collected from different projects, which was the aim of Task 6.1. Several climate data sets were collected for the different time periods, as summarized in deliverable 6.2, but finally four data sets (one for 1901-2010 and three projections until 2100) were used for the simulation runs: WATCH forcing data was used for the period 1901-1978, bias-corrected ERA-Interim data was used for the period 1979-2010, and the three projections for the period 2011-2100 assuming the IPCC A1B emission scenario were based on ENSEMBLES outcomes from 1) MPI-REMO, 2) KNMI-RACMO, and 3) DMI-HIRAM. These regional climate model outputs were also bias-corrected against WATCH forcing data to ensure a consistent time series. These climate datasets represent control data (CNTL) in a series of artificial biosphere model experiments. In addition, using a distribution-transformation method, datasets with reduced variability but conserved long-term mean were produced (REDVAR) for model experiments (Beer et al., in revision). The spatially distributed data represents gridded data (0.25 deg grid cells) with 21 land cover types created using GLC2000 and MODIS VCF land cover data (1 km resolution), a WWF biome map and climate data for the natural C_4 grass distribution, and FAO statistics of agricultural C_3/C_4 distribution; and soil data from the Harmonized World Soil Database v1.1 (1 km resolution). Management data for croplands and grasslands, and information about crop rotation, variable in space and time, were applied with some modification from the project NitroEurope-IP.

Task 6.2: Offline model factorial experiments to identify critical thresholds for assessing vulnerability
Lead: UNIABDN
P. Smith (task leader) and M. Kuhnert [UNIABDN]; C.Beer [MPI-Jena]

The objective of task 6.2 was to identify critical thresholds for assessing vulnerability of ecosystems. Therefore, the spatial simulations were set up in two experiments to detect impacts of gradual climate change and differences in climate variability on land carbon dynamics. The models were run with the two versions of climate data, CNTL and REDVAR. For the European land surface, ORCHIDEE and LPJmL show increasing stocks until 2100, i.e. the land acts as a C sink (Figure 2.6_1, left hand side). Both models also agree on a stronger sink activity in case of lower variability (Figure 2.6_2, right-hand side). The model JSBACH, however, shows a change of dynamics around 2050, suggesting a tipping point after which the land surface stops acting as a C sink and becomes a C source (Figure 2.6_1, LHS) with stronger effects for the lower (REDVAR) variability (Figure 2.6_2, LHS). Due to the representation of fire activity in LPJmL and dynamic vegetation, this model shows stronger oscillations. Interestingly, this model also predicts a carbon sink in the future. Model differences in 2100 are larger than differences between CNTL and REDVAR forcing or RACMO versus REMO forcing, suggesting less agreement among the models than is seen in the forcing data.

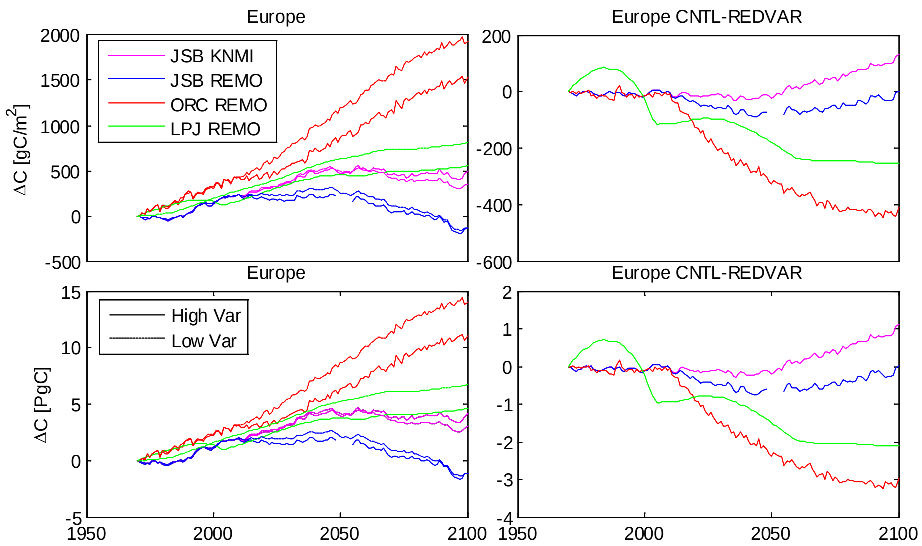

Figure 2.6_1: European land carbon differences to the 1970 value (anomalies) for the generic models JSBACH (JSB), ORCHIDEE (ORC) and LPJmL (LPJ) using the climate datasets based on WATCH forcing data, ERA-Interim, and MPI-REMO. The results contain also one run of JSBACH with the future climate data based on KNMI-RACMO. The graph on the left hand side shows the results of the control climate (line) and the climate with reduced variability (dotted line), both with transient atmospheric CO_2. The right hand side shows the differences between the simulation results of the control run and the results of the simulations with reduced climate variability.

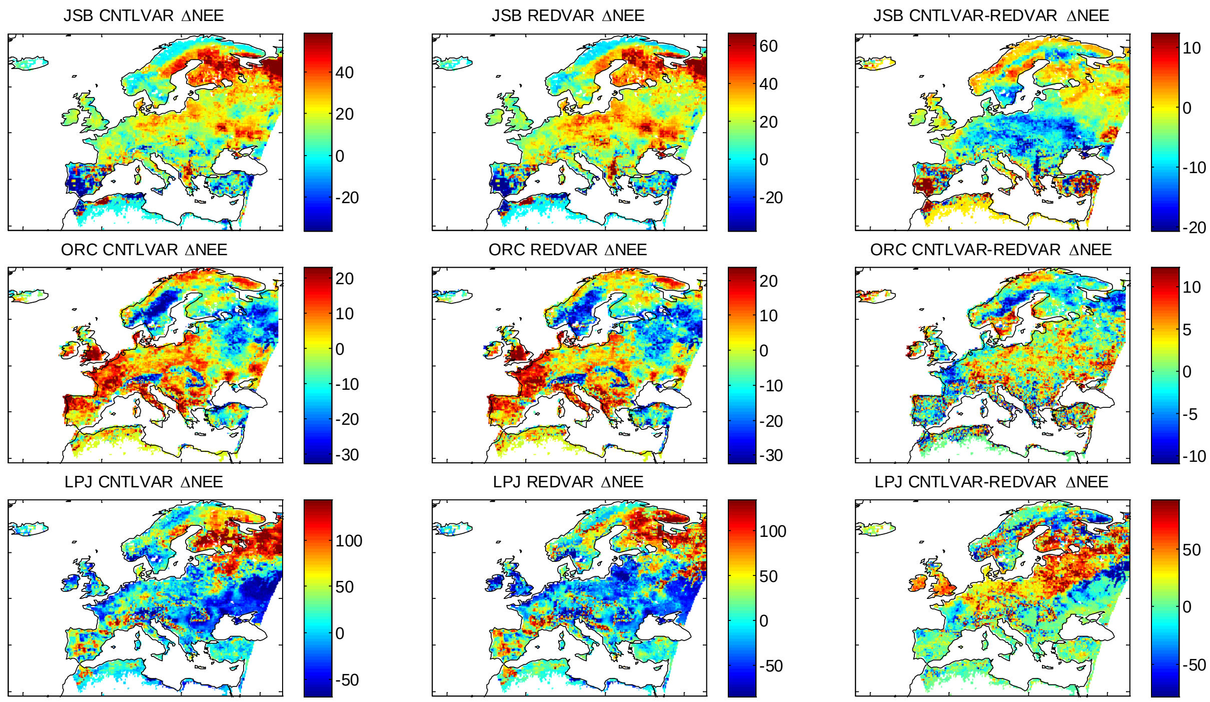

Figure 2.6_2: Difference maps of NEE [gC m-2 a-1] of a future period (2071-2100) and a recent period (1981-2010) for the models JSBACH (JSB), ORCHIDEE (ORC) and LPJmL (LPJ) (in rows). The left column shows the differences of the results simulated with the CNTL climate dataset, the column in the middle differences of the simulation results with the REDVAR climate dataset, and the right column shows the differences between the first two columns.

Figure 2.6_2 shows the spatial pattern of carbon balance projections in more detail, and shows the effects of climate variability on the C balance. First of all, there is no common spatial pattern amongst the models for NEE future-recent differences (Figure 2.6_2, left column). When looking at the effects of climate variability (Figure 2.6_2, right column) one can see distinct effects of climate variability of Central Europe versus Scandinavia and the Mediterranean in case of JSBACH and ORCHIDEE, but with the opposite sign. LPJmL shows stronger effects due to fire and vegetation density shifts, with a stronger future source in Central Europe and the north for higher variability (CNTL) (Figure 2.6_2, lower right panel).

We also investigated the impact of wild fire on ecosystems. A comparison of the results of the dynamic vegetation model LPJmL simulated with control climate and climate with reduced variability (all other factors being equal), shows that climate variability accelerates fire along biome boundaries and these two factors together decrease tree abundance and productivity to an extent, where the treeline between steppe and temperate forests is likely to be shifted northwards. Here fire is likely to decrease carbon storage in living vegetation, but the impact on NEE needs to be studied in more detail, as biomass is not always fully combusted and post-fire mortality adds dead biomass to the litter pool, thereby influencing heterotrophic respiration. Because of these processes, time-lags in NEE could occur and this requires further analysis. Where vegetation productivity is reduced below a critical level, fire spread is limited, and the area burnt is not projected to decrease, despite an increase in future climatic fire danger. This is the result of non-linear interaction between fire and vegetation dynamics.

Task 6.3: Offline model ensemble runs with climate scenarios to identify where and when critical thresholds are likely to be reached in the future **Lead: UNIABDN**

P. Smith (task leader) and M. Kuhnert [UNIABDN]; C. Beer [MPG];

The objective of task 6.3 was to identify where and when critical thresholds are likely to be reached in the future. As mentioned above there are no fixed values that define a threshold of vulnerability, but NEE is a good indicator for climate impacts on the ecosystem. Figure 2.6_3 shows land carbon stock dynamics until 2100 simulated by sectorial models for three SREX regions, 11 (Scandinavia), 12 (West, Central and East Europe) and 13 (Mediterranean). Except for BASFOR and PaSim in SREX 11, these models project an increase of carbon stocks for the future. BASFOR is a forest model and considers only spruce in these simulations which suggest that spruce ecosystems will act as a carbon source in future. Accordingly, the negative impacts on spruce may force a change in the species selected for planting on areas currently planted with spruce. The crop model EPIC shows a strong carbon sink in all cases. All sectorial models show a higher sink with lower variability.

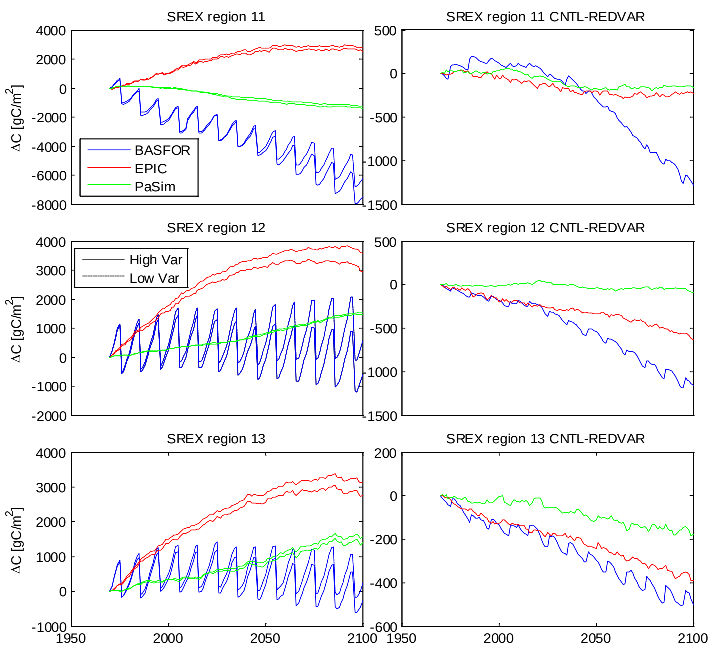

Figure 2.6_3: Simulation results of the total ecosystem carbon stock dynamic for the models BASFOR, EPIC and PaSim separated in three different SREX regions. The graphs on the left show simulation results of the control climate (line) and the climate with reduced variability (dotted line). The graphs on the right show difference maps of control runs minus the simulation runs with reduced climate variability.

Table 2.6_1 summarizes the qualitative results for the changes of the carbon pools in the years 2050 and 2100 in comparison to 1970. The table shows that there is considerable variability among the models on whether European ecosystems will act as a source or sink in future, on whether and when the C balance shifts from sink to source, and whether increased variability will lead to a greater likelihood of shifting from sink to source, emphasising again the uncertainty in future response of European ecosystems to climate extremes, as encapsulated by the processes included in the models.

Table 2.6_1: Qualitative summary of the model simulation results: A source describes carbon fluxes from the ecosystem to the atmosphere, while a sink described the carbon balance in benefit of the ecosystem.

Model	NEE (2050)	NEE (2100)	Shift to source by more extreme events
PaSim (grass)	sink	Sink	Yes
BASFOR (forest)	source	Source	Yes
EPIC (crops)	sink	Sink	Yes
DAILYDAYCENT (crops)	sink	Sink	Yes
ORCHIDEE	sink	Sink	Yes
JSBACH	sink	Source	Changing
LPJmL	sink	Sink	Changing

Task 6.4: Erosion synthesis modelling to examine the impact of future climate variability / extremes on the vulnerability of soils to erosion **Lead: IIASA**

M.Obersteiner (task leader) and M.van der Velde [IIASA];

EPIC is the only model that considers erosion in its simulations, and results indicate, that overall, the absolute carbon stored in cropland tends to increase due to higher biomass production with climate change. However, soil organic matter stocks in arable land tend to decrease, due to the higher erosion rates resulting from increased climate variability, and a combination of impacts on biomass production and mineralization rates. Importantly, the regional reduction in soil organic carbon due to climate variability can off-set the gain in carbon stocks resulting from the long term trend in climate alone.

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2.7. WP7 Carbon Vulnerability Synthesis Lead: INRA

After publishing (Van Oijen et al. 2013) the probabilistic vulnerability assessment method developed by CarboExtreme (see D7.2), an analysis of the vulnerability of the carbon cycle to climate change and extreme events by sector and ecosystem type had been developed. This has been achieved through projections at the EU scale which combine environment distributions (exposure) and ecosystem response distributions (response) conditional to a given level of environmental exposure. In this way, the direct analysis includes both the effects of variability (in climate) and of uncertainty (in model parameters and structure). An inverse approach has also been developed to address vulnerability and risk in terms of climatic drivers leading to hazardous ecosystem responses. The probabilistic risk assessment has been applied to climate projections (regional climate model forced by the A1B scenario) based on an ensemble of three generic ecosystem models and of 5 sectoral (forests, grasslands and annual crops) models.

Task 7.1 Conditional probabilities of % change in continental scale annual C sink
Lead: UNIABDN
P.Smith (task leader) and M.Kuhnert [UNIABDN]; M. Wattenbach [GFZ Potsdam]

The probability analysis based on the simulation results of work package 6 and considers the results of 8 different ecosystem models that can be divided in four cross-sectoral models (JSBACH, CLM, LPJmL and ORCHIDEE), which consider all land use types, and four sectoral models that only consider forest (BASFOR), grasslands (PaSim) or croplands (EPIC, DAILYDAYCENT). The analysis based on two approaches considering, first, the physical based environmental variable as threshold for a hazardous event (Oijen et al. 2013), second, the extreme impact defined by a biological variable that shows the response of the ecosystem (Rolinski et al., in preparation). In the first approach (from now on called the direct method), the drought impact is defined by the SPEI index (Vicente-Serrano et al., 2010), which is calculated from the difference between rainfall and potential evapotranspiration. Negative values indicate dry conditions and the thresholds SPEI < -1 (moderate drought) and -2 (strong drought) define the extreme drought impacts in the presented study. In the second approach (from now on called inverse method) a drought impact is defined, if the net ecosystem exchange (NEE) falls below 0 (indicating a source of carbon for the atmosphere). The two methods were applied for three different regions representing Northern, Central and Southern Europe according to the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX 2012).

In the first variant (F), the threshold SPEI < -1 is used. In the second variant (R), a linear regression of SPEI (x-axis) and NEE provides the SPEI value for which NEE is equal to zero. This value is used as a threshold to define hazardous conditions. With the third variant, the threshold of the direct method is based on the results of the inverse method (I).

The results show little variation between the models and regions, but larger differences between the modifications of the direct method. While the direct method (F) indicates an almost similar probability, of slightly less than 20 % for a hazardous event, the two other methods (both involving the ecosystem response in the setting of the threshold) suggest a probability of more than 40 %. The strongest variability between the different regions and modifications show the sectoral models EPIC (single crop species) and PaSim (grass lands). Both are managed systems, which may affect the results. In contrast to the other results, the inverse modification of the direct method is for PaSim much lower (especially in Middle Europe) than the regression method. This may indicate a non-linear relation of SPEI to the effects on NEE. The results of EPIC show for the winter crops (winter wheat and rye) lower probability of a hazardous event than the summer crops (corn and barley), except for Southern Europe. In summary, the probability of hazardous events in the period 2071-2100 is determined to be 20-50%, irrespective of model or region. The methods that consider also the ecosystem response in the determination of thresholds show higher probability for hazardous events than the unmodified direct method. For the probability analysis, the impact of increasing atmospheric CO_2 concentration appears to be a minor factor compared to the absolute values.

Task 7.2 Continental scale carbon vulnerability indicator **Lead: INRA**

M. van Oijen (task leader) [NERC-CEH]; JF Soussana [INRA]; A.Rammig, S.Rollinski, K.Thonicke [PIK]

Two complementary and consistent indicators have been developed. First, the direct probability risk assessment (van Oijen et al. 2013) has provided a first indicator which is the carbon loss by European ecosystems (in TgC) resulting from climate extremes corresponding to droughts (SPEI values below one). Second, the inverse approach has defined threshold values of the SPEI indicator that would turn the European carbon sink into a source. These two indicators are consistent and have been calculated for the European continent and for three SREX regions (Northern Europe, Central Europe and Mediterranean), for natural vegetation and for sectors (arable crop species, grasslands and spruce forest) (see D7.4).

Results show that the vulnerability of the European continental carbon cycle to droughts is likely to increase towards the end of the century and to cause a widespread loss of carbon from terrestrial ecosystems at the entire Europe scale and for Central Europe and Mediterranean regions. This increase in carbon cycle vulnerability is consistent across methods (direct and inverse vulnerability approaches) and is mostly consistent across ecosystem models (generic models, forest, crop and grassland models). However, in an ensemble of 8 models, there are two outliers: the JSBACH land surface model projects a very low carbon impact of increased droughts; conversely, the LPJmL dynamic vegetation model projects a very large negative impact of droughts leading to a carbon loss of ca. 700 TgC per year at the Europe scale (the current terrestrial carbon sink of Europe reaches less than half of this value). A full understanding of differences in vulnerability estimates between models will require further work. It appears, however, that the only model projecting changes in vegetation types (i.e. LPJmL) concludes to higher vulnerabilities than the remainder of the models which have constant vegetation.

Comparisons across regions confirm the lower vulnerability of Northern Europe and point to the high vulnerability of the Central Europe and Mediterranean regions. Comparisons across sectors indicate: i) a large future vulnerability of semi-natural vegetation (forests and grasslands) according to the generic models, ii) a large future vulnerability of grasslands, and iii) a more variable vulnerability of arable crop species. Differences across rainfed crops species indicate that, on average, the future vulnerability of wheat would be lower than that of barley, rye and corn. Also, the vulnerability of spruce forests is projected to be low. However, we cannot estimate from this study the variability of vulnerability across sectorial models, since a single model was used for forests and for grasslands and two models only were used for arable crops.

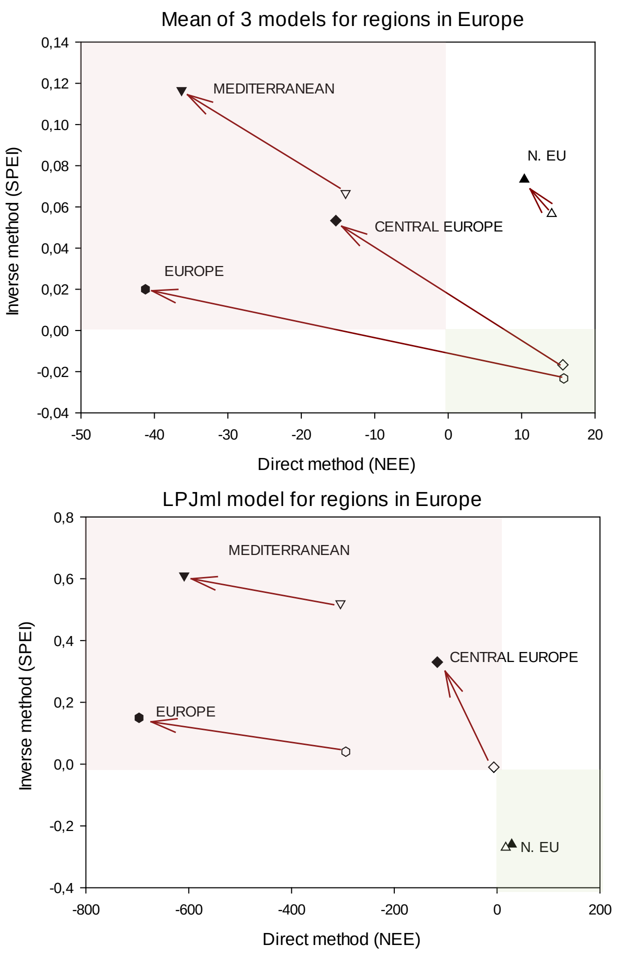


Fig. 2.7_1: Current (1971-200, open symbols) and future (2071-2100, closed symbols) ecosystem vulnerability under the A1B scenario of three regions in Europe (Northern Europe, Central Europe, Mediterranean) and of entire Europe. In the direct method, vulnerability is calculated as carbon loss due to drought in TgC per region and per year. Top panel, mean of three models (CLM, JSBACH, ORCHIDEE). Bottom panel, LPJmL model. Note the difference in scales between panels. Arrows indicate vulnerability changes from current to future time period. Shaded areas indicate vulnerability (red) and no vulnerability (green), respectively.

Task 7.3 Recommendation of adaptation and mitigation strategies Lead: PIK

K.Thonicke (task leader), W.Cramer, A.Rammig, S.Rollinski [PIK];]

Two vulnerability approaches, developed under Task 7.2 (direct approach, van Oijen et al. (2013) and the inverse vulnerability approach, Rolinski et al. in prep), were applied to simulation results from large-scale ecosystem models. These models were run for future climate change scenarios using 4 general ecosystem and 3 sectoral models from WP6. Both vulnerability approaches were used to identify the vulnerability and risk to drought under climate change. Different aspects of climate change, building on the design of factorial experiments in WP6, namely the influence of climate variability and CO_2 fertilization, were investigated in this task as well to calculate the respective vulnerability on natural vegetation, forests, grasslands and crops. Results were analyzed for the entire European simulation domain and additionally aggregated for 3 SREX regions as well as for entire Europe (see Fig. 2.7_1).

It turned out that both vulnerability approaches similarly identified natural vegetation in Central and Eastern Europe and the Mediterranean region as being increasingly vulnerable to drought by the end of the 21st century. Here, nearly all generic ecosystem models identified similar regions, with the inverse approach showing agreement for smaller area. Natural vegetation is more vulnerable to climate variability than to failing CO_2 fertilization. Crops, grasslands and forests show, however, different regions affected and also different scale of how vulnerability is related to risk. Vulnerability of spruce forests is increasing in Central and Eastern Europe and parts of Scandinavia. Depending on the approach chosen, risk is equally high in those regions. Vulnerability of crops depends very much on the crop type, with corn becoming more vulnerable in northern France and Germany, whereas wheat being more vulnerable to drought also in Western Europe and on the Iberian Peninsula. Grasslands show an increase in vulnerability and risk in central Europe and the Mediterranean region with little difference in the relationship between vulnerability and risk. The Mediterranean region and South-eastern Europe are the only regions, where the vulnerability of the carbon balance for natural vegetation, grassland, crops and forests increases.

The response of different ecosystem types to risks from changing climate variability was evaluated by comparing scenarios for control climate variability (CNTLVAR) with scenarios for reduced climate variability (REDVAR, see Beer et al. subm. and WP6). For both scenarios, vulnerability and risk were calculated for natural vegetation, forests, crops and grasslands. Results were compared for the entire European simulation domain as well as for the 3 SREX regions and entire Europe. Future, potentially increasing climate variability leads to higher vulnerability of natural vegetation, forests and grasslands than a reduced CO_2 fertilization effect. For grassland, a similar pattern can be stated with increasing vulnerability especially in the Mediterranean. For crops, the results are not as pronounced. Results were extensively described and mapped in the Deliverables D7.4 and D7.5. Since the sectoral models had limited capacity to test various management options, potentials for adaptation, which would allow estimating the potential to buy time and delay impacts, could not be tested extensively. What can be said is that climate variability will be most likely the factor, which will limit the capacity of the investigated ecosystem types to adapt to climate change. Vulnerability increases even more, should the CO_2 fertilization be less effective, i.e. by being co-limited by available nutrients.

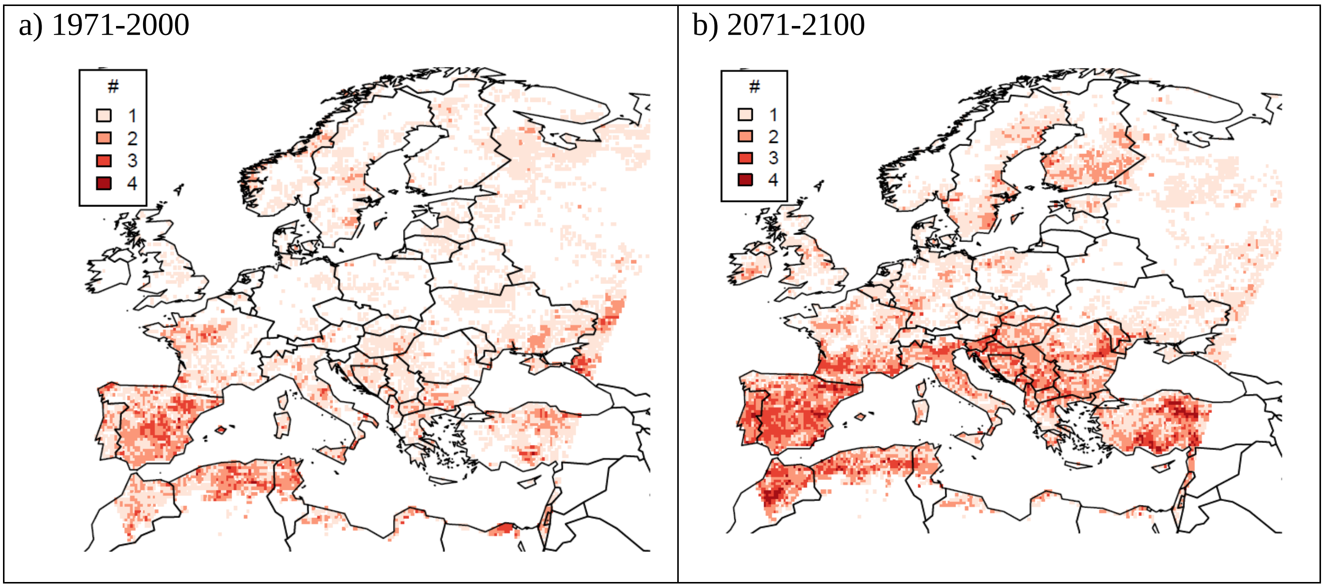


Fig. 2.7_2: Vulnerability of European ecosystems to drought. Number of models in agreement (#) out of 4 generic ecosystem models with vulnerability > 0.3 during the current (a) and future (b) period for the inverse probabilistic risk assessment approach.

2.8 WP8 Policy Interaction, dissemination Lead : PIK

Task 8.1 Expert elicitation of risks and vulnerabilities Lead: PIK

K.Thonicke (task leader), A.Walz [PIK/Univ. Potsdam], W.Cramer [PIK/IMBE], D.Frank, M.Reichstein [MPG], P.Smith [UNIABDN], JF Soussana [INRA]

The most urgent risks and vulnerability of the Carbon Cycle to extreme meteorological events have been collected, ranked and discussed among senior CARBO-Extreme researchers and selected external experts invited to a first workshop on April 15/16, 2010. The invited experts included stakeholders and decision-makers in carbon management from seven European countries as well as European Environmental Agency and European Commission.

When confronted with CARBO-Extreme, they well confirmed that the magnitude and frequency of extreme meteorological events were crucial for the functioning of the existing ecosystems and their carbon cycle. Discussing the types of climate extremes causing the strongest effects, droughts, windstorms and floods were given the greatest priority.

With a special emphasis on lag effects (e.g. increasing risk of fire due to drought) and indirect effects (e.g. increase in mortality due to drought), they emphasised the need for investigations of the ecosystems and their responses as a complex system and over a longer period.

Human made impacts on European ecosystems were of great concern to the invited experts, as ecosystem management can seriously threaten the carbon sequestrated by existing ecosystems. At the same time, ecosystem management is considered the only option to possibly reduce some of the risks through climate extremes. Important aspects of the discussion included the choice of appropriate indicators to communicate vulnerability and risk of the ecosystems to extreme meteorological events, uncertainties, and the risk of fire risk. “Use it before you loose it!” was one of the statements that explains in short the management question concerned with fire risk. CARBO-Extreme therefore added the aspect of wildfires to its research agenda by building on activities of single CARBO-Extreme partners involved in according research projects.

Task 8.2 Review of project targets in response to stakeholders Lead: PIK

K.Thonicke (task leader), A.Walz [PIK/Univ. Potsdam], W.Cramer [PIK/IMBE], D. Frank, M. Reichstein [MPG], M. Kuhnert [UNIABDN], D. Frank [WSL], A. Ibrom [DTU]

During the workshop on March 07/08, 2013, we had the chance to present and review the key findings and questions of the CARBO-Extreme project with you as decision-makers in or knowledge brokers for Carbon Management. The composition of the group covered a wide range of decision-making levels, i.e. from local to global, and a good coverage of Europe, with the exception of Mediterranean regions.

The discussion revealed strong appreciation of the innovative methodological concept to quantify vulnerability and risk of carbon sequestration to meteorological extreme events, and first quantitative estimates for Europe. Areas of high vulnerability (“hot spots”) might be priority areas in technical and management-based climate adaptation for agricultural and forest systems, while also being subject to profound alteration of the un-managed ecosystems, with potential implications for conservation concepts. The indicators were considered helpful to enhance communication in administration and policy-making, and strong interests were expressed in applying the concept also to different response and triggering parameters.

An important discussion developed following the presentation of controversial results from several experimental sites. Due to the inconsistencies between the findings from at different experimental sites and the inability to explain them, important knowledge gaps became evident. This situation revealed, that knowing what researchers still do not know, is an essential piece of information for decision-making.
A strong requirement was expressed to continue existing experiments and set up a coordinated network of long-term experimental sites which might be funded by individual national governments and funding agencies.
Finally the European Environmental Agency suggests using its Climate Adaptation Platform (http://climate-adapt.eea.europa.eu/) for further dissemination of CARBO-Extreme results.

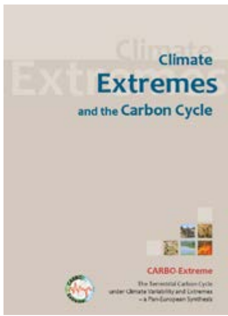
Task 8.3 Dissemination, contributions for workshops, briefings; brochure and flyers, summary for policy makers and web-page Lead: MPG

M.Reichstein (task leader), D.Frank [MPG]; C.Bounama, K.Thonicke, A.Walz [PIK/Univ. Potsdam]

CARBO-Extreme communicated obtained scientific knowledge concerning the research topic of the carbon cycle under climate variability and extreme events as well as project activities through:

- over 70 publications (peer-reviewed and non-peer reviewed)

  (see http://www.carbo-extreme.eu/index.php/Publications/Project)



- participation of CARBO-Extreme researchers in numerous (inter-) national conferences [e.g. the Planet under Pressure Conference London (March 2012), EGU General Assembly Meetings (Vienna, 2011, 2012, 2013), AGU Fall Meeting 2012 (San Francisco), Open Science Conference on Climate Extremes and the Biogeochemical Cycles (Seefeld, April 2013, http://www.bgc-extremes2013.org) and the upcoming 9th International Carbon Dioxide Conference, Beijing, China (June 2013)] – see also "List of Dissemination Activities"
- via the continuously updated project webpage www.carbo-extreme.eu
- project flyer (download via www.carbo-extreme.eu)
- the compilation of the final results in a summary for policy makers
- the project brochure
- via several press releases and information about CARBO-Extreme reported in different media (see http://www.carbo-extreme.eu/index.php/Press/Press).

These activities were conducted in close collaboration with WP9.

3) The potential impact

Improved understanding of European ecosystems is essential to estimate potential release of carbon from these ecosystems into the atmosphere, and thus their potential further enhancement of climate change. Building on important research on the effect of increasing mean temperatures and changing mean precipitation on ecosystems and their carbon cycle, the effects of an increase in inter-annual variability has much been debated over the past years. CARBO-Extreme has taken up the discussion and aimed to enhance our understanding of the impact of increasing magnitude and frequency of meteorological extreme events on European ecosystems and their carbon cycle. Bringing together different methodological communities, including experimental ecology, long-term observations and modelling, innovative forms of collaborations could be initiated and new insights obtained over the course of the project.

A main cross-cutting issue within CARBO-Extreme was the definition of “extreme event”. To overcome the definition of extreme events from the perspective of meteorological events, i.e. impacts on the ecosystems, an alternative perspective is required focusing on the ecosystem response. A cascade of extreme ecosystem responses is known from individual physiological responses of plants to species reordering and ecosystem or even biome shift, however, linking them to extreme meteorological settings is still an important challenge.

CARBO-Extreme results and experiences have been directly communicated and discussed with experts from the decision- and policy making domain in a second workshop in March 2013. Here, the need for information on the vulnerability of ecosystems and also – more abstract – their carbon cycle was clearly stated. Reasons for such interests include the productivity of agricultural as well as forest ecosystem, but also conservation and climate mitigation issues.

In large parts of public society, the potential of ecosystems to mitigate climate change is still considered as high. This consideration partly builds on CO_2 fertilisation effects through changes atmospheric composition. However, our research shows that the carbon sink in the living terrestrial ecosystem is likely to turn into a source of carbon emissions to the atmosphere in many part of Europe with increased magnitude and frequency of extreme meteorological events. This restricts our options for climate mitigation with direct relevance for policy making as well as personal decision making context. So informing public society, for instance through the CARBO-Extreme brochure, provides better insights in potential impacts of climate change including the increase in magnitude and frequency of extreme meteorological events.

Decision-makers have been aware of the issue of increasing climate variability for years. So far, the expected increase in extreme meteorological events as predicted by climate research has been combined with experience and data on ecological impacts caused by past extreme events. CARBO-Extreme can provide further insights into such impacts, a) by first quantitative estimates of the magnitude of carbon release at risk with increasing climate variability, and b) through innovative concepts to further investigate the processes and the multidimensional causes of extreme responses of ecosystems.

These insights can be further exploited in various ways, especially in various joint efforts of both the policy and science domains. Some CARBO-Extreme insights might even directly enhance the knowledge base for policy making and land management practices.

The **dissemination of the obtained knowledge and results of a project** is a crucial. CARBO-Extreme addresses a wide range of target groups at a national and European level, from policy-makers, stakeholders and other decision-makers to the research community, students and any interested general public for whom the knowledge about carbon fluxes and storage and the climate variability with extreme events is fundamental. Whilst policy-makers, stakeholders and other decision-makers were e.g. specifically addressed by work package WP8´s workshops (see above), the transfer of the obtained scientific knowledge and results to this target group is also ensured by the involvement of CARBO-Extreme researchers in many high-level policy relevant boards and contribution to the IPCC reports as lead authors.

Participation of CARBO-Extreme researchers in policy relevant boards:

Philippe Ciais (beneficiary 2 CEA) is co-chair of the Global Carbon Project and the Climate KIC GHG platform. The annual production of the anthropogenic CO_2 budget and initial work to produce regional budgets in the RECCAP project are relevant regarding CARBO-Extreme work because extreme years are correlated with CO_2 growth rate anomalies, and the connection between climate and CO_2 anomalies is not fully understood.

Nina Buchmann (beneficiary 4 ETH Zurich) is member of the Landwirtschaftlicher Forschungsrat (Agricultural Research Council) of Switzerland (since 2008), member of the Board of Trustees (Kuratorium) of the Öko-Institut e.V. (since 2009) and member of the Steering Committee of the Swiss research programm „Research for Development (r4d)“, jointly organized by the SNF and the SDC (since 2013).

Jean-Francois Soussana (beneficiary 5 INRA) is member of the Scientific Council of the French Agency for Environment and Energy (ADEME), head of the Scientific Council of the FACCE (Agriculture, Food Security and Climate Change) Joint Programming of Research (21 European countries, ministerial level), French representative in the Council of the Global Research Alliance

on agricultural greenhouse gases (34 countries, ministerial level) and head of the Scientific Council of the French research agency Committee on Ecosystems and Sustainable Development.
CARBO-Extreme input to high level advisory boards is provided by Pete Smith (beneficiary 8 UNIABDN) as Science Director of Scotland's Climate Change Centre of Expertise (2011-present) with regular policy briefings to Scottish Government on climate issues including climate extremes and variability. Pete Smith is giving evidence in the Scottish Parliament to Rural Affairs, Climate Change and Environment (RACCE) Committee, including information on climate extremes and variability. As member of UK Defra's Science Advisory Council (2011-2013) he gives regular input on impact of climate extremes, especially through review of the UK Climate Change Risk Assessment drawing on CARBO-Extreme work. Aspects of climate variability impacts form part of his contributions as UK National Ecosystem Assessment Expert Group Member and Coordinating Lead Author on regulating sevices (2009-2011). Pete Smith is member of the Programme Development Group for the UK Centre for Ecology and Hydrology (2008-2013), New Zealand´s Agricultural Greenhouse Gas Research Centre's International Science Advisory Group (ISAG) (2010-present) and UK Co-Chair of Climate Mitigation and Adaptation Working Group of UK-China Sustainable Agriculture Innovation Network (SAIN) (2009-present). As a fellow of the Royal Society of Edinburgh Pete Smith has given input to various RSE consultations on climate change issues drawing on CARBO-Extreme work.

IPCC reports:
Sonia I. Seneviratne (beneficiary 4 ETH Zurich) and Markus Reichstein (beneficiary 1 MPG) are lead - and co-author of "*Seneviratne, S.I., N. Nicholls, D. Easterling, C.M. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo, K. McInnes, M. Rahimi, M. Reichstein, A. Sorteberg, C. Vera, and X. Zhang, 2012: Changes in climate extremes and their impacts on the natural physical environment. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, pp. 109-230*."
Jean-Francois Soussana (beneficiary 5 INRA) is lead author for *IPCC AR 5, WGII, Chapter 23, Europe*, Pete Smith (beneficiary 8 UNIABDN) is convening Lead Author for *Agriculture and Forestry Chapter of Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, Mitigation volume (2010-present)* and Philippe Ciais is author of the *IPCC CLA Chapter-6 carbon and other biogeochemical cycles from 2010 to 2013*, and Wolfgang Cramer (formerly beneficiary 6 PIK) is *IPCC Coordinating Lead Author (WG2, Chapter 18, Detection and Attribution of Observed Impacts of Climate Change*.

In the following are summarized the **main activities for dissemination of the obtained knowledge and results of CARBO-Extreme to policy-makers, stakeholders, the research community, students and any interested general public**:
To inform the public about aims and progresses of the project, the CARBO-Extreme website www.carbo-extreme.eu was released briefly after the start of the project and has been kept updated since. In addition a flyer has been produced to communicate the project to the public. The flyer was very helpful for instance, to approach decision-makers and stakeholders for the first expert workshop in April 2010. It is available as a download from the public project webpage (http://www.carbo-extreme.eu/uploads/Project/Project/Carbo-Extreme_flyer.pdf).

Beginning of 2013, the CARBO-Extreme team compiled a high-quality brochure of 44 pages that captures the principle findings of the project to inform the general public and the scientific community as well as stakeholders and decision makers about the outcome of the project. The brochure is distributed amongst the CARBO-Extreme beneficiaries, associated site partners, the European Commission, stakeholders, as well as on scientific meetings, e.g. at the Open Science Conference on Climate Extremes and the Biogeochemical Cycle (Seefeld, 2013), and the ICDC9 conference (Beijing, June 2013).

Information about CARBO-Extreme was spread to a general public via several press releases and reports in different media (links and downloads available via http://www.carbo-extreme.eu/index.php/Press/Press), amongst others:

- press release “Heat waves, ice-storms, droughts and hurricanes –their impact on the carbon cycle” published the 03/28/2013 via idw scientific information service
- press release “Wetterextreme beschleunigen Klimawandel” via the University of Innsbruck the 02/04/2013
- Wild weather can send greenhouse gases spiralling (Nature 496,147 (11 April 2013) doi:10.1038/496147a)
- Wetterextreme beschleunigen Klimawandel *by tirol ORF radio* (02.04.2013)
- Wetterextreme beschleunigen Klimawandel *iPoint - das Informationsportal der Universität Innsbruck* (16.04.2013)
- Folgenreiche Wetterextreme (*Dolomiten, 3.April 2013*)
- Wetterextreme heizen den Klimawandel an (*Tiroler Tageszeitung, Printausgabe vom Mi, 03.04.2013* und in *Tiroler Tageszeitung online*)

The “Open Science Conference on Climate Extremes and the Biogeochemical Cycles” (see http://www.bgc-extremes2013.org), a joint initiative of CARBO-Extreme, the US-based network INTERFACE, and the international activity iLEAPS funded by the International Geosphere-Biosphere Program, with over 150 researchers from Europe, Asia and the US, together with the related Nature article “Wild weather can send greenhouse gases spiralling” (Nature 496,147 doi:10.1038/496147a) from 11th April 2013 contributed substantially to spread the knowledge about climate variability and the carbon cycle and CARBO-Extreme in the research community.

CARBO-Extreme researchers participated in numerous inter-)national conferences with talks and posters, e.g. the Planet under Pressure Conference London (March 2012), EGU General Assembly Meetings (Vienna, 2011, 2012, 2013), AGU Fall Meeting 2012 (San Francisco), Open Science Conference on Climate Extremes and the Biogeochemical Cycles (Seefeld, April 2013, http://www.bgc-extremes2013.org) and the upcoming 9th International Carbon Dioxide Conference, Beijing, China (June 2013) [see also “List of Dissemination Activities”].

Further dissemination of CARBO-Extreme knowledge were e.g., Open Days at "Long Night of Science" events, the DAAD/BMBF science tour "Understanding Biodiversity and Climate Change" in November 2012, or the use of the project brochure synthesizing project results in Ecology lectures at UAH.

CARBO-Extreme researchers were also strongly committed to dissemination within the research community. Around 60 peer reviewed scientific publications related to CARBO-Extreme published until 31.May 2013 by CARBO-Extreme researchers - 12 of them in high profile journals like Global Change Biology, Nature, Nature Geoscience, New Phytologist, Science (i.e. journals with a Journal Impact Factor 2011 by Thompson Reuters of over 6) - contributed to make the project results highly visible in the research community (see “Publications” at http://www.carbo-extreme.eu).

Currently (status May 2013), from the 60 peer reviewed CX publications 30% are Open Access (golden way); 8% are published in delayed Open Access journals, the rest is published in closed access journals. As CARBO-Extreme wants to strengthen Open Access publishing within the project, we will try to make those articles available via the "Open Access green way": we will contact the respective authors and if legally possible we will create postprints and publish them via the Max-Planck institutional repository linked via the CARBO-Extreme web page.

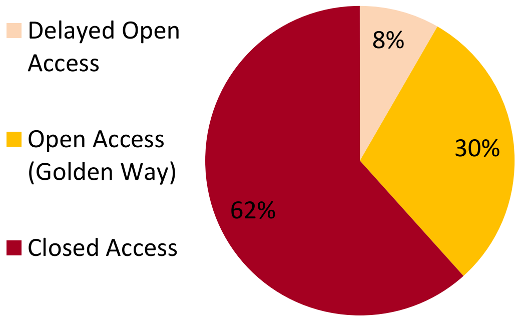


Fig.3.1 CARBO-Extreme publiations open access (May 2013

In addition a special issue of Biogeosciences on "Climate extremes and biogeochemical cycles in the terrestrial biosphere: impacts and feedbacks across scales" is planned (see http://www.biogeosciences.net/submission/scheduled_special_issues.html#36). The special issue will address the relations between climate extremes and biogeochemical cycling in terrestrial ecosystem, emerging from the global conference on this topic (www.bgc-extremes2013.org). Its guest editors are amongst others the CARBO-Extreme members Markus Reichstein and Michael Bahn, and CARBO-Extreme advisory board member Yiqi Luo.

Contributions to future projects:

CARBO-Extreme has been contributing substantially to the launch of the AnaEE Project (Infrastructure for Analysis and Experimentation on Ecosystems) which is part of the European Strategy Forum on Research Infrastructures Roadmap (ESFRI) as a new distributed EU infrastructure for ecosystem research. AnaEE entered the Preparatory Phase on November 2012 (3.5 years) and the Construction Phase will commence in 2014.

The concept of AnaEE is to set-up a distributed and coordinated network of state of the art *in situ* and *in vitro* experimental platforms equipped with the latest technology. The majority of the EME sites that have been contributing to CARBO-Extreme are involved in the design and in the discussion of the preparatory phase. They will be likely associated with sophisticated analytical and modeling platforms coupled to networks of instrumented observation and monitoring sites that will provide indispensable calibration and validation of datasets throughout Europe. The network, when reaching its full scale implementation phase will enable the prediction of the response of the main continental ecosystems to environmental and land use changes, including changes in extreme events.

Agriculture and forestry are highly exposed to climate change since they directly depend on climatic conditions. Policy makers and stakeholders are now facing the need of managing the trade-offs between increased immediate human needs and maintaining the capacity of the biosphere to provide goods and services in the long term. The key challenge of AnaEE is to increase the global food supply to accommodate a world population rising to 10 billion or more people while preserving a safe operating space for humanity by avoiding dangerous environmental change. AnaEE through its integrated and experimental approach to ecosystem functioning will provide a quantum leap in the quality and availability of data and projections on continental ecosystems responses to global changes and to management enabling policy makers and stakeholders to design sustainable ways to manage ecosystem services for all citizens. The strong experimental component of AnaEE, that will also build on the results and the network that participated in CARBO-Extreme, will link cause and effect and will operate as an integrated research system going well beyond the current observational and monitoring approaches which cannot fully address these key environmental questions.

One of the main aims of AnaEE is to generate validated data and knowledge that may inform policy decisions related to the environment, land-use and ecosystem services. Through that process, it will develop new tools and technologies packaged in the form of products and services for a variety of end-users from scientists to policy makers. Novel instruments, tools and methods are needed as part of the upcoming AnaEE construction phase and will be a source of new business opportunities for EU industry actors. New technology based on AnaEE will allow EU industry to develop new products, expand current markets and consequently create jobs and socio-economic benefits for society at wide.

We consider, that by means of a critical link and interaction with the AnaEE project, CARBO-Extreme has been enabling more efficiency and better harmonization of research services; something that is of importance for a number of stakeholders that will be responsible for better tackling global challenges and societal needs such as the most urgent environmental or food security challenges. In this respect, CARBO-Extreme has and will further support innovation through the development of bio-economy and the supply of innovative technologies.

We see further impact potential as followed:

Exploitation potential 1: The developed concept of probabilistic vulnerability and risk indices was considered a promising communication support by decision- and policy makers. This concept including both a climate as well as a response based hazard definition has great potential to be further exploited and tested by administration of European and national levels. The proposed indices were highly appreciated and well understood, despite their high level of complexity. Decision makers understood immediately the potential of the two complementing approaches of a climate as well as a response based hazard definition, and alternative hazard definitions were discussed in more depth. The one drawback identified for the concept, however, are the high data requirements, which in practical terms allows only using the concepts on modelled data. This, again, is not considered a problem for higher level decision-makers. Future potential to exploit the concept include the discourse-based identification of thresholds for the hazard definition and of a variety of possibly critical response variables. Then the concept could be used to estimate the effect on vulnerability and risk of a variety of measures to protect terrestrial carbon sinks in soils and living biomass under increasing magnitude and frequency of meteorological extreme events.

Exploitation potential 2: CARBO-Extreme modelling results in conjunction with the developed vulnerability and risk indicators will help to identify hotspots of climate vulnerability against future climate variability for both managed and unmanaged ecosystems in Europe. For agricultural systems, these results indicate not only hotspots of vulnerability, but also priority regions for technical and management based adaptation. Although the range of adaptation options is smaller and turn-over phases much longer for forest ecosystems, the same applies to managed forests. In contrast to the managed systems where priority regions for societal adaptation are indicated, the hotspots of vulnerability in unmanaged ecosystems will reveal areas of high probability of profound alteration within the natural ecosystems with implications on nature conservation concepts.

Exploitation potential 3: Despite some reservations from both sides, the active dialogue between the scientific community and decision-makers has large potential for added-value. Better understanding the physiology of extreme events, namely drought and heat waves, is a major concern to the decision-makers from European administration to local land manager. Based on the experience from our second expert workshop in March 2013, we can – once more – underline the importance of such an exchange for two main reasons, the information exchange itself and the identification of knowledge gaps important to decision-makers. In the case of CARBO-Extreme, the information generated within the project was of great interest in particular for higher level decision-makers, namely national and EU level where mitigation effects of ecological carbon storage are relevant issues. The second dimension of the same dialogue is the discussion of what both communities do not understand, but what would be of great interest to understand. Contradictory results, possibly even from a variety of data sources and methodological backgrounds, prove here as highly stimulating and enhance the exchange profoundly. This is the honest and unpretentious discussion required to identify common research questions of high relevance for society which can be addressed by innovative scientific settings.

Exploitation potential 4: The added value in better understanding the extreme ecosystem responses, instead of sticking to the extreme meteorological events, is highly appreciated by decision-makers. To identify the circumstances under which extreme ecosystem response occur along the cascade from physiological reaction of single plants to biome shift, should be a priority in ecological research. Here, the collaborative setting of CARBO-Extreme combining a wide variety of methodological communities is seen as a must to enhance process understanding. So far, short-term extreme responses on the level of physiological reaction and species composition have been investigated on experimental sites. However, a) the results from these sites are contradictory, and b) once experiments had been finished, the ecosystems quickly recovered, so profound ecosystem change has hardly ever been observed within an experimental setting. A coordinated network of long-term experimental sites, possibly funded by diverse national agencies across Europe, is considered an important milestone towards producing necessary process understanding, also amongst decision-makers. In addition to long-term experiments, the need for coordinated efforts is well recognised by scientists as well as decision-makers. Great added-value could be generated in bringing comparable data from different experimental sites and publications together. Standardised methods, measures and metadata on experimental settings are required to enhance comparability and enable such joint analysis of large samples. Such standardisation is not typical for the scientific community, where originality of methodologies and the singularity are important assets. Still, there have been positive examples of similar standardisation efforts recently, such as GEO-BON and EU-BON activities aiming for standard inputs of biodiversity observations, or the highly valuable TRY database where numerous scientists feed data on plant functional traits into following a standard protocol.

Exploitation potential 5: A strong potential is still be exploited in further calibrating modelling approaches with empirical data to increase the prognostic power of scientific ecosystem models. Thanks to the richness and variety of data sources being collected and combined in CARBO-Extreme, methods could be developed and tested to adapt parameterisation of the existing models to observed data. This data infusion technique has so far been applied to single points in space and has proven successful for grasslands. However, we are still facing big challenges a) for European forests, where management shows a large impact on the carbon cycle; and b) in the calibration across larger areas, if not all European terrestrial ecosystems. Overcoming both these challenges promises a strong rise in the expected accuracy of simulated vulnerability of the terrestrial carbon cycles and potential losses of sequestrated carbon.

Address CARBO-Extreme Project web page: www.carbo-extreme.eu

Contact names of CARBO-Extreme beneficiaries

(1) Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V.
(Max-Planck-Institut für Biogeochemie, Jena, Germany)
Dr. Markus Reichstein (mreichstein@bgc-jena.mpg.de)
Dr. Dorothea Frank (dfrank@bgc-jena.mpg.de)

(2) COMMISSARIAT ENERGIE ATOMIQUE CEA
(Laboratoire des Sciences du Climat et de l'Environnement, 91191 Gif-sur-Yvette, France)
Dr. Philippe Ciais (philippe.ciais@cea.fr,

(3) Consiglio Nazionale delle Ricerche
(Isituto di Biometeorologia – IBIMET, Firenze, Italy)
Dr. Francesco Miglietta (f.miglietta@ibimet.cnr.it)

(4) Eidgenössische Technische Hochschule Zürich
(Institute of Plant Sciences; now: Institute of Agricultural Sciences)
Prof. Nina Buchmann (nina.buchmann@usys.ethz.ch)
(Institute for Atmospheric and Climate Science)
Prof. Sonia I. Seneviratne (sonia.seneviratne@env.ethz.ch)

(5) Institut National de la Recherche Agronomique
Dr. Jean-Francois Soussana (Jean-Francois.Soussana@paris.inra.fr)

(6) Potsdam-Institut für Klimafolgenforschung e.V.
Dr. Kirsten Thonicke (Kirsten.Thonicke@pik-potsdam.de)

(7) UNIVERSITEIT ANTWERPEN
Prof. Ivan Janssens (ivan.janssens@ua.ac.be)

(8) The University Court of the University of Aberdeen
Prof. Pete Smith (pete.smith@abdn.ac.uk)

(9) Universita degli Studi Della Tuscia, Viterbo, Italy
Dr. Dario Papale (darpap@unitus.it)

(10) Centre National de la Recherche Scientifique, Montpellier France
Dr. Jean-Marc Ourcival (jean-marc.ourcival@cefe.cnrs.fr)
Dr. Serge RAMBAL (serge.rambal@cefe.cnrs.fr)

(11) Cranfield University
Prof. Guy Kirk (g.kirk@cranfield.ac.uk)

(12) DANMARKS TEKNISKE UNIVERSITET, DTU
Prof. Dr. Andreas Ibrom (andreas.ibrom@risoe.dk)

(13) Institutul de Cercetari si Amenajari Silvice (ICAS)
Dr. Olivier Bouriaud (obouriaud@gmail.com)

(14) Internationales Institut für Angewandte Systemanalyse (IIASA)
Dr. Michael Obersteiner (oberstei@iiasa.ac.at)

(15) Met Office (METO)
Dr. Chris Jones (chris.d.jones@metoffice.gov.uk)

(16) Natural Environment Research Council
Dr. Marcel Van Oijen (mvano@ceh.ac.uk)

(17) SVERIGES LANTBRUKSUNIVERSITET (SLU)
Dr. Monika Stromgren (Monika.Stromgren@slu.se)

(18) Universität Innsbruck (UIBK)
Dr. Michael Bahn (Michael.Bahn@uibk.ac.at)

(19) VERENIGING VOOR CHRISTELIJK HOGER ONDERWIJS WETENSCHAPPELIJK ONDERZOEK EN PATIENTENZORG (VUA)
Dr. Richard de Jeu (richard.de.jeu@falw.vu.nl)

(20) EIDGENOESSISCHE FORSCHUNGSANSTALT WSL
Dr. David Frank (david.frank@wsl.ch)

(21) Gottfried Wilhelm Leibniz Universität Hannover (LUH)
Prof. Georg Guggenberger (guggenberger@ifbk.uni-hannover.de)

(22) Lunds Universitet (ULUND)
Dr. Torben Christensen (Torben.Christensen@nateko.lu.se)

(23) Fundacion Centro de Estudios Ambientales del Mediterraneo (CEAM)
Dr. Arnaud Carrara (arnaud@ceam.es)

(24) UNIVERSITE PARIS-SUD XI (UPS)
Dr. Eric Durfene (eric.dufrene@u-psud.fr)

(25) Universidad de Alcalá (UAH)
Miguel Ángel de Zavala Girones (ma.zavala@uah.es)