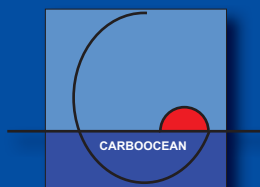# Integrated assessment of the European and North Atlantic Carbon Balance

-key results, policy implications for post 2012 and research needs-

Brussels, 2009

CARBOEUROPE IP

CARBOOCEAN

COOPERATION

Integrated assessment of the European and North Atlantic Carbon Balance

– key results, policy implications for post 2012 and research needs –

edited by

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Foreword

In Europe, we are leading the world with new actions to reduce carbon emissions. Thanks to the international leadership of the European Union, the United Nations conference in Bali in December 2007 paved the way for a new global agreement to tackle climate change. Negotiating a new agreement will be a long, tough process as individual nations seek ways to reduce their greenhouse gas emissions without compromising economic growth. In international negotiations such as these, the first step to success is for all parties to agree on the basic premises: the need for action and the scientific evidence which identifies the problem and presents the best solution. Only arguments based on sound scientific evidence will carry weight.

In struggling to combat climate change by reducing carbon emissions we are effectively attempting to manage the future carbon balance of the planet. To do that we must have accurate data, not just on the net amount of carbon in the atmosphere, but also on the sources and sinks of carbon at various scales.

The task of compiling statistics on the continental and ocean carbon balance is extremely demanding and requires an integrated approach where scientists from different disciplines work together at European and international levels. That is why in the 6th framework programme for research two large-scale integrated projects, CarboEurope and CarboOcean, were funded by the Directorate-General for Research (Environment Directorate), in order to assess and quantify the carbon balance of European terrestrial ecosystems and the Atlantic Ocean, and put the continent of Europe into a global perspective. These projects brought together more than 120 teams of top European scientists who are working to provide the data we need and the understanding to interpret that data. Research results will give us the evidence we need to guide future policymaking. Furthermore, additional projects targeting more specific scientific questions in relation to the carbon balance in Europe and beyond have also been implemented (NitroEurope, CarboAfrica and CarboNorth).

Given its important socio-economic and policy implications, research on the carbon cycle remains a key priority under the 7th framework programme for research and technological development.

This publication provides a comprehensive overview of scientific results and their policy implications, as emerged from EU-funded integrated research actions on the carbon cycle, and underlines existing knowledge gaps and future research priorities. It will therefore be of particular interest and value to a wide range of stakeholders including policymakers, the scientific community and the general public. It also represents an important contribution to the ongoing debate on climate change and the greenhouse gas balance in Europe and beyond.

José Manuel Silva Rodríguez
Director-General of the
Directorate-General for Research

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Executive summary – Overview

Land and ocean carbon cycles are intimately linked with each other as active parts of the Earth's climate system (**Fig. I.1**). At this moment the marine and terrestrial carbon cycles are able to partially compensate for the man-made CO_2 emissions through carbon uptake. In future the land sink may turn into a carbon source to the atmosphere due to land-use, land-use change, climatic change and rising atmospheric CO_2 levels. Globally averaged, the ocean will always act as sink for CO_2 emissions to the atmosphere, but the sink strength may change considerably due to climate change, changes in ocean circulation, as well as biogeochemical feedback processes to warming and increasing CO_2 levels. Therefore, the integrated assessment of carbon sources and sinks in relation to the climatic feedback is essential for environmental policy. Such an assessment is only possible through an integrated approach as successfully carried out by CarboEurope-IP and CarboOcean-IP, which will be reported in the following.
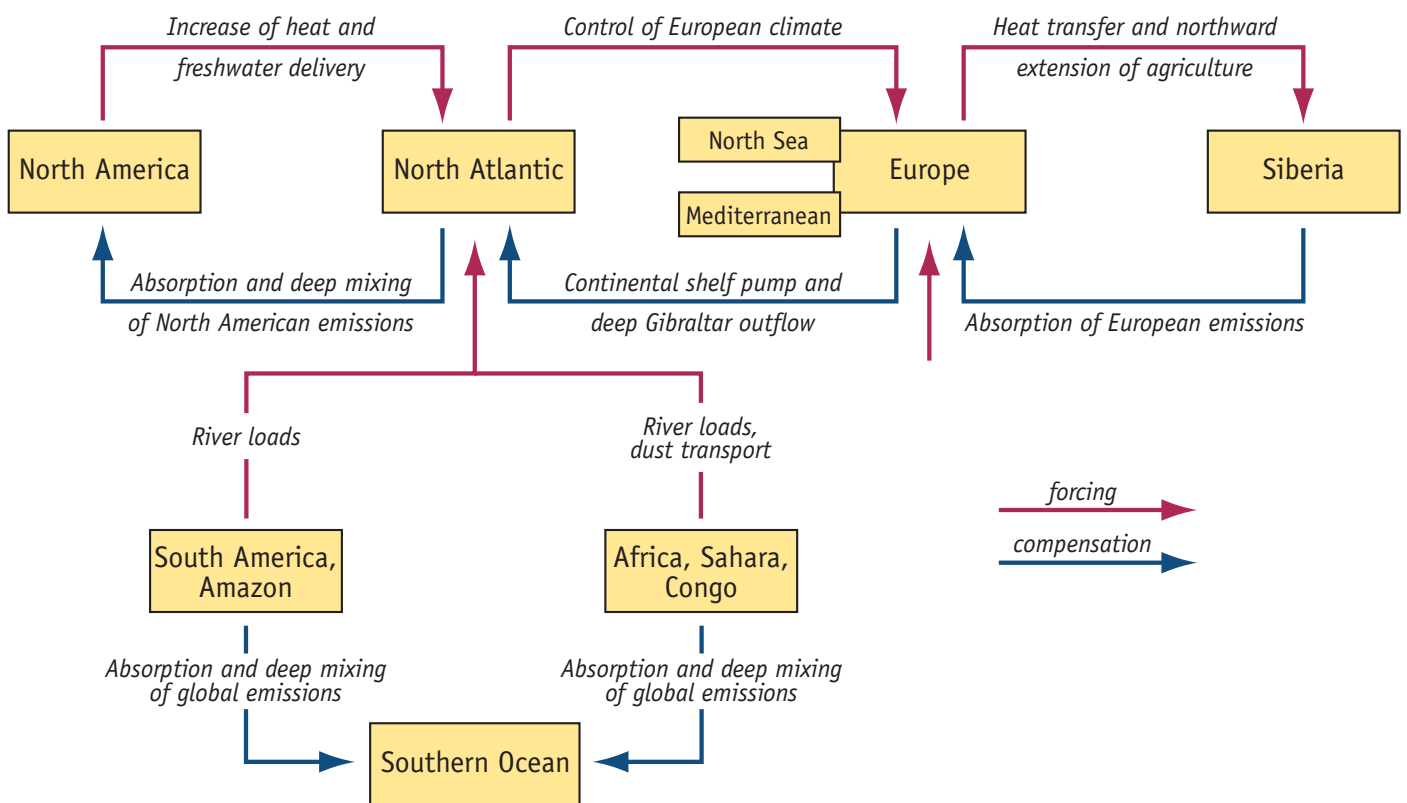
Fig. I.1: Positive forcing and compensation processes of relevance for the European carbon balance as part of the Earth system.

Executive Summary of the terrestrial carbon balance (CarboEurope-IP)

- The land surface of continental Europe (the geographic region between the Atlantic coast and the Ural Mountains) is a carbon sink for CO_2 of 300 Tg C yr^{-1} (as indicated by atmospheric and ground-based measurements). The estimated sink has almost doubled since 2003, mainly due to additional processes understanding.

- Including the carbon-equivalents of methane and N_2O into the non-fossil fuel carbon balance (100 yr time horizon) reduces the continental sink by about 70% to 81 Tg C-CO_2eq yr^{-1}; and it makes the EU-25 carbon-neutral or even slightly negative.

- About 80% of the continental fossil fuel emissions and about 90% of the EU-25 fossil fuel emissions remain in the atmosphere and contribute to global warming. The mitigation potential of the terrestrial vegetation is not realised because of the green-house gas emissions by intensive agriculture.

- Almost 60% of the continental CO_2 sink is located outside the EU-25 in eastern Europe, mainly European Russia. The large forest sink of eastern Europe is in part compensated by emissions due to peat mining. Including non-CO_2 greenhouse gases, the entire continental sink (100%) is located in eastern Europe. The non-CO_2 gases act as the equivalent of a "toll" (100y time horizon) taken by the nitrogen cycle on the productivity of the biomes. In this case the "toll" is as high as the productivity.

- Grasslands sequester more carbon in soils than forests (57 versus 20 g C m^{-2} yr^{-1}). Even if the emissions of non-CO_2 gases are included, the carbon sequestration in grassland soils remains higher than in forests. Croplands are a source of CO_2 which signifi-cantly increases when non-CO_2 greenhouse gas emissions are included. Managed peat-lands are an additional major source.

- Forests remain the most efficient land-use type for carbon sequestration (74 g C m^{-2} yr^{-1}) when the increment in woody biomass is included. However, this sink is the result of atmospheric nitrogen deposition. The forest carbon sink is similar in magnitude to the CO_2-equivalent N_2O emissions from agriculture.

- The total continental CO_2-carbon sink is 20% of the fossil fuel emissions of continental Europe (1600 Tg C yr^{-1}) and 13% of the fossil fuel emission of the EU-25 in 2005 (1060 Tg C yr^{-1}). The terrestrial CO_2 sink is only 17% of the continental total greenhouse gas emissions (about 1700 Tg C-CO_2eq yr^{-1}), and only 11% of the EU-25 total greenhouse gas emissions (about 1100 Tg C-CO_2eq yr^{-1}).

- The uncertainty in the magnitude of the terrestrial sink remains high. This is a consequence of the heterogenous landscape of Europe, and the diversity of management practices at small scale.

- The seasonal and inter-annual variation in several key processes that determine the carbon sink of Europe is large. In the dry year of 2003, the terrestrial sink for CO_2 sequestration failed. The carbon losses were equal to five years of carbon sequestration.

- CarboEurope has successfully pioneered the simultaneous application of the bottom-up and the top-down approaches at the continental scale. The close match found between the two estimates gives major confidence to the result. It points at the urgent need for an Integrated Carbon Observing System, ICOS, across Europe.

Additional findings and achievements

- The new approach adopted by CarboEurope-IP was to evaluate each source and sink by estimating each value through both a top-down and a bottom up assessment. This has improved the quantification of the carbon balance and decreased the uncertainty associated with each value.

- Soils are the ultimate sink for carbon, but can also be a source of carbon if not managed properly. CarboEurope-IP has set up a network of observation sites to verify changes in soil carbon during the commitment period of the Kyoto Protocol.

- A regional experiment has demonstrated the complexity of the interaction between the land surface and the atmosphere. Progress has been made at quantifying the regional scale carbon sink from regional atmospheric observations and the uncertainty involved.

- Not only climate extremes of drought but also storms and associated insect damage can substantially harm the sink and affect the emissions of non-CO_2 gases.

- Despite regular harvesting European forests have been a sink of carbon since the 1950s. This is a result of forest management practice, and of the forest age structure. Increased age will bring these forests closer to harvest. In addition, the demand for pulp or bioenergy may increase the demand for biomass. If so, the forest sector may become a carbon source in future.

- CarboEurope has shown that old-growth forests continue to be a carbon sink.

- Contrary to earlier assessments, European agriculture, both arable and animal husbandry, is only a minor source of CO_2-carbon, but a major source for non-CO_2 greenhouse gases.

- As a result of management peat-lands, even though of small area, create hotspots of greenhouse gas emissions, despite the fact that management is possible with reduced emissions.

- Deposition of active nitrogen from the atmosphere, originating from human activities, has increased carbon sequestration across Europe, but the associated emissions of non-CO_2 greenhouse gases appear to cancel out this carbon gain.

Executive summary of the marine carbon balance (CarboOcean-IP)

"CarboOcean-IP is quantifying the marine carbon sources and sinks"

CarboOcean is currently in its fourth year of an entire project duration of 5 years. Therefore, data and model evaluation are still under way and not yet finished.

Main findings:

- The highest water column inventories of man-made CO_2 exist in the northern North Atlantic close to the areas of deep-water formation. The Southern water column contains less human-induced CO_2 than in the North Atlantic, but the volume of the oceanic region is much larger. Global marine CO_2 uptake for year 2000 according to global Earth system models amounts to about 2.3 Gt C per year from a fossil fuel emission of about 7 Gt C yr^{-1} in year 2000.

- A prototype of an Atlantic carbon observing system has been established through the use of Voluntary Observing Ships equipped with high-precision automated CO_2 sensors. The North Atlantic air-sea carbon flux can now be determined on a monthly-to-seasonal basis with unprecedented accuracy with 10° resolution in latitude and longitude. The North Atlantic carbon sink has varied during the past 15 years between 200 and 470 Tg C yr^{-1}. The marine uptake of CO_2 in the North Atlantic region between 20°N and 65°N declined since 1994/95 and increased again since about 2002. It reached a total sink of 320 Tg C yr^{-1} in 2005.

- In-situ measurements, ocean modelling, and atmospheric inverse modelling consistently indicate a weakening of the Southern Ocean carbon sink in the decade between 1981 and 2004 by 80 Tg C yr^{-1} relative to the trend expected from the increase in atmospheric CO_2.

- The anthropogenic carbon uptake by the oceans is dominated by physical-chemical buffering, but biological and biogeochemical effects are also significant. Ecological impacts may be severe (e.g. through warming and pH changes). Mesocosm experiments suggest an increase in the carbon to nitrogen ratio in phytoplankton at rising CO_2 levels which may lead to an increase in CO_2 uptake.

- The future atmospheric CO_2 increase will depend on the amount of CO_2 emitted, the change in ocean circulation, and related biogeochemical processes. Climate model runs which include an interactive carbon cycle show an accelerated climate change.

- European regional seas, including enclosed and semi-enclosed seas, play an important role in the carbon budget, e.g. through the outflow from Mediterranean Sea into the North Atlantic and the continental shelf pump mechanism of the North Sea. The first measurement stations for atmospheric CO_2 in the Wadden Sea and in the North Sea present a promising outlook for improved continental scale greenhouse gas budgets.

Additional findings and achievements:

- Two large observational data base syntheses have been achieved through international collaboration: (a) A worldwide surface ocean CO_2 data set (SOCAT), (b) an Atlantic Ocean three-dimensional carbon deep section data set (CARINA).

- Contribution to the development and successful testing of a new international approach towards the design of a mooring incorporating a submersible winch capable of producing automated surface to ocean floor carbon and biogeochemistry data ("SeaCycler").

- Development and successful testing of new observational prototype floats for constraining future ocean interior carbon and oxygen inventory changes ("CARBOOCEAN oxygen floats").

- Development of a state-of-the-art isopycnic coupled physical-biogeochemical ocean circulation model, which realistically simulates the carbon transport in the ocean's interior along surfaces of equal density.

Climate change has become a common thread joining all nations in a global challenge. Unless this challenge is met, future generations will inherit the environment of this globe in a very much worse state than that in which we have received it from previous generations. Urgent measures are needed. We cannot expect any part of the globe to escape the impacts of climate change, but we should not expect the impacts to be equally distributed. Areas that are presently rain forests may dry out, dryland areas, which previously could not support crops, may become arable in the future; estimates of the precise impacts are still uncertain, but one thing is clear – the main suppliers of food, the wheat belts of the temperate and Mediterranean zones, are under threat.

Climate change has been initiated by the excessive fossil fuel consumption of industrialised nations. The problem could thus be solved by drastically reducing fossil fuel consumption by these nations, but given the momentum of the global economy, this seems highly unlikely. A rapid, drastic cut in carbon emissions would have serious implications for the economies of the non-industrialised world. In addition, as the wealth of those nations with transitional economies grows to reach the standards of the already industrialised nations, their fossil fuel consumption will continue to increase rather than decrease: a process driven by political goals. Together, these factors create an apparently unstoppable rising tide of atmospheric CO_2 concentration.

Aware of this future threat, the United Nations have initiated International Conventions, e.g. the UN-Framework Convention on Climate Change, UNFCCC, as part of the acceptance of the sustainability philosophy at the United Nations Conference on Environment and Development (UNCED), informally known as the Earth Summit, held in Rio de Janeiro from 3 to 14 June 1992. The UNFCC has initiated two major protocols, the Montreal Protocol, on the reduction of the emissions of Fluoro-Carbon volatile compounds, and the Kyoto Protocol on the reduction of emissions of CO_2, which includes carbon emissions from fossil fuels as well as the emissions from land use. Although at this point not all industrialised nations have signed these two protocols, it is the European Union that has been leading the political process for action to maintain the world in a viable state.

The political process of international negotiation on frameworks and conventions has been supported by an unprecedented process of international collaboration through the Intergovernmental Panel on Climate Change (IPCC). The IPCC synthesise the existing knowledge to reach a scientific consensus on the occurrence of present climate change and the likelihood of future dangerous change. The IPCC was honoured for its activities by receiving the Nobel Peace Prize in 2007, which summarised its knowledge in the Forth Assessment Report: "The understanding

of anthropogenic warming and cooling influences on climate has improved since the TAR [Third IPCC Assessment Report of 2001], leading to *very high confidence* that the global average net effect of human activities since 1750 has been one of warming, with a radiative forcing of +1.6 [+0.6 to +2.4] W m^{-2}".

The physics of climate change are in fact fairly simple, although the details are extremely complex. We all talk about the "greenhouse effect" of atmospheric trace gases, such as CO_2, nitrogen oxides, methane, and water vapour, but the analogy is not quite correct. In contrast to a real greenhouse, the atmospheric greenhouse effect is not based on the fact, that warm air and long wave radiation is kept under a lid (the glass roof). Rather, the atmosphere acts like an "oven", through a warming of the "glass" itself. The reason is, that the vibrations of the molecular dipoles of water vapour and CO_2 get in resonance with the infrared, thermal radiative energy emitted from the Earth's surface. This absorbed energy is converted to kinetic energy of molecular motion, resulting in heating of the atmosphere. Without this natural greenhouse effect, the equilibrium temperature of the Earth's surface would be about 33 ºC lower than it was at pre-industrial times. Increasing the amount of CO_2 in the atmosphere increases this "radiative forcing" and raises the equilibrium temperature of the Earth's surface beyond the natural equilibrium temperature which has existed over the past 10,000 years. This is known as "greenhouse warming".

The existence of a "greenhouse" effect and the significance of the level of atmospheric CO_2 concentration for the Earth's surface temperature have been known since the work of Tyndall and Arrhenius in the 19th century. In 1938 Callendar was the first to raise the issue of the potential alteration of the greenhouse effect and climate through human-made CO_2. Direct regular time series measurements of CO_2 in the air started at the South Pole and the Mauna Loa Observatory in Hawaii as part of the International Geophysical Year in 1957/58. These time series measurements have been continued up to now and extended to larger networks worldwide. The record of the increase of anthropogenic CO_2 in the atmosphere has been reliably extended backwards in time by analysis of air trapped in Antarctic ice cores.

Since about 1850 the atmospheric CO_2 concentration has been increasing beyond the rate expected from natural phenomena (**Fig. II.1**). Initially this increase was the result of land-use change (largely caused by emissions from deforestation), but after about 1900 fossil fuel emissions started to become a significant component. Since about 1950, fossil fuel emissions have been the dominant cause of increasing CO_2.

These anthropogenic emissions have been compensated in part by uptake in the oceans and in the terrestrial biosphere. Averaged over the whole globe the oceans will always act as a

sink for anthropogenic CO_2, but as the CO_2 concentration rises any further addition of CO_2 will be buffered less quickly. Latest oceanographic results reveal, that the ocean carbon sink has a considerable regional variability. A temporary decrease in the uptake strength of the North Atlantic and the Southern Oceans due to climate fluctuations has been identified. In contrast, the biospheric uptake has continued to increase, but exhibits huge oscillations in anti-concert with the atmosphere. These oscillations are in fact initiated by periodic changes in ocean circulation in the Pacific, the El Niño oscillation. The general increase of the land uptake has been interpreted as being an increasing effect of nitrogen fertilization of the land surface for crop production and un-intentionally by nitrogen oxides, which are a by-product of fossil fuel burning.

Fig. II.1 refers to CO_2 emissions only. To fully understand climate change, the effects of other anthropogenic greenhouse-gas emissions, such as di-nitrogen-oxide (N_2O) a by-product of the nitrogen cycle after fertilizer use, and of methane (CH_4), should be included. These emissions are very complex, because natural and anthropogenic effects intermingle, and so-called "natural" emissions may be induced by anthropogenic climate change. A deeper understanding of these interactions might be obtained by modelling the climate during the glacial periods. However, the 100 ppm glacial-interglacial variations in the atmospheric CO_2 concentration cannot yet be conclusively explained due to the complexity of the underlying processes. However, it is clear, that during this period the carbon cycle acted as a positive feedback to climate change, re-enforcing the glacial-interglacial temperature variations with a very high correlation.

The complexity of the interactions between human-induced and natural processes producing and absorbing CO_2 are summarised in **Fig. II.2** in which the red arrows show the fluxes due to anthropogenic carbon emissions, and the black arrows quantify the natural carbon cycle. The human-induced perturbation has become larger (6.4 Gt/yr) than the net balance of natural assimilation and dissimilation (0.8 Gt/yr). In addition, land use change, which is related to the food consumption of the human population has caused emissions due to land-use change of about 1.6 Gt/yr, which is again twice the natural carbon balance, and indirect net carbon sinks of about 0.2 Gt/yr in the ocean due to acidification of the marine surface.

The future of life on Earth depends on our ability to manage a planet with ever-increasing levels of atmospheric carbon dioxide and its consequent dynamic climate. Understanding the natural and anthropogenic carbon cycle is a prerequisite to deriving the strategies for mitigation and adaptation. That is why projects, such as CarboEurope and CarboOcean have been initiated by the European Union.
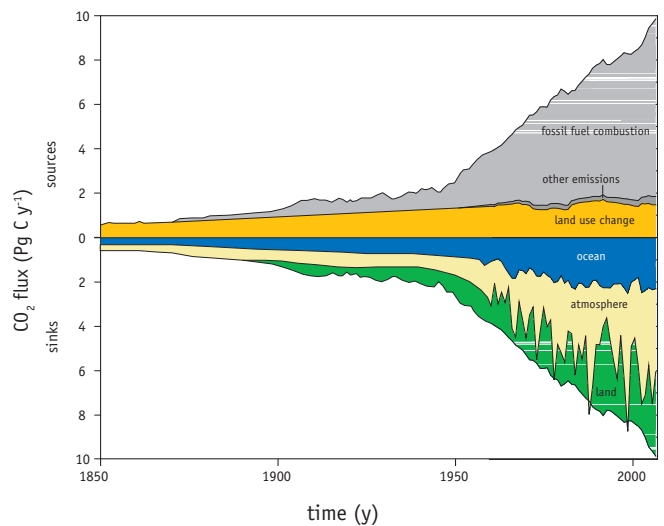
Fig. II.1: The development of carbon dioxide emissions, and the uptake by oceans, land and the atmosphere over time. (redrawn from Canadell et al., 2007)
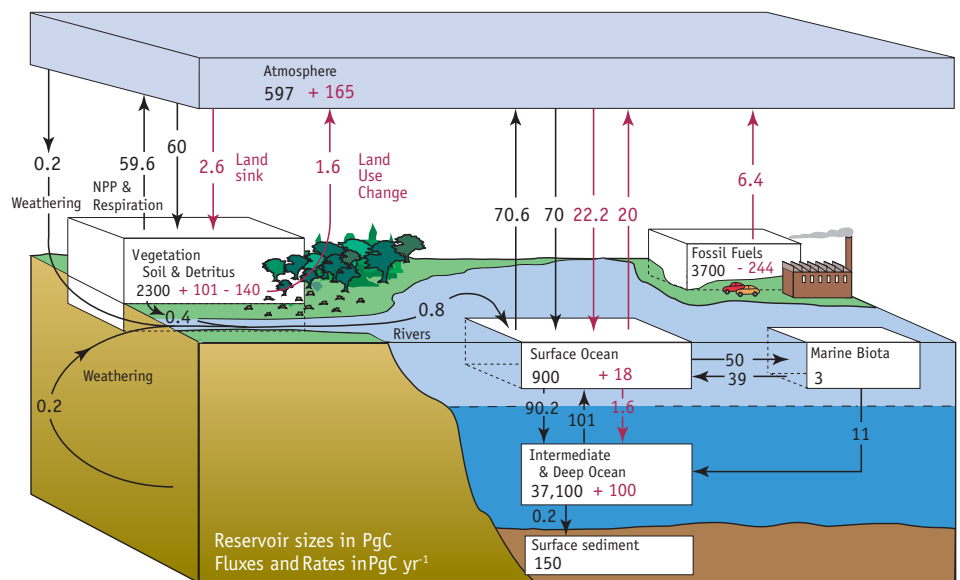
Fig. II.2: Carbon circulates freely between the atmosphere, the land biosphere and the oceans. This figure shows the different carbon pool sizes and fluxes between the carbon reservoirs, from Sarmiento and Gruber, 2002. Sinks for anthropogenic carbon, Physics Today, 30-36, Aug. 2002, doi:10.1063/1.1510279 with updated numbers by Sabine et al., 2004, The oceanic sink for anthropogenic CO_2, Science, 305(5682), 367-371. Copyright 2002, American Institute of Physics. Red arrows show fluxes due to the anthropogenic carbon invasion into the Earth system.

The overarching aim of our Carbon-Cycle research is "to understand and quantify the carbon balance of Europe and the associated uncertainties at local, regional, and continental scale". For the ocean, special emphasis is placed on the Atlantic and Southern Oceans as critical sink areas for carbon dioxide.

Although the general aim sounds clear and pragmatic, the work needed to achieve this aim is extremely complex. "To understand" the carbon balance requires researching the basic biological, chemical, and physical processes which control all the fluxes contributing to the carbon balance. "To understand" also requires the development of computer models which encapsulate our understanding of the underlying processes in a set of equations. "To quantify" requires capturing the full variation of the carbon balance with climate, ocean conditions, and land-history and management. This needs the establishment of a network of measurement stations, which previously did not exist. "To quantify uncertainties" means that all errors, biases and doubts about measurements are evaluated and enumerated. The aspiration of the "Integrated Projects" is to reduce the uncertainty in our estimate compared to the past.

The main tool to be used to assess uncertainties in CarboEurope-IP was the simple idea that each quantity would be measured twice, by approaching it from larger scales and from smaller scales. In many cases larger scales are simpler to assess than smaller scales, thus the resolution of the smaller scales becomes important. CarboEurope aimed at a resolution of the smallest scale to a length of between 10 and 50 km.

The main approach of CarboOcean is to combine surface and deep ocean carbon measurements for quantifying the fast and slow parts of the uptake and storage mechanisms. Process studies are carried out to determine quantitatively significant biogeochemical feedback processes between carbon cycling and climate. Fully fledged global coupled physical-biogeochemical models are used to project the future marine CO_2 uptake for given greenhouse gas emission scenarios.

Terrestrial and marine carbon cycle research is at the stage where progress to a new level of knowledge depends on adopting an "Integrated Approach". In this sense "integrated" means that the interaction between the atmosphere and the land or sea surface must be understood. It is no longer possible to isolate atmospheric research from the processes at the surface below. At the same time, the land and ocean surface processes are driven by atmospheric parameters, which are no longer static. "Integration" also means that the physico-chemical components of the carbon cycle can be linked to biological processes. This is essential because for the land component the main fluxes of the carbon cycle, the assimilation of CO_2 and the decomposition of organism-based carbon are under biological control. While the oceanic CO_2 uptake mainly governed by the ocean circulation, mixing, and inorganic chemistry, the role of marine biota in modulating the marine carbon fluxes is significant.

Integration of atmospheric, oceanic and terrestrial sciences brings the additional challenge of seamlessly linking the science communities of chemists, biologists, and physicists together: disciplines which work with different methodologies and experimental designs. Climate models can act as focal points because they must integrate marine and terrestrial effects of fossil fuel emissions, biological sources and sinks, and the human use of these environments which range between fisheries and deforestation for food or energy crops.

What happens on land in Europe is not independent of what happens in the North Atlantic, and the future role of the North Atlantic in the carbon cycle and as a climate driver depends strongly on the way we manage our land, and on our future fossil fuel consumption. If we do not manage our land properly, about 1000 times as much carbon could potentially be released from soils than is presently emitted from burning fossil fuels. Thus fossil fuel emissions and land-use are independent sources, but their effects are cumulative or compensatory, and both affect the processes which operate on the North Atlantic. "Integrated" means that we understand these interactions through bridging all relevant scientific disciplines and communities, and that we are able to express the policy implications, which then may lead to political decisions in an effective way. With Europe taking the global lead in the climate change mitigation and adaptation process, this type of integration is critical, and this is why two "Integrated Projects", one focusing on oceans, the other on the terrestrial surface of Europe were initiated.

Although the major effort in Carbon Cycle research is being carried out by CarboEurope-IP and CarboOcean-IP, their work alone is not sufficient and there are additional parallel activities: NitroEurope is investigating the interactions between the carbon cycle and the nitrogen cycle, and CarboNorth is focusing on processes in the permafrost region which is important in view of permafrost flow and the associated emission of greenhouse gases. Also in the marine research CarboOcean is accompanied by projects looking into specific aspects of the problem such as the impact of rising anthropogenic CO_2 on marine biology and chemistry (EPOCA). Europe is a complicated continent, with climates ranging from the Mediterranean to the arctic, and from moderate maritime to extreme continental. Although Europe is geographically an extension of the Eurasian continent, it also has links to Africa. Extensions of the research into neighbouring regions are therefore important, with research in Siberia (TCOS-Siberia) and Africa (CarboAfrica) playing a vital role.

In the long term, the challenge is to create the new knowledge in an integrated way, and to then understand and predict the future climate of Europe as it is, embedded in its surrounding oceans, continental neighbours, and the global context of climatic and environmental change.

Part IV:

An Assessment of the European Terrestrial Carbon Balance

CarboEurope-IP

edited by

E.-Detlef Schulze (coordinator),
John Gash, Annette Freibauer,
and Philippe Ciais

Jena, 2008

1. The CarboEurope-IP Approach

The CarboEurope-IP objective of mapping the fluxes of carbon into, and out of, the land surface of Europe created a challenge for the designers of the project: how to deal with the small-scale variability of the European landscape, at the same time as covering the whole geographic extent of the continent. The techniques available to measure or estimate carbon fluxes cover a range of time and space scales, but no single technique can produce the required product. The answer was found in an integrated suite of data collection and modelling, designed to deliver the objective based on the philosophy that each number must be checked by two estimates, one coming down from the large scale, and one up from a smaller scale (**Fig. IV.1**).
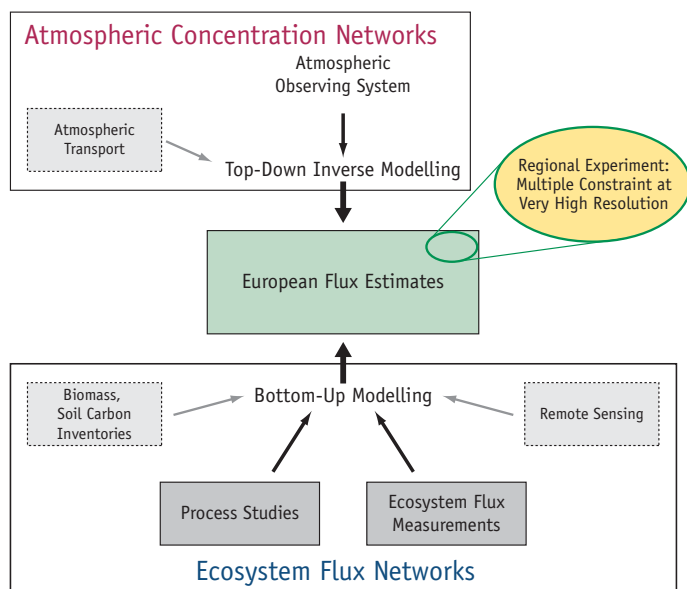
Fig. IV.1: Atmospheric and ecosystem observations constrain the quantification of the carbon balance.

This two-pronged approach required measurements at a range of scales:

- the concentration of CO_2 in the free troposphere, using flask-sampling from aircraft (vertical profiles through the troposphere);
- continuous measurements of CO_2 concentration in the atmosphere above the surface boundary layer, using tall towers; the exchange of CO_2 between component ecosystems and the atmosphere above the vegetation, using flux towers; and intensive gas exchange measurements at the soil surface to separate the responses of soils from the responses of the vegetation.

Thus, atmospheric measurements from aircraft and tall towers constrain the quantification of the land-surface flux. Measurements from flux towers and soil gas exchange measurements, both constrain the information about soil fluxes. As Detlef Schulze, CarboEurope-IP coordinator, says 'The intellectual novelty in CarboEurope-IP is the dual constraint of each number

being verified by top-down and bottom-up assessments in a hierarchical approach from the atmosphere to the soil. This gives modellers the confidence they need to calibrate and test their models. Only by closely integrating observations at various scales and modelling we can hope to make realistic predictions about the future.'

One core experiment of the programme is a set of high-precision observations of the concentration of atmospheric CO_2. The background concentration is measured from high-altitude or coastal sites where the air is unaffected by the ground level input and output of carbon from human activity, or the fluxes from the vegetation and soil. Other CO_2 samples are collected on tall towers which are situated where they will collect data that shows just those effects. These samples contain the integrated history of the air as it has passed over the continent and together give a continental-scale picture of the fluxes over the period of several days that it typically takes the air to move across Europe.

Building up from below, the exchange of CO_2 between different landscape elements and the atmosphere is measured in a network of about 100 sites across Europe. At the centre of each site is a flux tower. Here, micrometeorological techniques are used to derive the actual flow of CO_2 coming from the "flux tower footprint": an area of several hectares up-wind of the tower that is "seen" by the instruments. These measurements give an almost continuous record of the flux from a relatively small sample of vegetation and soil. A suite of soil and vegetation measurements made around the tower provide an additional bottom-up estimate of the carbon balance by measuring the slow build up of carbon in the biomass and soil. These measurements are also used to derive the component fluxes of carbon assimilation by photosynthesis (when plants use sunlight to build up sugars from water and carbon dioxide) and carbon emission by respiration (when soil microbes break down plant material and plants burn sugars to provide the energy they need to stay alive). All these data are then used to derive the parameters for the biogeochemical models – the models used to scale-up the fluxes to meet the top-down estimates of the continental carbon balance.

1. The CarboEurope-IP Approach

Additionally these techniques were brought together in an intensive, regional-scale field experiment. In this experiment all the fluxes, at all scales, were simultaneously measured and modelled in a series of campaigns in southwest France. The objective was to provide the data to allow meteorologists to develop and test the capacity of their short term, "meso-scale" models to predict the regional carbon balance; giving a more manageable regional-scale test of the continental-scale modelling initiative.

Satellites can give fine scale data over large areas; and at their highest resolution the scale is comparable with the footprint of the flux tower measurements. Satellite data therefore play a key role in extrapolating the results from the surface-based measurements to the continental scale. They can provide the relatively small-scale detail needed by biogeochemical models and meso-scale models, over the whole continent.

This strategy of two-way scaling: up from the flux measurements, and down from the continental network of concentration measurements requires integrated science across a range of disciplines. At the same time, integrated science requires integrated teams of people – to be successful there must be movement of information, ideas and people between scientific disciplines and groups of scientists. New thinking is needed in linking data, results and understanding across the scientific community. CarboEurope-IP has built an integrated team of scientists: this booklet outlines the progress they have been making and highlights some of the results.

The Integrated Ecosystem Approach

The flux of carbon dioxide between the land surface and the atmosphere is the net result of a number of biological, chemical and physical processes which are all occurring simultaneously and varying in response to different controls. These controls can act at different time scales and may be interconnected. Until now the components of the carbon balance have usually been measured and modelled separately. Often different groups of specialists have worked independently. For example plant physiologists researching the leaf response to sunlight have been working apart from microbiologists researching the population dynamics of soil microbes. Now, in CarboEurope-IP a new integrated approach to ecosystem research has been adopted (**Fig. IV.2**). This approach is based on treating the ecosystem as a complex web of components, any of which may interact with and influence the others.

Once these interactions are recognised, subtle but important feedbacks between the vegetation and the atmosphere start to become apparent. For example, it has always been obvious that during drought transpiration from plants and evaporation from the soil surface is reduced, but only with an integrated approach does it start to become clear how drought one year may affect the carbon balance the following year. Lower photosynthesis during drought leads to reduced sugars being stored and lower leaf growth; the following year there is then less plant material to be broken down by respiration. Capturing these process interactions presents a challenge both to the measurement scientists and to the modellers who must represent these processes with equations.

Fig. IV.2: Atmospheric measurements with aeroplanes, tower-based flux measurements and detailed process studies in the ecosystem are needed for quantifying and assessing a a complete carbon balance. (Photocollage: Y. Hofmann)

2. Soils

Soil has the potential to be a major longterm sink of atmospheric carbon (**Fig. IV.3**). CO_2 is extracted from the air during plant photosynthesis and later enters the soil as plants die or shed their old leaves and roots (**Fig. IV.4**). Most of the carbon is held in soil as organic matter. The fresh material, the "fast" part of the carbon store, is easily accessible to the microbes which feed on it. Micro-organisms use the sugars as building material for their own bodies and as substrate for their metabolism. This process, "respiration", releases carbon back into the atmosphere, but a part of the soil carbon can remain, bound tightly either in the biomass of organisms or into the mineral component of the soil. This stabilised, or "slow" carbon is less easily accessed by soil microbes and therefore can be regarded as locked into a carbon sink.

It is a major challenge to understand the processes by which carbon moves between the slow and fast pools and how this depends on soil type and soil management. Measurements in CarboEurope-IP have shown how respiration depends on the complex interaction of soil temperature and soil moisture: for example measurements in the Mediterranean climate zone have revealed that the maximum rates of respiration occur in the autumn, when rain falls onto hot soil. This can be simulated by an experiment in which a whole plot of Mediterranean scrubland was irrigated (**Fig. IV.5**).

Respiration depends mainly on microbial behaviour and population dynamics, rather than on straightforward chemical reactions and climate. This makes modelling respiration particularly difficult. Current models of respiration are simple empirical functions of soil temperature and moisture, but these models may not work well outside the conditions for which they were derived. Developing more generally applicable, process-based models of respiration is thus critical if we are to model the future carbon balance and to estimate how soils will behave under different management or climatic conditions. Eric Davidson and Ivan Janssens, have pointed out in 2006 that although respiration responds to temperature, this is a bulk response to several processes which are occurring simultaneously: microbial and root biomass, enzyme activity, and the diffusion of gases and liquids through soil and cell membranes all vary with temperature producing a convoluted response. In addition the availability of nutrients is critical and it emerges that respiration depends more on available resources, mainly carbohydrates, than on climate conditions. The concept of "fast" and "slow" pools is also too simplistic. Soil organic carbon can be effectively protected against microbial attack when it is locked away in soil aggregates, micropores or coated with a hydrophobic layer. Disentangling these processes will require new models. The measurements in CarboEurope-IP (**see Page 20**) are starting to provide the data which will allow more realistic soil models to be developed.

Fig. IV.3: Definitions of the term "productivity" in the carbon cycle. The initial process is the gross primary production (GPP), which corresponds to photosynthesis. Growth and maintenance requires about 50% of the assimilates for the energy requirement of the plants. Biomass is formed that appears as growth (net primary production, NPP). A proportion of this annual increase in biomass is returned to the soil as litter (leaves, roots, flowers) and, of this, a proportion returns to the atmosphere due to soil respiration. The "net ecosystem productivity" (NEP) is the balance between assimilation and total respiration. Independent of soil respiration are processes that remove carbon from the system without appearing in the respiration term. Examples are harvesting by man, grazing and fire. The balance of all this carbon turnover is called "net biome productivity" (NBP). (Schulze et al., 2000a)

2. The Role of Soil

Fig. IV.4: Living plants supply food to all other organisms in the ecosystem, the animals above ground and the myriad of decomposer in the soil. These organisms are all interconnected and controlled by pests and diseases. Input into the soil is via dead leaves and stems as well as via roots. The first step of decomposition is the grinding of biomass into small bits which can be mineralised by micro-organisms. These use fresh biomass as an energy source in order to break apart complex chemical compounds, atom by atom for their own metabolism and body biomass. In fact, breaking down old organic matter, makes living microbes look chemically old. The benefit of the mineralisation process for the plant cover is the recovery of nutrients which can be invested in fresh biomass. (Schulze, unpublished)
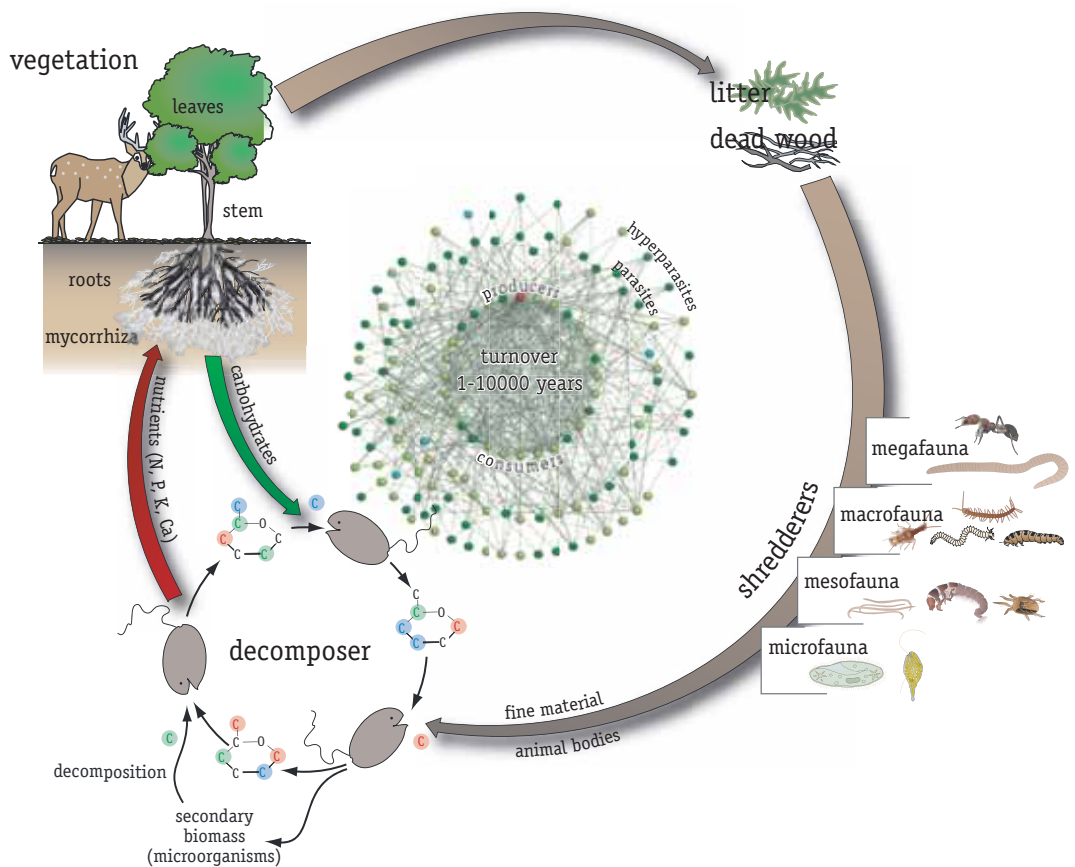
Fig. IV.5: A Mediterranean scrubland ecosystem was irrigated in August, the hottest time of the year, to demonstrate the effects of soil moisture and ecosystem respiration. With irrigation, photosynthesis increased only about 10% (not shown), while respiration was reactivated immediately. The respiration rate doubled compared to the dry control. (Valentini, unpublished)
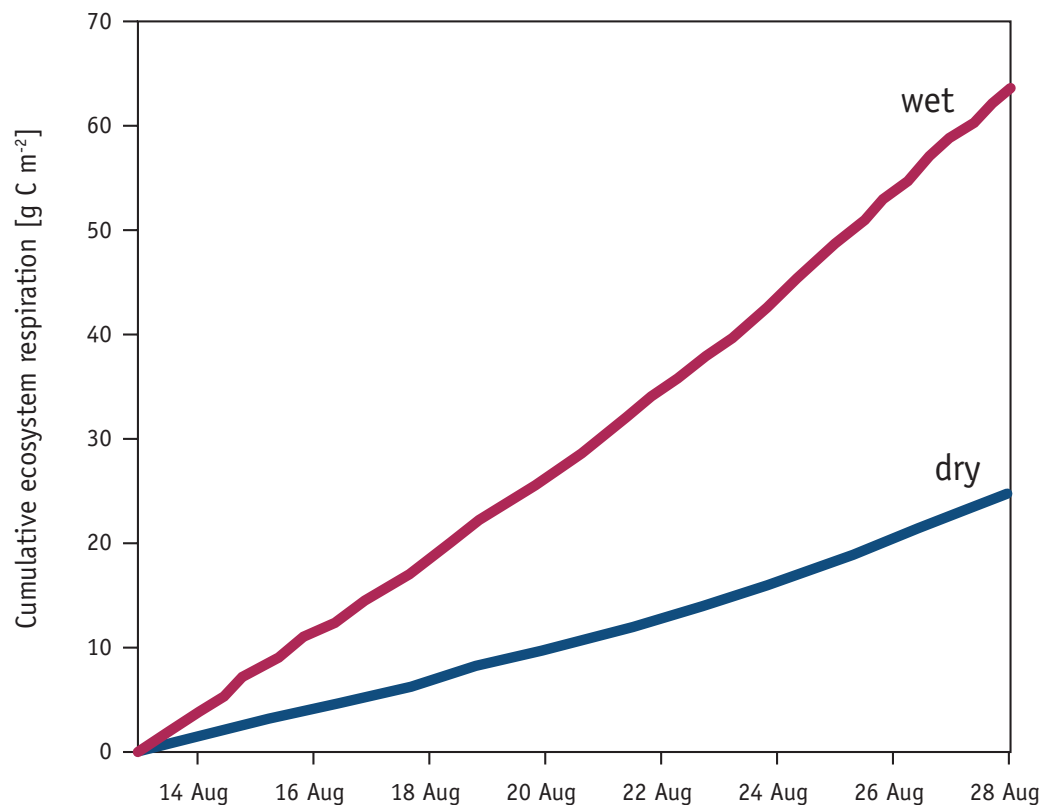
2. The Role of Soil

Soil carbon monitoring

CarboEurope-IP ecosystem observation sites measure the CO_2 flux continuously as the gas moves through the turbulent atmospheric boundary-layer above the vegetation (**see Page 32**). All the major vegetation types are being monitored: pasture, cropland, deciduous and coniferous forest, and wetland. However, these measurements are subject to error and it is important to check the long term totals against another, independent method. Previously, flux data have been compared with harvest or tree-growth data, but that gives only half the picture – the carbon accumulated (or lost) by the soil must also be monitored.

Carbon dating (**see Page 21**) will then be used to show how much new carbon has become locked into the mineral soil and removed from the carbon cycle. This procedure is consistent with the basic philosophy of combining top-down and bottom-up predictions at all scales. Flux measurements are a top-down measurement of the response of soils, but this needs to

be verified by bottom-up measurements of the soil. Combining top-down and bottom-up derived quantities is a most powerful tool to reduce uncertainties and to derive the most reliable estimates of the components of the carbon balance.

Soil sampling (**Fig. IV.6**) in CarboEurope-IP has the objective of verifying changes in carbon stocks in major land-use types. For this purpose croplands, grasslands, coniferous and deciduous forest were sampled at three sites for each land-use type (**Fig. IV.7**). In order to detect changes over a 5-year period, as it is prescribed by the Kyoto commitment period, 100 soil cores were taken at each site. Each core is separated into six soil layers. Thus, the sampling scheme yields 7200 soil samples. These samples are further fractionated according to their chemistry, measured for carbon and nitrogen and stable isotopes, and archived in special bottles, so that future generations of researchers can come back and check these findings (**Fig. IV.8**).

Fig IV.6: Soil sampling is an exhausting job, especially on heavy and stony soils. It takes a strong person to carry the 30-kg soil sampling equipment over long distances to the study sites, and it takes even more hands to carry back the soil samples. (Photo: M. Schrumpf)

12 sites:
3 deciduous forest sites
3 coniferous forest sites
3 grassland sites
3 crop sites

Norunda

Easter Bush

Soroe

Carlow

Gebesee
Hainich Wetzstein
Grignon
Hesse

Le Bray Laqueuille Bugac

Site Location and Surveyed Land Cover
Forest   Grassland   Crops

Main Site
Associated Site

N

0 100 200 Kilometers

ISRAEL

Map Background:

USGS GTOPO30
GISCO Country Borders
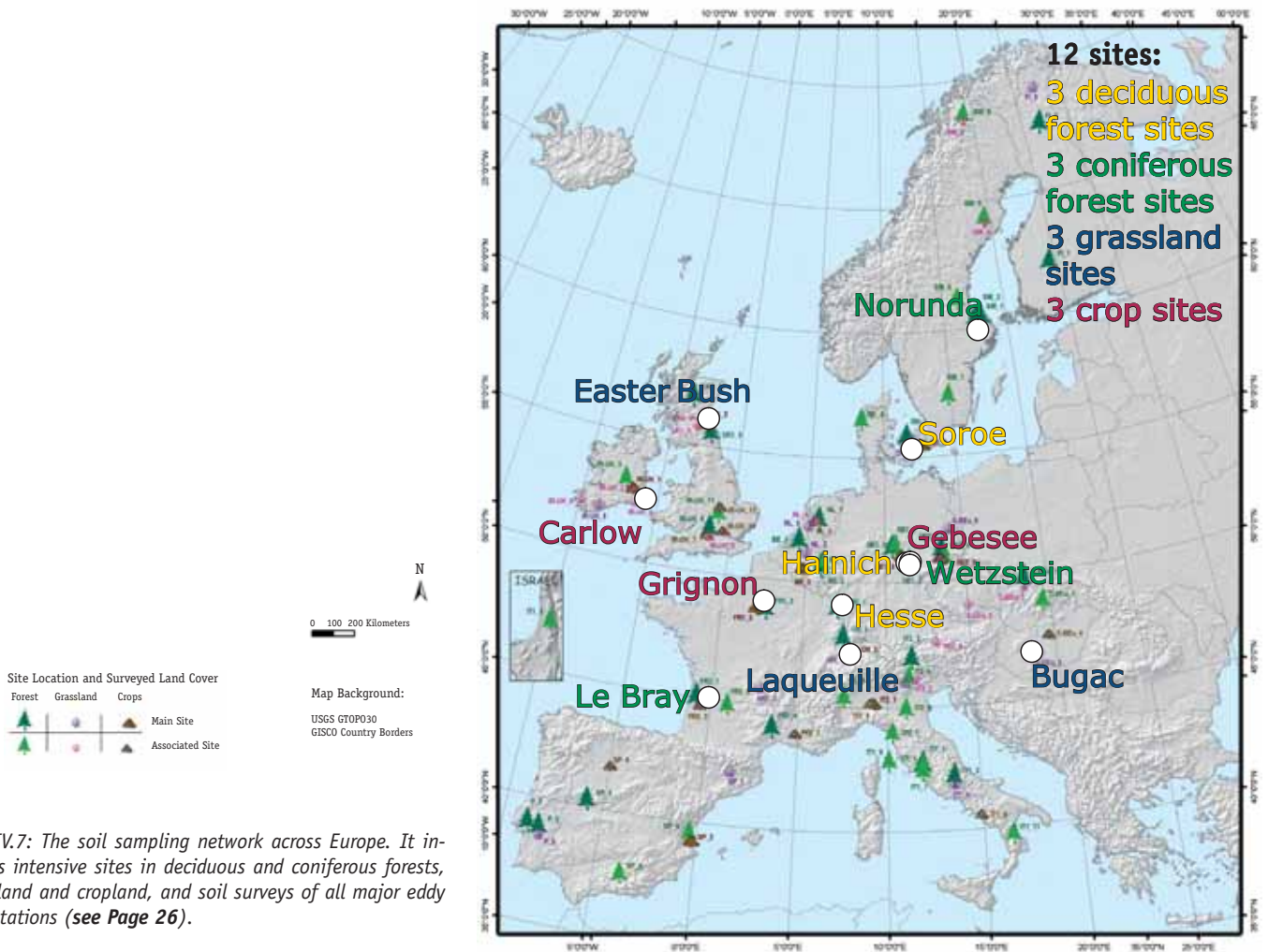
*Fig. IV.7: The soil sampling network across Europe. It includes intensive sites in deciduous and coniferous forests, grassland and cropland, and soil surveys of all major eddy flux stations (**see Page 26**).*

Fig. IV.8: Soil archive at the Max-Planck-Institute for Biochemistry in Jena. CarboEurope-IP has collected and measured 3600 kg of soil, which is presently archived in 7200 bottles. Each bottle is labelled with the location of sampling, and the date. (Photo: Y. Hofmann)

2. The Role of Soil

During the time frame of CarboEurope-IP it was possible to assess the carbon pools on the 12 intensive study sites and to map soil carbon on all flux tower sites. Present and historical land-use influence the depth profile of carbon amounts and its chemical fractions as well as their turnover times (**Fig. IV.9a,b**). Forests have higher carbon concentrations in the upper most soil layers but concentrations decrease with depth. In contrast, in croplands carbon concentrations are lower in the top soil, but remain high at soil depth.

The age of organic molecules that are bound to mineral surfaces is well beyond 1000 years.

One fact is now clear: only the carbon which forests and farms remove from the carbon cycle by becoming locked into the soil is a long term off-set against carbon emitted from burning fossil fuel. CarboEurope-IP has made studying the build up soil carbon in forest and farms a priority. However, Marion Schrumpf, CarboEurope-IP soil scientist, warns, 'To prove changes in soil carbon will require more time than provided by CarboEurope-IP. The small-scale heterogeneity of soils leads to very large sampling schemes, and the slow rate of change means that there must be long time steps between observations'.
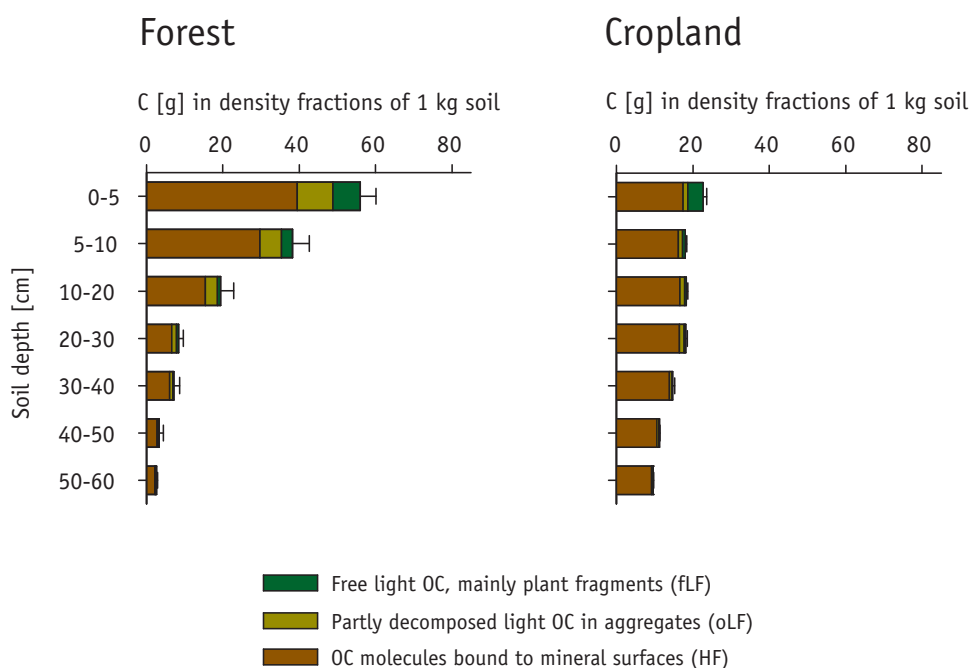
Fig. IV.9a: Depth distribution of organic carbon (OC) contents of a forest and a cropland soil. Different kinds of land use result in characteristic depth profiles of soil carbon. In undisturbed forest soils, carbon contents decrease with soil depth. Ploughing leads to a homogenisation of carbon contents within the plough layer (0-30 cm soil depth) of croplands. Harvest reduces carbon inputs to cropland soils and ploughing increases mineralisation so that carbon contents in the topsoil of croplands are lower than in forest or grassland soils. Since croplands are often found on deep, fertile soils, carbon contents in the subsoil can be higher than in shallower forest soils. Density fractionation can be used to separate total organic carbon (OC) contents of the soil in three functional pools: the free light fraction (fLF), which consists of largely undecomposed plant fragments, the occluded light fraction (oLF), which is formed by more degraded plant fragments temporarily protected against further decomposition within soil aggregates, and organic molecules bound to mineral surfaces (HF). The latter forms the most stable fraction of the three OC pools with turnover times of more than 100 years. Figure 8a shows that reduced carbon input and increased mineralisation in croplands lead to a reduction of the contribution of fLF and oLF in the total carbon content.

Forest

Carbon age [% modern carbon]

Cropland

Carbon age [% modern carbon]

Forest:
1080–100 years   >20 –2 years
before 1955   after 1955

Cropland:
2080–100 years   >141 – 58 years
before 1955   after 1955

Soil depth [cm]

Legend:
- Free light OC, mainly plant fragments (fLF)
- Partly decomposed light OC in aggregates (oLF)
- OC molecules bound to mineral surfaces (HF)
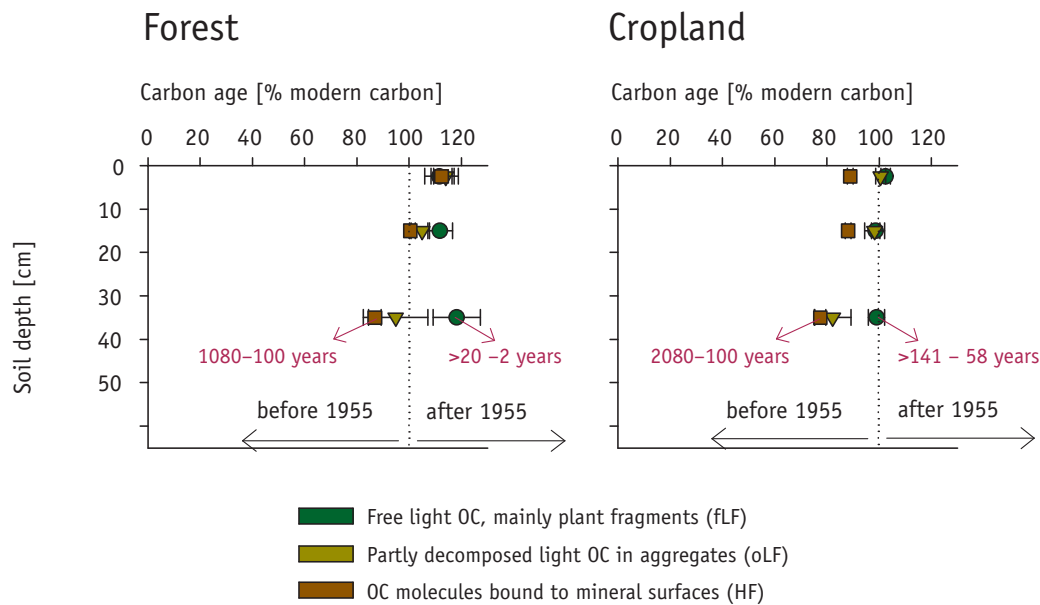
Fig. IV.9b: The radioactive ^{14}C isotope can be used to determine the mean age of organic carbon (OC) in the fractions since the ratio between ^{12}C and ^{14}C in the atmosphere is fixed in the plants and then changes with time following the decay rate of ^{14}C. The plant signal of wheat harvested in the year 1955 was used as standard material. By definition all ^{14}C concentrations smaller than this reference value are said to be old carbon, while higher concentrations are "modern" and originate after 1955. The reason for the increase in atmospheric ^{14}C concentration after 1955 are the nuclear bomb tests in the 1950s and 1960s which almost doubled the original ^{14}C concentration.

The Figure shows the ^{14}C content of different density fractions expressed as percent modern carbon. Values above 100% indicate a contribution of bomb carbon to OC contents and thus an average origin after 1955. The Figures show that in both, forests and croplands, carbon age increases with soil depths and for each soil layer, youngest carbon is found in the fLF and oldest in the HF fraction. The mean carbon age of the forest was younger than that of the cropland indicating more additions of new carbon to the forest soil. Oldest carbon with a mean age of 2080 ± 100 years was found in the HF of the cropland site. (Schrumpf, unpublished)

Robust findings:

Only carbon that is locked into mineral particles or wet peat is removed from the active carbon cycle. But a lot of this carbon can be activated again by land use and land-use change, such as ploughing up of grasslands.

To prove soil carbon stock changes over a 5-year commitment period requires a major effort of soil sampling. CarboEurope-IP has established a sampling design across various land use types that is robust enough to prove such changes.

Key questions:

What are the chemical and biological processes which move carbon into long term storage and can these be managed?

How should we model these soil-carbon stabilisation processes?

Can the slow accumulation of carbon in soil be detected within periods of less than a decade?

3. Forests and Farms

3.1 Forests

Are forests better than farms at removing carbon from the atmosphere? The public certainly think so: the many tree-planting schemes reflect a belief that CO_2 emissions can be off-set by new forest growth. But is there hard scientific evidence to back up this perception? Planting new forests, where none existed before, will extract CO_2 from the atmosphere and convert it to standing timber. However, tree plantations decompose existing soil carbon and extract nutrients for growth. It takes 60 years before plantations on grassland are carbon neutral (Thuille and Schulze, 2006). Mixed-age forests will always contain standing timber and therefore a store of carbon, but how does the carbon uptake change with time, and when forests age, do they continue to be a net sink for carbon? Similarly, is agricultural land (cropland and pasture) a source or a sink of carbon? Above-ground there may be no visible increase in carbon, but what is happening below the surface, is carbon building up in the soil? Key questions such as these are being addressed by the CarboEurope-IP plant and soil scientists.

Europe's forests are almost entirely managed (**Fig. IV.10a,b,c**). Trees are felled when they approach commercial value and most of the above-ground biomass, i.e. the wood, is removed and sold. It is then used for a variety of purposes such as paper, fuel, or in the construction industry. Over time, most of this wood will either be burned or allowed to decompose: the carbon will then be returned to the atmosphere as carbon dioxide gas. On the other hand, forests produce large quantities of leaf and woody litter, which as it decomposes can enrich the soil with organic matter. Agricultural land is of course even more highly managed than forests and the carbon in the food produced will become carbon dioxide almost immediately. CarboEurope-IP has the task of evaluating the carbon fluxes from forest and farms and assessing how these very different ecosystems contribute to the carbon cycle.

Annual carbon balance data are now available from more than 500 forest sites over the world. The variation between individual sites, and from year-to-year, is large but taking the data together a coherent picture is emerging. Carbon absorbed by the actual vegetation increases with higher rainfall and temperature, until an annual total of about 1500 mm rainfall and an average annual temperature of 10°C are reached. Beyond these values, photosynthesis saturates and there is no further increase in the amount of carbon absorbed. Ideal conditions for higher carbon absorption are also favourable for the breakdown of dead organic material by microbes, thus leading to faster return of the absorbed carbon to the atmosphere. As a result, Luyssaert et al. (2008) showed that the net carbon balance of forests is rather similar over the whole world. Variations between forest sites are not the result of climatic differences, but more likely to be due to factors such as forest age, management and history of disturbance.

Fig IV.10a: The wood is harvested by heavy machinery. The harvester fells the tree and cuts it into pieces. (Photo: E.-D. Schulze)

Fig IV.10b: Forwarder carries logs out of the forest. (Photo: E.-D. Schulze)

Fig IV.10c: Logs are piled up for transport into sawmills. (Photo: E.-D. Schulze)

3. Forests and Farms

Philippe Ciais headed a CarboEurope-IP analysis of European forest inventory and harvest data over the past 50 years. He found that for all countries in Europe the environmental conditions, in combination with current forest management, have resulted in forests efficiently sequestering carbon, while at the same time meeting the demand for wood (**Fig. IV.11**). However, the study warned that shorter rotation times and a return to using forest for biofuel could cancel the benefits that have accumulated over the past five decades. Thus, old forests may not be seen in the future (**Fig. IV.12**).

Based on all available data of inventories and flux towers Luyssaert et al. (2008) conclude that the forest sink is 195 Tg C y^{-1} which is smaller than the estimate made by Janssens et al. in 2003. About 50% of this forest sink is located in the forests of European Russia.
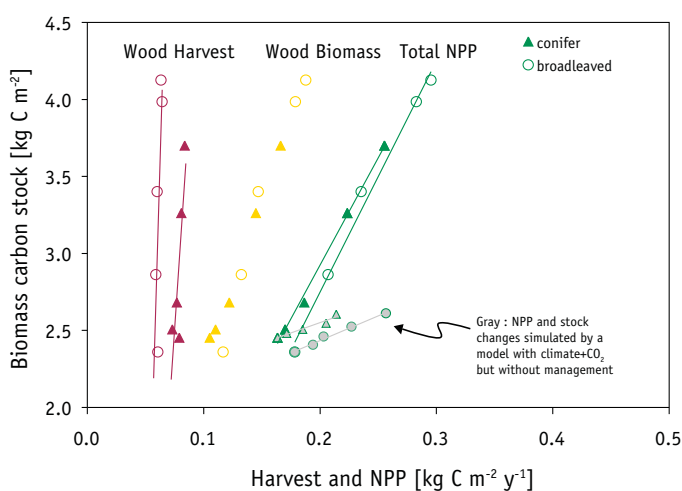
Fig. IV.11: During the last 50 years, Europe has, on average, multiplied the biomass carbon stocks per hectare by 1.75 and the net primary productivity by 1.67. The forest shows that forest biomass increased with the rate of growth (total NPP). Wood harvest was only a small fraction of total NPP. Therefore wood biomass increased despite the harvest. A model simulation shows that the increase in biomass and productivity is caused not by changing climate, but due to management decisions by foresters. (Ciais et al., 2008b)

Fig. IV.12: 120-year old managed beech forest at Leinefelde in Germany with a 40 m high measuring tower. The straight timber and the tall trees are the result of 120 years of good management by foresters. (Photo: E.-D. Schulze)

3. Forests and Farms

The Hainich Forest

In unmanaged forest no timber is extracted and when trees die the wood is left to decompose and the nutrients recycled. Are these forests carbon-neutral or do they continue to act as carbon sinks? Measurements in the pristine forests of Amazonia show that such forests can continue to act as carbon sinks. Nitrogen fertilization (**see Page 40**) and possibly the effects of increased atmospheric CO_2 concentration and higher temperatures resulting from climate change all suggest we should expect unmanaged forests to continue absorbing carbon (**see Page 29**); but at what rate and for how long? These questions are being addressed at a CarboEurope-IP measurement site in the Hainich Forest in Germany.

Hainich Forest (**Fig. IV.13**), which has not been managed commercially for over 60 years, is being used to study the carbon dynamics of natural woodland. All the stores of carbon and the components of the carbon balance are being monitored in one of the most intensive forest experiments ever mounted.

Contrary to earlier predictions and despite the fact that many of the living trees are 200 to 300 years old, and root stocks are up to 600 years old, Hainich unmanaged forest is acting as a sink of carbon. Martina Mund, of the Max-Planck-Institute for Biogeochemistry, is leading the research team at Hainich, she said 'It was a surprise to find that an old, unmanaged forest
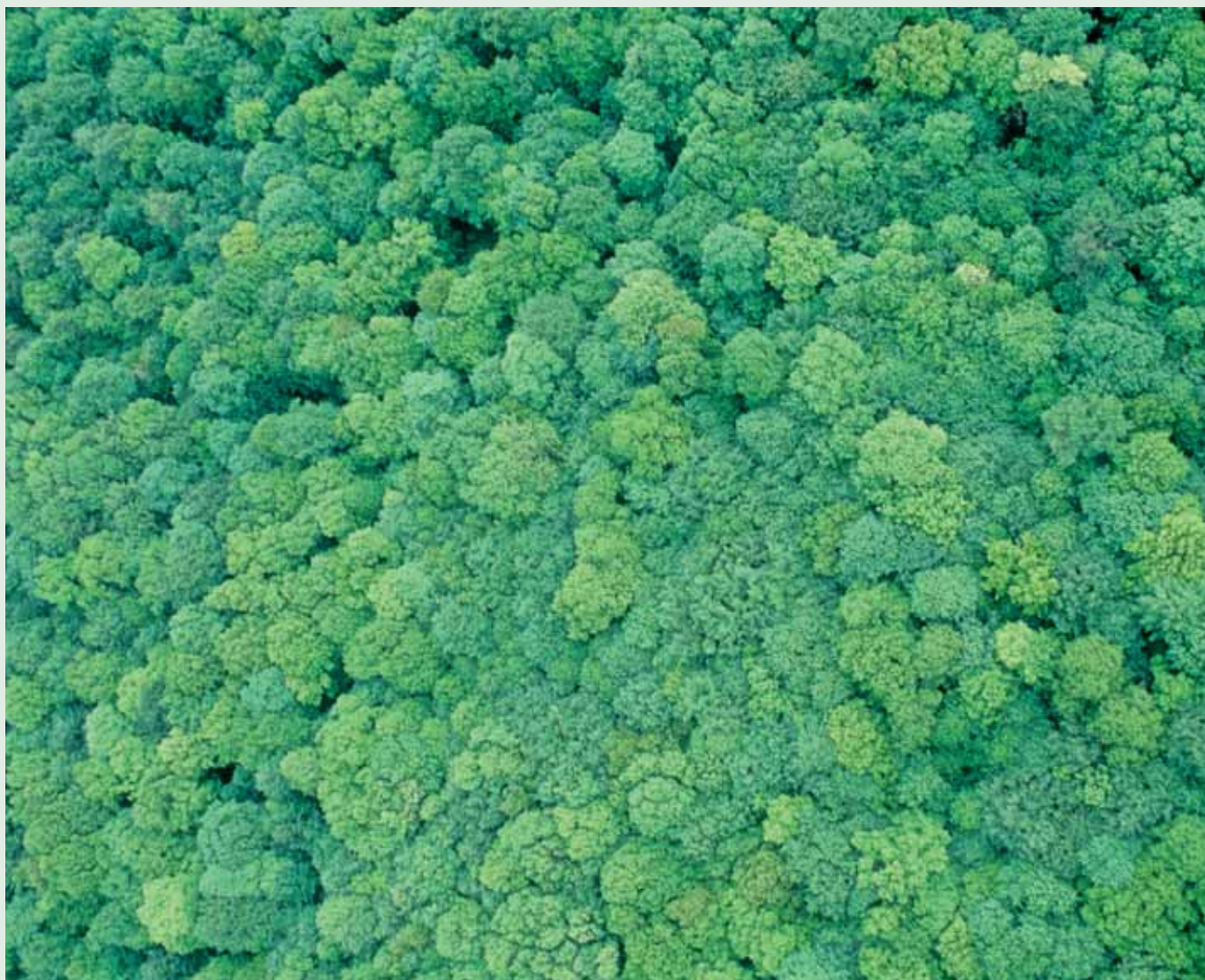
Fig. IV.13: The Hainich National Park (Germany) from above (Photo: T. Stephan).

like Hainich was a sink for carbon. The question now is why? Is this forest moving to a new equilibrium driven by outside influences? If so what are those influences and for how long will they continue to cause this forest to be a net sink of carbon?' The CarboEurope-IP whole-ecosystem, top-down/bottom-up approach to measurement is starting to produce the answers to these questions. Eddy covariance measurements (**see Page 32**) are telling us that the Hainich forest is a sink of carbon. The inventories and surveys are revealing that most of the carbon is going into the trees, the soil being only a small sink for carbon. Long term monitoring is in progress to establish the trends in carbon absorption.

A re-inventory of a survey in year 2000 shows that almost all plots, independent of basal area continued to change stem volume and accumulate biomass (**Fig. IV.14a**). The yearly stem increment was even larger in Hainich than recorded by the highest yield class of yield tables (**Fig. IV.14b**).
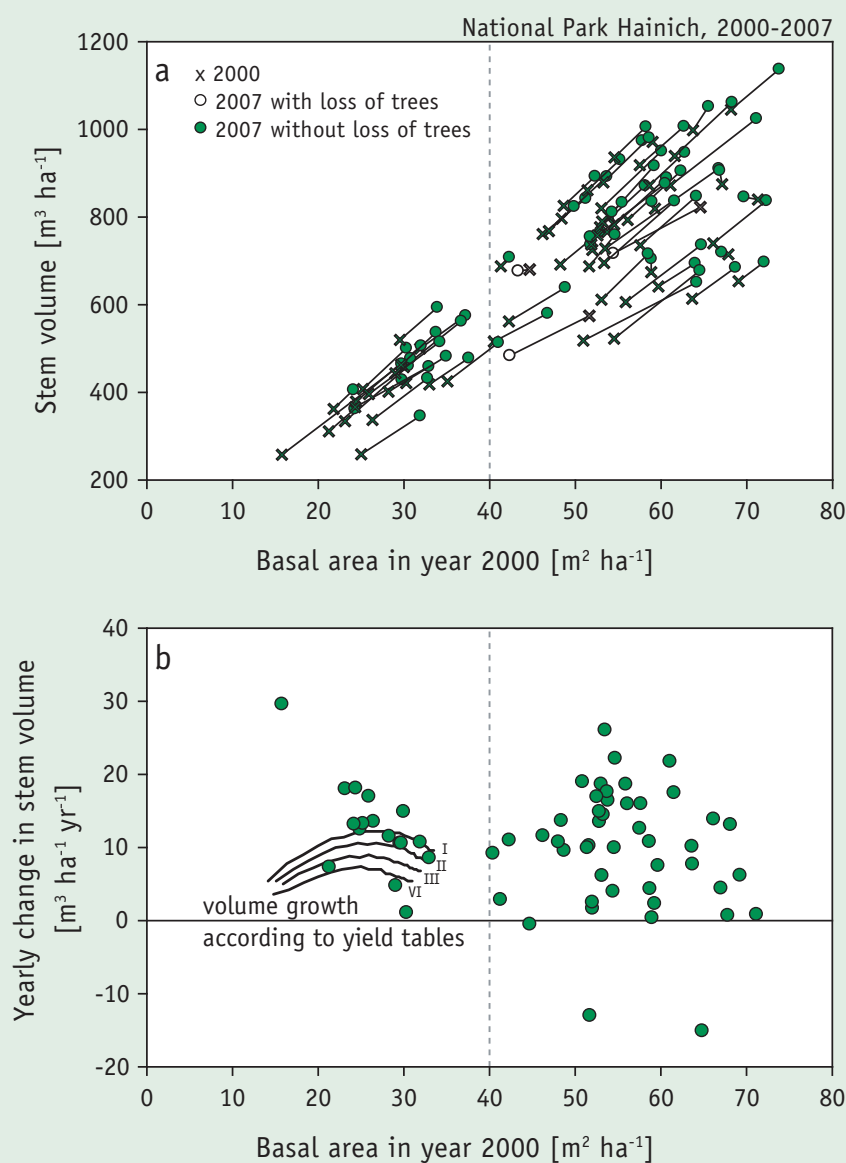
Fig. IV.14a: Stem volume as related to basal area on several plots of a repeated inventory of the Hainich National Park, Germany. The inventories were made in year 2000 and 2007.

Fig. IV.14b: Annual change in stem volume between the years 2000 and 2007 as related to basal area in year 2000. Negative numbers indicate the loss of a major canopy tree. The small parabolic curves show the yearly increment in stem volume of different yield classes according to yield tables. It is interesting to note that yield tables cover only the lower end of basal areas which are found in the unmanaged forest, and that the unmanaged forest stands reach higher annual wood increment rates than predicted by yield tables. (Hessenmöller et al., 2007).

3. Forests and Farms

European forests as a carbon sink and as wood resource

The forest inventory is a robust method of measuring the build up of carbon by forests. At the heart of the technique is the mensuration survey of conventional forest resources or timber. Foresters have carried out these surveys in many European countries and in some countries national data go back as far as the 19th century. All the individual trees in a sample plot are counted and a sub-sample of trees are measured for their dimensions (**Fig. IV.15**). Allometric relationships are then used to convert these data to the total weight of carbon stored by the trees above and below ground. There are some 400 000 plots in western Europe monitored at intervals of 5 or 10 years. Data are reported as part of the national carbon statistics required under the Climate Convention and the Kyoto Protocol.

European forests are intensively exploited for wood products, yet they also form a potential sink for carbon. European forest inventories can be combined with timber harvest statistics to assess changes in this carbon sink. Analysis of these data sets between 1950 and 2000 from EU-15 countries, excluding Luxembourg, but adding Norway and Switzerland, reveals that there is a tight relationship between increases in forest biomass and forest ecosystem productivity, but timber harvest grew more slowly. The type of silviculture that has been deployed over the past 50 years can efficiently sequester carbon on timescales of decades (**Fig. IV.11**).

Fig. IV.15: Survey work in a forest in Germany. Mensuration of a) breast height diameter and b) stem position for future re-inventories. (Photo: D. Hessenmöller and M. Pöhlmann)

Old growth forests

It is generally thought that with ageing, old-growth forests as shown in **Figure IV.16** cease to accumulate carbon and are therefore carbon-neutral. For that reason they are not yet included in international treaties. But evidence examined by CarboEurope-IP suggests that these forests continue to remove carbon dioxide from the atmosphere at rates that vary with climate and nitrogen deposition (**see Page 38**). The sequestered carbon dioxide is stored in live woody tissues and slowly decomposing organic matter in litter and soil. Old-growth forests therefore serve as a global carbon dioxide sink. Searching the literature and databases for forest carbon-flux estimates, revealed that in forests between 15 and 800 years of age, biomass continues to increase with age and the ratio of respiration over growth does not approach an equilibrium with age. Luyssaert et al. (2008) demonstrate that "the long standing view of forest growth seems to be deficient and even old growth forest continue to take up carbon. This means that for the next decades they will be sinks". The ratio of respiration and growth remains below 1 up to very old stand ages.

Over 30% of the global forest area is unmanaged primary forest, and this area contains the remaining old-growth forests. Half of the primary forests are located in the boreal and temperate regions of the Northern Hemisphere (**Fig. IV.17**). On the basis of the CarboEurope-IP analysis, these forests alone sequester about 1.3 ± 0.5 gigatonnes of carbon per year. This suggests that 15% of the global forest area, that is currently not considered when offsetting increasing atmospheric carbon dioxide concentrations, provides at least 10 per cent of the global net ecosystem productivity. Old-growth forests accumulate carbon for centuries and contain large quantities of it. However, much of this carbon, even soil carbon, may move back to the atmosphere if these forests are disturbed or converted into agricultural land.

Fig. IV.16: Pristine old growth forest in the National Park of Uholskyje of the Kapartian Mountains, Ukraine. This forest is 50 m tall. It has a multi-layered understorey which provides continuous regeneration. (Photo: E.-D. Schulze)
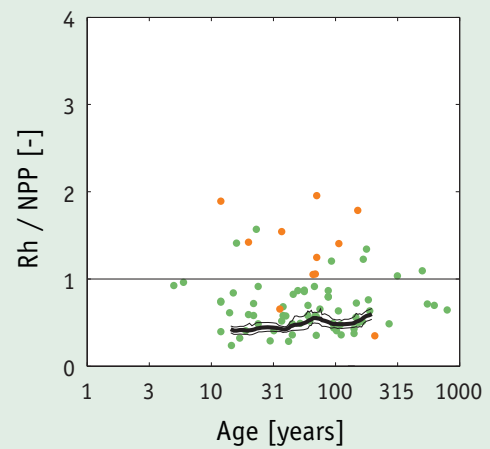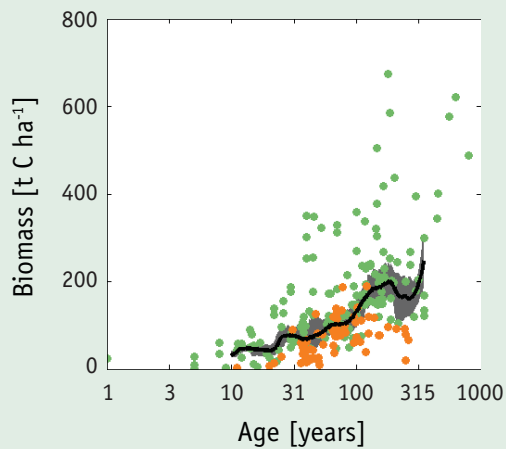
Fig. IV.17: Carbon stocks in forest biomass and the observed ratio of heterotrophic respiration (Rh) and net primary productivity (NPP). The green dots show observations of temperate forests and orange dots of boreal forests. The thick black line shows the median within a moving window of 15 observations. The grey area around this line shows the 95% confidence interval of the median. The data show an increase of biomass with age. At the same time the ratio of heterotrophic respiration and net primary productivity (Rh/NPP) remains an average below unity. (Luyssaert et al., 2008)

3.2 Croplands

Farms cover more than half of Europe's land surface (**see map on back-cover**), and of all land uses, carbon from agricultural land is thought to constitute the largest terrestrial emission of CO_2 and other trace gases to the atmosphere. On the other hand, European farms are highly managed and the regulatory framework and market in which they operate has made them very flexible and efficient (**Fig. IV.18**). Farmers have already shown how they can successfully manage their land to meet policy objectives, such as conserving biodiversity, and this flexibility offers the real possibility of managing farmland to mitigate the greenhouse gas emitted by burning fossil fuel (Smith et al., 2008).

Because many of the changes in carbon occur in the soil, we know less about the carbon balance of agricultural land than we do about forests. Also, with crop rotation the carbon entering the soil changes every year (**Fig. IV.19**). But this lack in knowledge is disappearing: CarboEurope-IP is collecting and analysing new data from cropland at 9 sites in 6 nations.

Before CarboEurope-IP, the best estimates of the cropland carbon balance were obtained from simple budgets of carbon loss and land use change. Now, results from the first years of observations in CarboEurope-IP are giving the first measurement-based insight into the cropland greenhouse gas balance for Europe. Pete Smith of the University of Aberdeen explains, 'Before CarboEurope-IP began, croplands were thought to be a large source of carbon, but new measurements and modelling results from CarboEurope-IP now make us believe that during the 1990s, croplands were either a very small source of carbon or may even have been a small carbon sink. CarboEurope-IP has shown that croplands have significant potential to store additional carbon, with a number of practices, such as reduced tillage, improved rotations, and increased crop productivity, able to lock up additional soil carbon'. Field observations still classify croplands as a minor source but all models predict that cropland are carbon neutral or a small sink. This uncertainty will remain until the re-inventory of soils has been accomplished.

Fig. IV.18: Agricultural landscape near Gebesee in Thuringia, Germany (Photo: E.-D. Schulze)
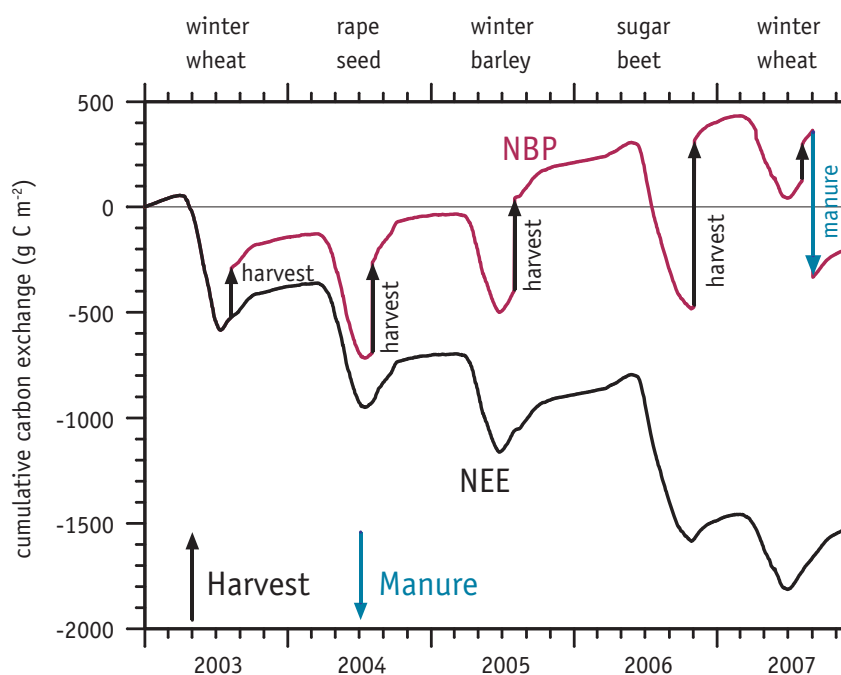
Fig. IV.19: Cumulative carbon exchange by various crops, with net ecosystem exchange (NEE) integrating the carbon balance irrespective of harvest and the net biome productivity (NBP) indicating harvest losses and manure application. In early spring agricultural fields with summer crops may be sources for CO_2 before the crop covers the soil. Then carbon dioxide is removed from the atmosphere (decreasing value) and the vegetation is a sink. There is a step change after harvest due to carbon removal in harvested products, and depending on management and crop type the field will be a source when balanced over the year. (Kutsch, unpublished)

3. Forests and Farms

3.3 Grasslands

Pastures are managed differently to croplands – there is no regular ploughing, which in cropland aerates the soil and increases the microbial populations which break down stored-carbon and emit CO_2. The grassland carbon balance must therefore be assessed separately. In contrast to previous thinking, new measurements and modelling in CarboEurope-IP are now revealing that grasslands are locking up carbon. Also in grasslands year-to-year variability is high. A simple data-based approach has led to an improved estimate of the size of this European net grassland carbon sink. Importantly, it shows that this sink can be readily managed and that a less intensive use of grasslands is likely to increase carbon sequestration, provided that nutrients do not become limiting. Grassland management, such as cutting, grazing and manuring, has a large impact on whether or not grasslands lock up carbon. On the other hand, emissions of the other main greenhouse gases, methane and nitrous oxide, have been shown to partly offset some of the benefits from increased soil carbon storage in grasslands (**Fig. IV.20,21**). In Europe, a major part of the emissions are produced when animals are housed inside, making it important that the greenhouse gas balance of animal/pasture systems are established at the whole farm level. Such a "whole-economic system" approach will be needed in future also for agriculture and forestry, serving as the basis for a "full-carbon-accounting" system. Although greenhouse gas emissions from cattle have received major public attention recently, the emissions and grassland are small compared to emissions from traffic (**Fig. IV.22**).

The new estimates of CarboEurope-IP suggest that grasslands are a stronger sink than estimated in 2003. The total sink approaches that of forests with uncertainty because we do not know the effects of periodic ploughing.

Fig. IV.21: Map showing model results of difference in mean soil organic carbon (SOC) stocks in grasslands between 1990 and 2080 for a climate change scenario (A2), including changes in NPP (net primary productivity), advances in technology and regional differences in SOC stocks. (Smith et al., 2005)

Fig. IV.20: Carbon cycling in grazed grassland. The main carbon fluxes ($t\ C\ ha^{-1}\ yr^{-1}$) are illustrated for intensive grassland grazed continuously by cattle at an annual stocking rate of 2 livestock units per hectare. (Soussana et al., 2004).

Fig. IV.22: "Baseler Fasnacht" (The carnival of the city of Basel): This poster focuses on the public discussion that cows emit methane and thus contribute to climate change. Cows and the associated milk industry is important to Switzerland. Thus the poster reminds us that the cow-emissions are small compared to the roaring traffic, most of which is transit-traffic in Switzerland, and the industrial emissions. (Photo: B. Schulze)

CO_2 flux measurements by "eddy covariance"

CO_2 is transported between the atmosphere and the surface by diffusing through the turbulent atmospheric boundary layer just above the vegetation. By measuring the vertical wind velocity and the concentration of the gas many times per second it is possible to calculate the net flux of CO_2 between the atmosphere and a patch of land upwind of the instruments (the footprint), typically of several hectares. This technique, called "eddy covariance", measures the CO_2 flux over minutes and hours, and can be aggregated, often with the use of correction and gapfilling algorithms, to daily and yearly fluxes (**Fig. IV.23**). The short time resolution makes the data ideal for understanding the biological processes controlling the CO_2 flux and to link these findings to new model development and improvement of existing models. Daily and weekly timescales are often used for parameterisation and validation of models that describe ecosystem and atmospheric fluxes. The longer time scale is used to derive long term estimates of the carbon budget at individual sites.

Since eddy-covariance data require careful evaluation and uncertainty estimation, CarboEurope-IP has put a lot of effort into quality control and error analysis. The data quality was characterized by footprint analysis (a description of the homogeneity of the area where the signal comes from assuming a horizontal terrain), by comparison of the software used to calculate the fluxes, spike detection, filtering and a number of additional tools. The central database of CarboEurope-IP developed standard methods for data filtering and gap-filling, including uncertainty evaluation, (**Fig. IV.24**) resulting in a combined and harmonized CarboEurope-IP dataset that is now starting to reveal a consistent picture of how carbon fluxes vary over Europe at different timescales. Additional experiments were run in the ADVEX-subproject to understand problems that arise in complex terrain. Under these conditions lateral transport of air, or "advection", may prevent the eddy covariance technology giving a true picture of the fluxes. Advection may occur under turbulent and non-turbulent conditions, and it remains difficult to detect in many situations. This work has highlighted the need for critical investigation of all long-term sites to certify the balance.

Reduction of uncertainty and bias detection in the carbon fluxes estimates at ecosystem level is particularly important and a recent study concluded that additional independent measurements are needed, such as biometric measurements of productivity and measurements of respiration in order to check the consistency of the flux balance.

Fig. IV.23: Maintaining eddy flux instruments over a crop field. (Photo: W. Ziegler)

Eddy covariance has been widely adopted as a method of meas¬uring CO_2 fluxes and there is a network of more than 400 sites around the world, with over 100 operating in CarboEurope-IP (**Fig. IV.25**). This global network, "Fluxnet", which started from an EC-funded project of FP4, is probably the largest scien¬tific collaboration in terrestrial ecology there has ever been. Currently, global scale synthesis activities are ongoing using data from the worldwide network of sites, processed and standardised using the CarboEurope-IP methodology. Ricardo Valentini of the University of Tuscia and co-initiator of "Fluxnet" says 'Each Fluxnet field site is producing information on the carbon balance of a particular ecosystem and how it responds to different weather and plant conditions; put together the whole network of sites is now giving us a measurement-based picture of how the Earth's land surface breathes and how it responds to climate.'

NEE_or - half hourly dataset: original data, gapfilled with MDS and gapfilled with ANN

NEE_or - quality flags (0 = original, 3 = bad quality)

NEE_or - daily values for MDS dataset and ANN dataset

● MDS   ● ANN   ● Original

Fig. IV.24: Example of eddy covariance dataset (Hyytiala forest site, Finland, 2004). Negative values indicate CO_2 sink, the red and black dots are two different gapfilling methods applied and their difference is an indication of the uncertainty introduced. In the central plot the quality of each half hour is indicated. (Papale, http://gaia.agraria.unitus.it/database)
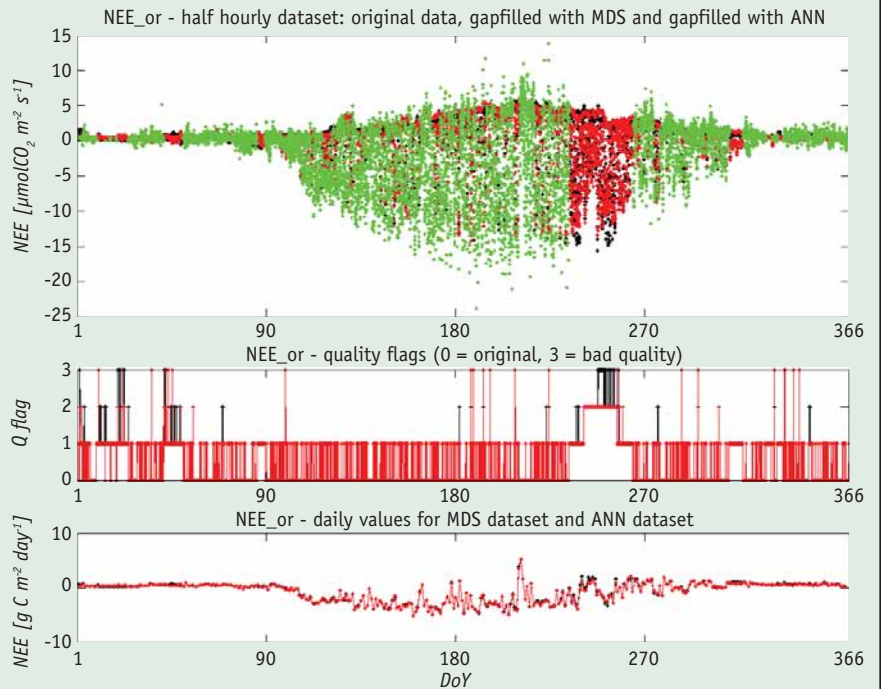
	main flux sites	active associated sites	total
coniferous	12	11	23
deciduous	8	3	11
evergreen broadleaf	4	2	6
mixed coniferous/ deciduous	2	1	3
crops	9	16	25
grassland	15	8	23
total	50	41	91

Site Location and Surveyed Land Cover

Forest   Grassland   Crops

Main Site

Associated Site

Map Background:

USGS GTOPO30
GISCO Country Borders

N

0   100   200 Kilometers
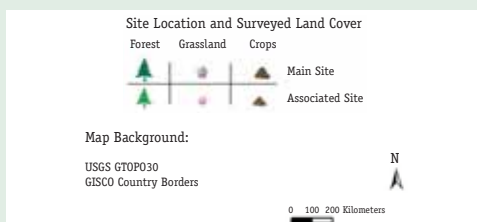
Fig. IV.25: Flux network of Europe. There are 122 flux towers across Europe supporting CarboEurope-IP as main sites (50 towers) and as associated sites (72 Towers). The towers explore the net carbon fluxes of deciduous and evergreen forest, of grasslands and of croplands.
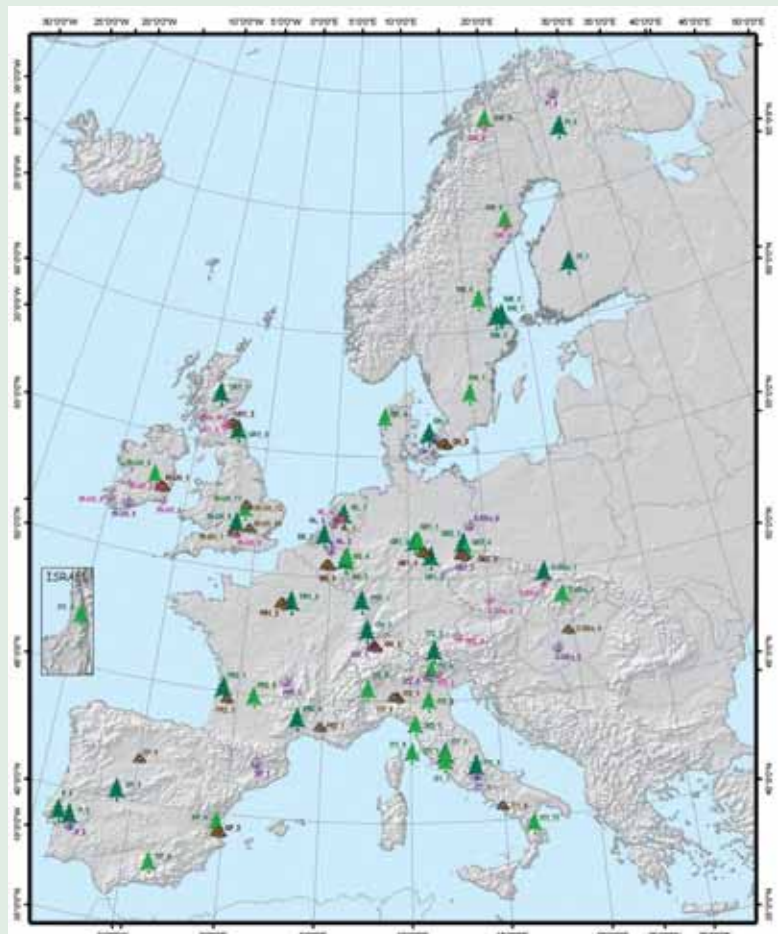
Effects of Changing seasons

A study led by Shilong Piao found that the carbon balance of terrestrial ecosystems is particularly sensitive to climatic changes in autumn and spring. This is important because over the past two decades over northern latitudes spring temperatures have risen by about 1.1°C and autumn temperatures by about 0.8°C. At the same time satellite observations of the Earth's surface have revealed a greening trend, characterised by a longer growing season and more photosynthesis. One would expect that in the future, this spring and autumn warming might enhance annual carbon sequestration by extending the summer period of net carbon uptake.

Piao and his co-workers analysed interannual variations in atmospheric carbon dioxide concentration data and ecosystem carbon dioxide fluxes. Surprisingly, they found that atmospheric records from the past 20 years showed a trend towards an earlier autumn-to-winter carbon dioxide build-up (**Fig. IV.26**), suggesting a shorter net carbon uptake period. We are not only observing an early greening in spring but also an earlier browning in autumn (**Fig. IV.27**) in many but not all ecosystems. This unexpected trend is supported by the ecosystem flux data, which suggests increasing carbon losses in autumn. Both photosynthesis and respiration were found to increase during autumn warming, but a greater increase in respiration out-weighed the increase in photosynthesis resulting in an increased net loss. The opposite occurs in springtime when warming increases photosynthesis more than respiration. In fact, winter cereals show carbon uptake in the warm winters (**Fig. IV.28**). Surprisingly, the effects on the rate of transpiration are very small. The research concluded that northern terrestrial ecosystems may currently lose carbon dioxide in response to autumn warming, with a sensitivity of about 0.2 Pg C per °C, offsetting 90% of the increased carbon dioxide uptake during spring.

There is a surprising year-to-year variation in the net carbon balance of farmland sites, with a complex interaction between temperature, water availability and management being the most important factor. In contrast the pattern is more stable in forest sites, because there is no change in the vegetation. Also, tree diversity helps to maintain ecosystem functions even in extreme years, such as the dry year of 2003. Despite the variations, we can reach the general conclusion that forests and grasslands are absorbing carbon, while agricultural sites are likely to be a source of carbon.

Fig. IV.26: Stubble in early September 2008, Chernozem, Thüringer Becken. (Photo: E.-D. Schulze)
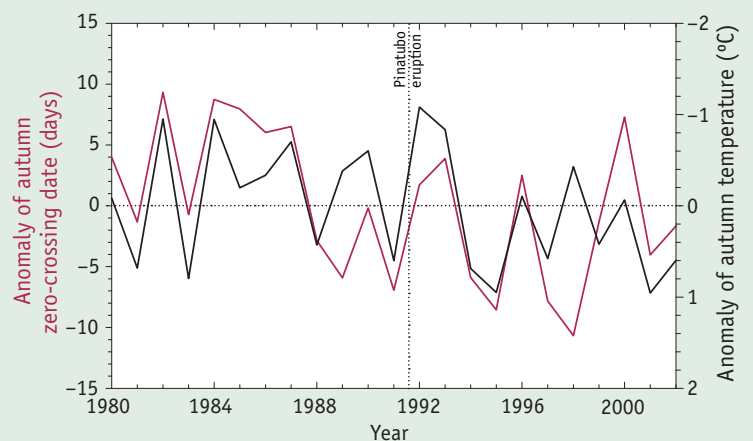
Fig. IV.27: The browning of Europe is closely related to increasing temperatures in the northern hemisphere. Atmospheric CO_2 concentration data analysis from long-term records of the global NOAA-ERSL air-sampling network (red) is closely linked to the autumn temperature at Point Barrow, Alaska (black) - shown as differences (anomaly) from the long-term average. The station oversees the region between 51° and 90° N. (Piao et al., 2008)
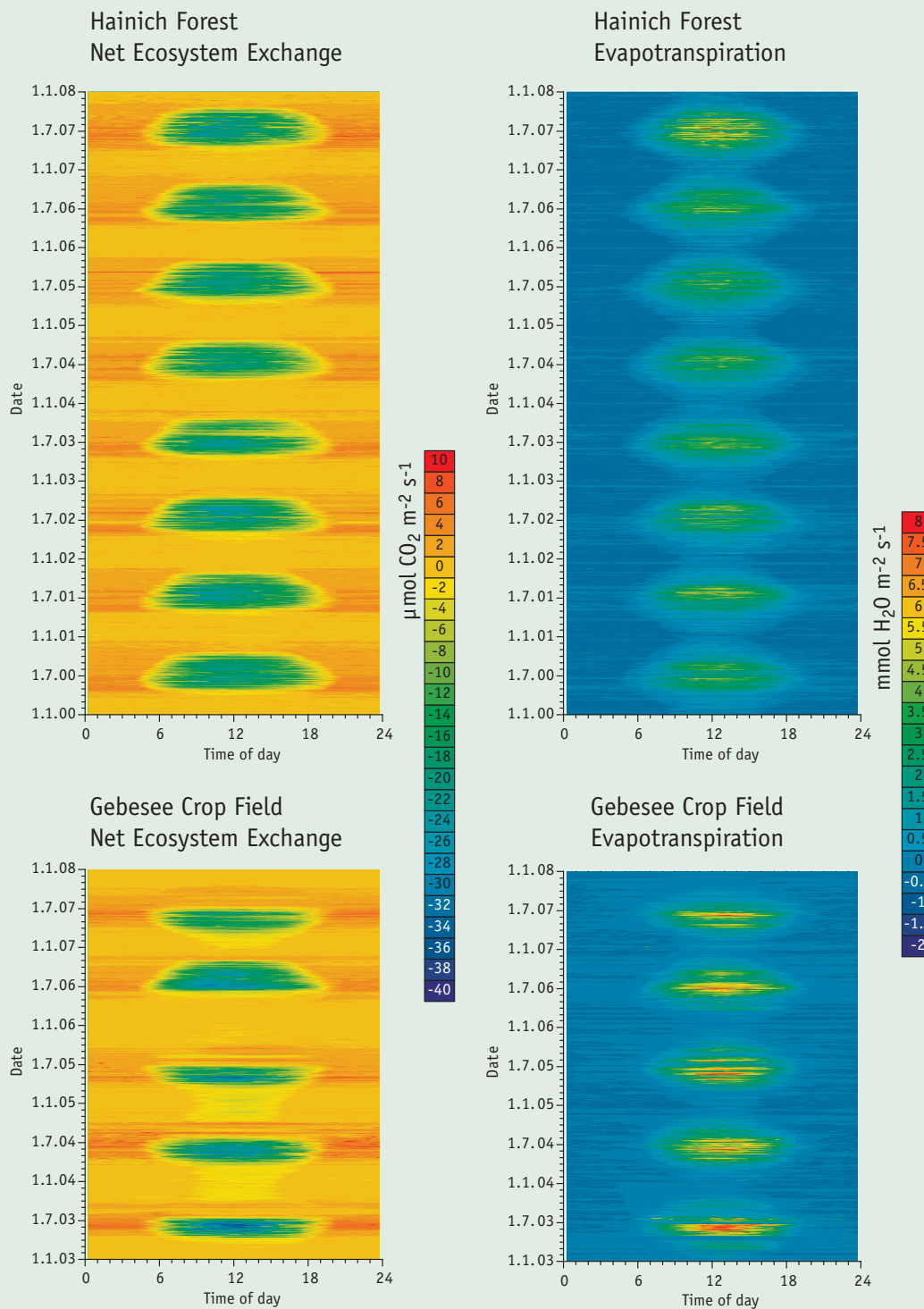
Fig. IV.28: Annual and daily progress of net ecosystem CO_2 and H_2O exchange of Hainich Forest and a cropland in Gebesee, Germany. Uptake of CO_2 by photosynthesis is characterised by negative numbers (yellow, green and blue colours) and CO_2 emissions due to respiration in winter and during night by positive numbers (red colours).In eight subsequent years measured in Hainich Forest the seasonal pattern of CO_2 fluxes is relatively constant. Only small summer depressions can be detected during dry periods in 2003 and 2006. In five subsequent years measured in Gebesee, CO_2 assimilation is characterised by the crop type with highest uptake rates in spring and early summer and CO_2 emissions during the fallow periods. Small uptake rates during winter can be detected in 2004, 2005 and 2007 when winter crops were grown. H_2O fluxes (evapotranspiration) are mainly driven by climatic conditions in the two ecosytems. (Kutsch, Rebmann unpublished)

3.4 Land-use Change

CarboEurope-IP has not focused its work on changes in the carbon stocks of existing land use (land use without land-use change) or those resulting from land-use change (the change from one category of land-use to another), but these can significantly affect the European carbon balance. We therefore include an analysis here. Certain aspects have been covered by CarboEurope, such as the investigation of the effectof afforestation of grasslands on organic soils (Thuille and Schulze, 2006), the studies of changes from arable agriculture into grasslands, and crop abandonment (Steinbeiss et al., 2008; Don et al., 2008). A few studies looked into the future considering different economic scenarios (Schulp et al., 2008). However, at the same time various reviews on the effects of land-use change have become available (Guo and Gifford, 2002; Paul et al., 2002). Generalisations at the European scale are difficult, but the Climate Secretariat of the United Nations Framework Convention on Climate Change (UNFCCC) summarises the national reports, which give detailed information about the areas of changed land-use and estimates of the changes in the associated carbon pools of the EU-25.

Table 1 summarises the information of the national reports of the UNFCCC (http://unfccc.int/national_reports/items/1408.php). In the EU-25 a total about 24 million ha were changed into other land-uses. The main winners were croplands (8.4 million ha) followed by forests (6.5 million ha) and grasslands (6.1 million ha). The main losers were grasslands (12 million ha) and crop abandonment (6.9 million ha).

The resultant changes in carbon stocks and greenhouse gas emissions suggest that these land-use changes resulted in a total GHG-sink of 10 Tg C yr^{-1} in 2005. Including the changes in carbon stocks of existing land-use (land use without land-use change) results in an additional sink of 100 Tg C yr^{-1} in 2005, but these stocks may in future be harvested.

Although some of the numbers are highly uncertain, such as the numbers indicating the change from grassland to forest, which should be a source, we must acknowledge, that this is the most complete summary available. The numbers indicating changes in stocks of existing land cover are included in the CarboEurope-IP Assessment. Thus, only the Land-use Change in soils has not been included, yielding a removal from the atmosphere of about 10 Tg C yr^{-1} in 2005.

Modelling land-use change using the LPJ and ORCHIDEE model Yields 36 to 41 Tg C yr^{-1} as sink activity in year 2000. This is in the range of reported land-use and land-use change.

UNFCCC 2005		Change to							
Change in land area	Change from	Forest	Grass	Crop	Wetland	Settlement	Other	total loss	
Original land-use	Forest	0.00	0.60	0.29	0.07	0.58	0.20	1.74	Mill ha
	Grass	3.56	0.00	7.96	0.02	1.02	0.06	12.62	Mill ha
	Crop	1.07	5.19	0.00	0.02	0.56	0.07	6.91	Mill ha
	Wetland	0.32	0.01	0.00	0.00	0.02	0.11	0.46	Mill ha
	Settlement	0.31	0.24	0.16	0.03	0.00	0.02	0.76	Mill ha
	Other	1.30	0.07	0.01	0.09	0.08	0.00	1.55	Mill ha
	Total gain	6.56	6.11	8.42	0.23	2.26	0.46	24.04	Mill ha
Change in carbon stocks	Forest	0.00	-0.02	-0.43	-0.03	-0.41	-0.20	-1.09	Tg C yr^{-1}
Soils only	Grass	5.72	0.00	-7.98	-0.05	-1.53	-0.11	-3.95	Tg C yr^{-1}
	Crop	1.25	6.25	0.00	-0.01	-0.59	-0.05	6.85	Tg C yr^{-1}
	Wetland	0.01	0.00	0.00	0.00	0.00	-0.01	0.00	Tg C yr^{-1}
	Settlement	0.20	0.29	0.06	0.00	0.00	-0.03	0.52	Tg C yr^{-1}
	other	0.78	0.13	0.00	-0.21	-0.01	0.00	0.69	Tg C yr^{-1}
	Total gain	7.96	6.65	-8.35	-0.30	-2.54	-0.40	3.02	Tg C yr^{-1}
Land-use change 2005	Total + GHG	-17.43	-5.34	8.75	0.69	3.60	0.78	-8.96	Tg C
Land-use 2005		-118.91	7.55	1.79	1.04	0.14	0.00	-108.39	Tg C

Table 1: Summary of the national reports on land-use change and changes in carbon stocks by land use. The top part of the table lists changes in land-area in year 2005. The bottom part lists changes in carbon stocks in soils (+3.02 Tg C yr^{-1}). The bottom lines list the net removals from the atmosphere by land-use change (-8.9 Tg C yr^{-1}) and land use (-108.39 Tg C yr^{-1}). The areas listed by UNFCCC need further investigations.

3. Forests and Farms

Robust findings:

There is a large year-to-year variation in the net carbon balance mainly of farmland sites which is driven by climate variation and land management.

Forest are the main carbon sink of continental Europe despite timber extraction and management (195 Tg C yr^{-1}) with 50% of this sink being located in European Russia.

Grasslands sequester about half of the amount as forests (90 Tg C yr^{-1}). In fact, the rate of sequestration of carbon into soil per unit land area is larger in grasslands than in forests (60 vs 20 g C km^{-2} yr^{-1}).

Croplands are carbon sources (-10 Tg C yr^{-1}) but croplands have the potential to be managed as a carbon sinks. Increased carbon uptake of crops in spring are balanced by greater emissions in autumn.

Key questions:

How do we manage European forest and farmland to increase the soil-carbon store?

What happens with all the carbon following stand replacement?

How do we devise a full greenhouse-gas accounting system including the use of products?

How to verify the areas and effects of land-use change as reported by UNFCCC?

4. Peatland

4. Peatlands

Natural peatlands are a typical boreal and arctic landscape (**Fig. IV.29**). They are a net sink for carbon dioxide but emit methane, CH_4, when the peat is water-saturated. Peatlands can give off carbon dioxide, CO_2, if the surface dries out, allowing oxygen to reach the peat, and aerobic respiration to take place. Typically, the surface of a peat bog will switch to aerobic respiration in early summer. Unmanaged peatlands are generally close to being carbon-neutral with the CO_2 and CH_4 emitted being balanced by the CO_2 accumulated in new peat. In the far north, the length of the snow-free period is also an important factor, as although respiration may continue under the snow cover, photosynthesis is only possible when the surface is exposed to sunlight.

Traditionally, peatlands have been used as a source of energy (**Fig. IV.30**). In the maritime, temperate European zone, broadly stretching from Ireland through to Germany, relatively large areas of peat have been drained for agriculture. When this occurs the peat decomposes, emitting CO_2. Although peatlands cover only 3% of the land surface in this zone, CarboEurope-IP scientists estimate that the CO_2 source from converted peatland roughly equals a quarter of the carbon sink from European forests. In addition, peatlands used for agriculture are often hotspots for N_2O emissions as a consequence of fertilizer application.

Restoration of some peatlands by flooding is taking place in response to the need to maintain biodiversity and manage floods (**Fig. IV.31**), but this increases the methane (CH_4) emission. Because CH_4 is a more potent greenhouse gas than CO_2, estimating the net impact of peatland restoration on global warming is not straightforward. In nutrient-poor peat bogs restoration has led to net savings of greenhouse gases in all studies; but restoration of nutrient-rich fen peatlands, bears some risk of increasing net greenhouse gas emissions, in particular when they remain flooded over summer. However, for CO_2 and other trace gases, so far there are hardly any annual or longer measurements available.

CarboEurope-IP is making new measurements of CO_2 and CH_4 fluxes over various fen peatlands to produce the first multi-year balances of greenhouse gases and carbon at fens. Results from a fen nature reserve restored ten years ago show that restoration can bring benefits for the climate: although CH_4 emissions from the saturated land and water surfaces were high compared to the relatively dry land on the ridges, overall, the area has become a net sink of carbon and greenhouse gases. Small landscape elements, such as peatlands, can have a large impact on the overall carbon and greenhouse gas balance, but are easily overlooked and are not yet captured by models. The importance of peatlands in the regional hydrological balance goes far beyond the greenhouse effect.

Fig. IV.29: Peatland in Siberia. (Photo: E.-D. Schulze)

Fig. IV.30: The use of peat as an energy source: The drying of peat-bricks for burning, Ireland. (Photo: A. Börner)
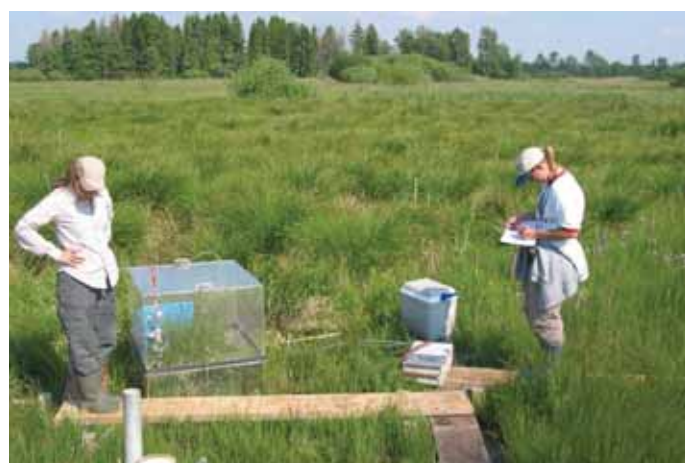
Fig. IV.31: Measurements of net ecosystem exchange (NEE) by transparent chambers in a restored fen peatland in South Germany. The campaigns comprise frequent repeated measurements over a day, giving the response of NEE to changing light and temperature. (Photo: A. Freibauer)

4. Peatland

European peatlands

CarboEurope-IP scientists are using "eddy covariance" to measure CO_2 and CH_4 (**see Page 32**) to capture the "breathing" of fens.

For the first time measurements will allow emissions to be linked directly to the physiological response of the vegetation as it responds to the environment.

CarboEurope-IP initiated a European synthesis of all available measurement data from peatlands in Europe. European peatlands hold 42 Pg of carbon in the form of peat and are therefore a considerable component in the European carbon reserve. European peatlands annually emit 20 to 30 Tg carbon (**Fig. IV.32a,b**). If CH_4 and N_2O emissions are included, the net greenhouse gas source increases to 50 Tg carbon equivalents.

The depth to the water table is the most critical environmental parameter for the greenhouse gas balance of peatlands, followed by temperature and vegetation type. Deeply drained peatlands under agricultural use are strong sources of CO_2 while shallow drainage for forestry can maintain a neutral greenhouse gas balance. The CO_2 sink increases linearly with rising mean annual water table. Significant CH_4 emission only occurs when the mean annual water table is within 10 cm of the surface.
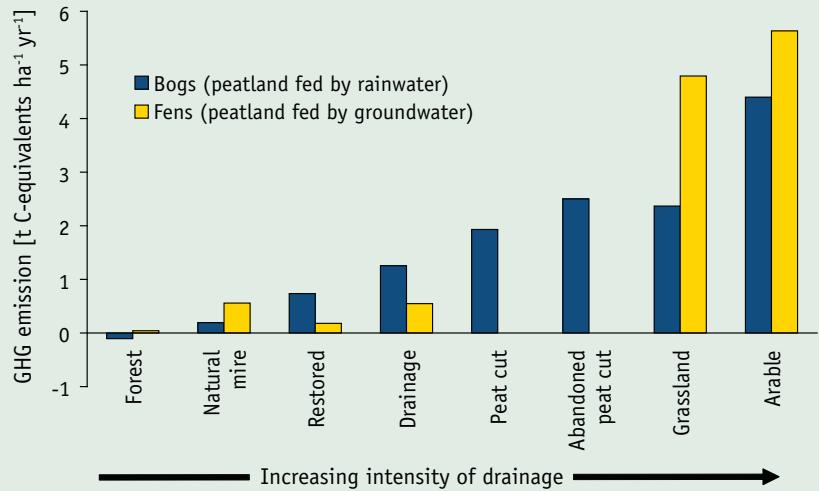
Fig. IV.32a: European average greenhouse gas emissions from peatlands under different land use. Emissions are given in C-equivalents, calculated as the sum of CO_2, CH_4 and N_2O according to their respective global warming potentials (GWP100): 1 kg CH_4 = 21 kg CO_2, 1 kg N_2O = 310 kg CO_2. Emissions increase with the intensity of drainage and land use. The columns show various types of management on peatlands. (Byrne et al., 2004)
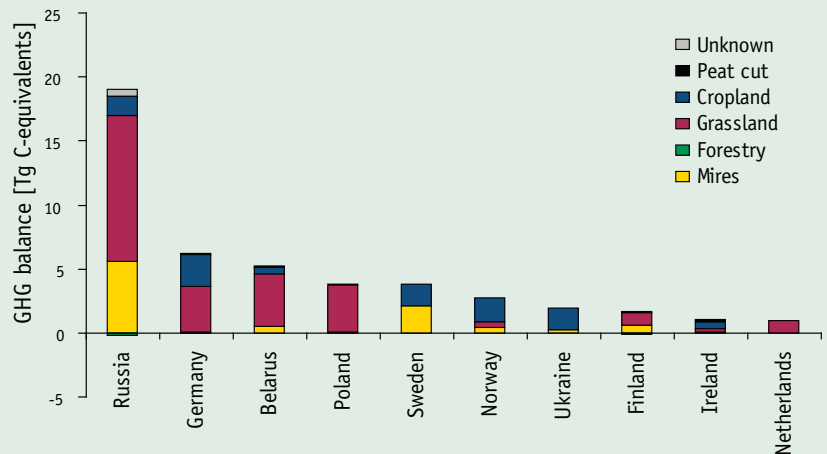
Fig. IV.32b: Conservative estimate for the peatlands greenhouse gas budget of the top ten peat countries by area in Europe. The columns show various types of management on peatlands. (Drösler et al., 2008)

Robust findings:

The relatively small area of peatlands has a relativly large impact on the overall carbon and greenhouse gas balance of Europe.

The emissions from managed peatlands take about 1/3 of the carbon sink of european forests.

Peatland restoration reduces CO_2 emissions but can increase CH_4 emissions; the overall impact of restoration is usually a net saving of greenhouse gases but depends on the nutrient levels of the peat.

Key questions:

What is the annual greenhouse gas balance of peatland and its vulnerability to climate change?

How should we model the physiological behaviour of peatlands to estimate their greenhouse gas balance?

How should we manage peatlands to optimise the competing environmental demands of maintaining biodiversity but decreasing their global warming impact?

5. The Impact of Added Nitrogen and Management

5.1 Effect of nitrogen deposition

The measurements of carbon flux made in CarboEurope-IP all indicate that the forests of Europe are acting as sinks of carbon, but there is a large variation among the different sites. This is to be expected because the measurements are taken in differently managed forests, of different ages and with different soil and climatic conditions. Tree growth merges into a constant growth rate with age. However, at any moment the rate of carbon uptake at a particular site will depend on the age composition and density of the stand. Forest management also influences growth rates by controlling stand density, and management practices have been changing over recent decades. Additional factors that might be influencing forest growth rate are increased temperature and carbon dioxide concentration, or nitrogen deposition from the atmosphere.
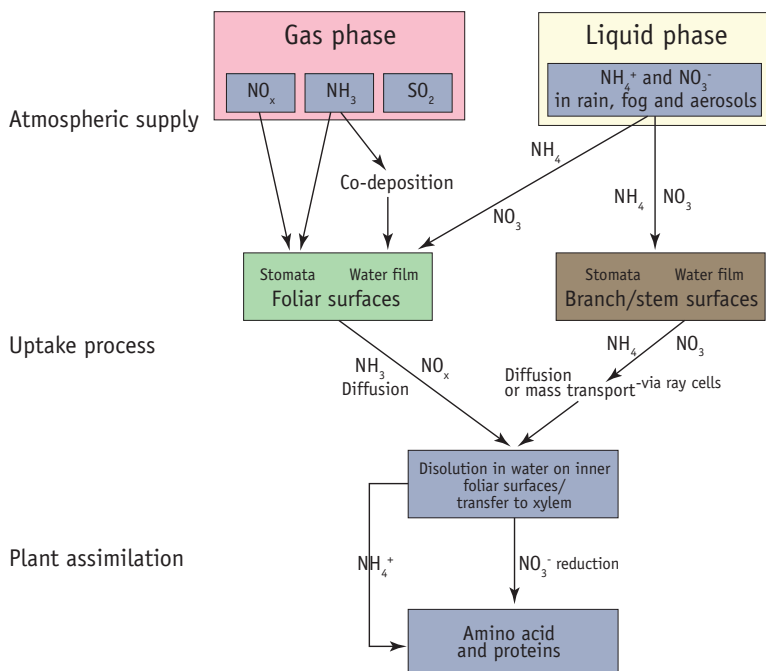
Fig. IV.33: Major pathways for the uptake of gaseous and liqid nitrogenous compounds into the canopy from the atmosphere. (Harrison et al., 2000)

The apparent variability in the observations has been unravelled by a CarboEurope-IP study which removed the effects of stand age by considering the whole forest management cycle. The results showed that nitrogen deposition was the major factor controlling the size of the carbon sink. Atmospheric nitrogen pollution occurs when gases such as NO_x and NH_3 are created during combustion of fossil fuel and the spreading of fertilizer and liquid manure from animal farming. Nitrogen oxides and aerosols return to earth largely as "wet deposition" in rain drops. Gases and small particles can also be taken up by plants as "dry deposition" (**Fig. IV.33**). Most forests are growing on nitrogen deficient soil and this deposition therefore acts as a fertilizer, increasing tree growth. CarboEurope-IP modelling studies have shown that nitrogen deposition and atmospheric CO_2 increase should have a strong synergistic effect on carbon uptake. The synergy is particularly strong when high nitrogen deposition and recently-planted forest occur together.

Federico Magnani of the University of Bologna led a research group which analysed the data from sets of different aged stands of the same species growing in the same forest. It was possible to create 20 age-sequences of forest rotation cycles. Calculations then gave the carbon which would be accumulated over the whole forest rotation and its components of photosynthesis and respiration. This accumulated carbon was compared with the average annual temperature and the rate of nitrogen deposition known from another study. Both photosynthesis and respiration were strongly correlated with average annual
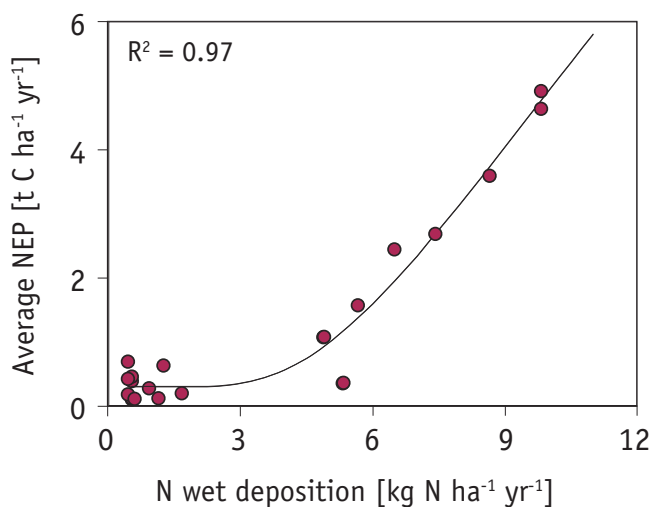
Fig. IV.34: Environmental control of the average carbon exchange of forest ecosystems over an entire rotation period. Average NEP is strongly related to nitrogen deposition. (Magnani et al., 2007)

temperature, but the net sum of these terms was only weakly dependent on temperature. The result was the confirmation of a strong relationship between the net build up of carbon and the rate of nitrogen deposition (**Fig. IV.34**). Federico Magnani said, 'The results from this research show that we are actually controlling the carbon balance of our forests by the inadvertent addition of nitrogen fertilizer. We believe that forests respond to temperature largely because microbial activity increases and

the soil organic matter decomposes more rapidly. This releases more nutrients which are needed for tree growth. By adding extra nitrogen through fertilizer or air pollution we throw a system which was previously in equilibrium out of balance and it responds by greater growth, increasing the amount of carbon stored in the wood and soil.' However, the magnitude of the effect is still under discussion.

These findings are supported by observations and experiments of nitrogen deposition into European forests performed in other EU projects (C-NTER, NitroEurope) and data from the ICP forest monitoring network (International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests).

Taking these factors into account, Magnani (and his group) conclude that around 200 kg of carbon can be sequestered per kg of nitrogen deposition. In contrast, long term manipulation experiments led by de Vries, showed that only 30-70 kg of carbon was sequestered per kg nitrogen (20-40 kg in aboveground biomass and 10-30 kg in soils). A critical comparison of ecosystem manipulation and observational studies could provide further insights into the key factors controlling carbon-nitrogen relations in forest ecosystems.

5.2 Effects of forest management

Most European forests are managed for timber production with the wood being harvested and removed. The type and intensity of forest management varies, depending on economic factors and the type and amount of timber being produced. But how should they be managed to maximise their carbon uptake and provide a long term store of carbon in the biomass and soil? Answering this question needs new thinking and new science. CarboEurope-IP has compared the carbon stored by European beech forests under different management systems: an age-class forest with even-aged stands, a mixed-age forest in which single trees are selectively cut (selection system) and an unmanaged forest (**Fig. IV.35**). The largest differences were found in tree biomass, with the unmanaged forest holding the highest biomass stock of carbon. The soil in the unmanaged forest also contained more carbon, although it is not clear if this difference is caused by the absence of timber extraction, by differences in historical management, or by small differences in soil properties.
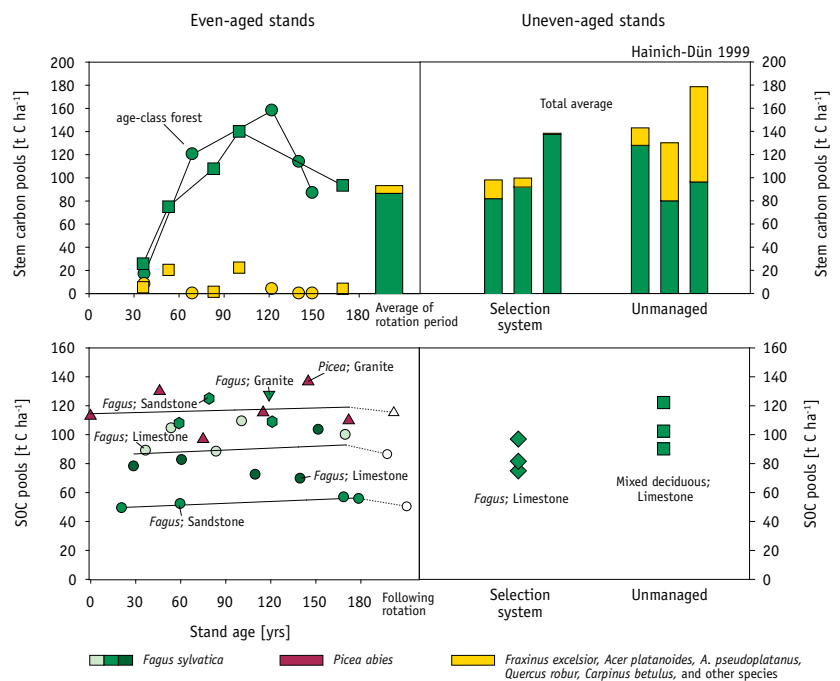
Fig. IV.35: Carbon pools in stem biomass of mixed beech forests on limestone (above) and in the mineral soil (SOC: soil organic carbon) of mixed/pure beech and spruce forests on different bedrock (below) as a function of stand age and silvicultural system. Dotted lines at the end of the SOC-age-sequences show the decrease of the SOC pools after harvest at the beginning of the following rotation.
(Mund and Schulze, 2005)

Robust findings:

When excluding the effects of forest age, nitrogen deposition from air pollution is the major factor controlling the forest carbon sink. Up to 200 kg of carbon may be sequested per kg of deposited nitrogen.

Forest management of thinning affects mainly the standing biomass.

Key questions:

How should forest be managed to provide a long term store of carbon in soils under changing environmental consitions?

Is N-deposition a link between fossil fuel emissions, land-use and forest growth?

6. Climate extremes

In 2003 Southern and Central Europe suffered its worse heatwave in living memory. A combination of record breaking temperatures and low rainfall led to a large number of human deaths from heat stress, as well as to a failure of summer crops and forest fires. The impact of the high temperatures and lack of rainfall caused major changes to the vegetation, and therefore the carbon cycle, across Europe.

When CarboEurope-IP scientists analysed the carbon balance in 2003 they found that the extreme summer heat and lack of rainfall had resulted in the amount of carbon absorbed in plant growth being 30% less than that in normal years. The plants reacted to lack of water more rapidly than soil microbes, and photosynthesis was reduced earlier than respiration. The net result was that for 2003 the continent's land surface became a source of CO_2. Overall, the dry summer removed the equivalent of five years of carbon assimilation. Grain yields reached a 40-year minimum in 2003 (**Fig. IV.36**).

CO_2 enters the leaves of plants through the same small pores (stomata) in their leaves through which water vapour evaporates. This means that during a drought when plants restrict their water use, they also take in less CO_2. This lower absorption of carbon reduces the supply of fresh sugars needed for the chemical processes which emit CO_2 as sugar is used to keep the plant alive (plant respiration). When photosynthesis shuts down through lack of water there is less CO_2 emitted. In the dry soil, despite the high temperatures, there is relatively little microbial action producing CO_2 by the breakdown of organic material. Put simply, biological processes cannot function without water, and during drought the whole ecosystem shuts down. Trees desiccated and turned brown in Southern France in summer and not in the autumn of 2003 (**Fig. IV.37**).

Extreme events are not only important in themselves they also give scientists a rare opportunity to test the robustness of their models by comparing their predictions with data collected in new conditions, outside the ones for which the models were derived. Phillipe Ciais, of the Laboratoire des Sciences du Climat et de l'Environnement, said, 'Our model predictions compared well with the data collected in 2003 at the CarboEurope-IP sites. This gave us the confidence to apply our carbon balance models to predict plant growth and crop yield over the whole continent of Europe. The results surprised us, and ring a warning bell for the future. Extreme drought is likely to have a bigger impact on the carbon balance of Europe than we had previously thought.'

Worryingly, the conditions experienced in 2003, are likely to become normal summer conditions for plants in 50 years time. Recent regional climate studies indicate a higher likelihood of such heatwaves in the future, with droughts impacting regions where currently they are infrequent.
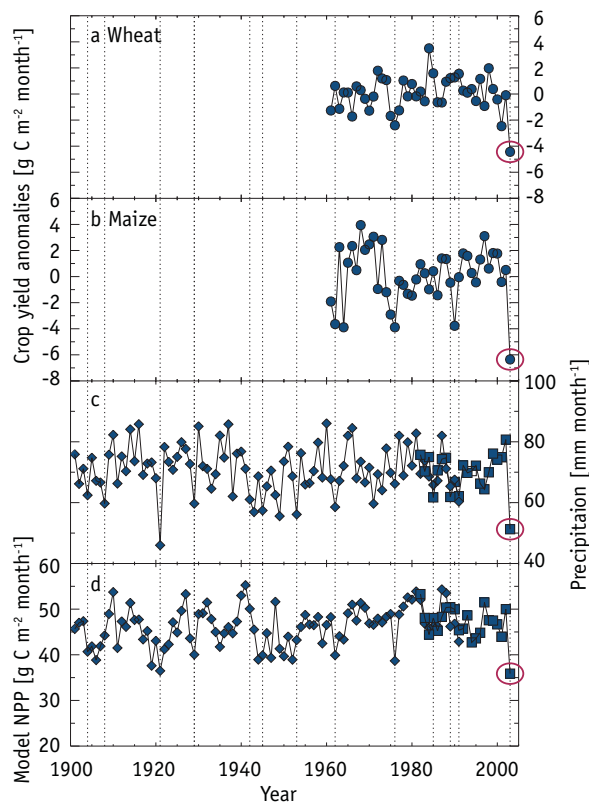
Fig. IV.36: Observed crop yield and modelled crop net primary production (NPP) changes in response to climate variability over France and Italy during the past 100 years. a) Winter wheat yields. The trace shows area-weighted national yield records after a linear trend has been removed from the data to subtract the effects of improved agriculture and reveal the climate-induced variability. b) Same for maize. c) Annual precipitation over the same domain. d) Model-simulated NPP obtained by averaging all cropland grid points in France and Italy. Dashed vertical lines indicate the driest years of the past 100 years, the red circles indicate the dry year of 2003. (Ciais et al., 2005)

Fig. IV.37: Desiccated trees with brown leaves in Southern France in the summer (not autumn) of 2003. (Photo: P. Ciais)

6. Extreme Events

Impact of extremes

The first major impacts of climate change will occur through extreme events rather than through changes in average conditions. For example, although the forests across Europe are vulnerable to lower average summer rainfall, it will be the extremes – droughts and winds that will do most damage – irreversibly destroying eco-systems, or replacing one type with another. Often when wild-fire destroys a forest (**Fig. IV.38**) it is replaced by a different type of forest or by bush-type savannah. In-creases of insect outbreaks (**Fig. IV.39**), as triggered by increasing temperature and drought, may be just as effective in destroying the forest as fire, and the in-creasing frequency of extremes of wind have devastated European forests through windthrows (**Fig. IV.40**). Dur-ing the last two centuries storms were responsible for 53%, fire caused 16% and insect outbreaks another 16% of total damage. An increase of droughts is expected to increase the damage by fires and by insects in the future.

The effects of drought one year are mainly felt the fol-lowing year, through tree damage, reduced leaf growth, and changes in the carbon pools such as the timing and amount of leaf fall. Combinations of two sequential drought years, or a dry summer being followed by a dry winter, are especially dangerous. If the winter rainfall following a drought is not sufficient to refill the soil moisture store, trees may not be able to access enough water to survive the second summer, becoming more vulnerable to forest fire and insect attack, or simply dy-ing through lack of water. In addition, the reserves of sugars packed away by trees during the summer play a critical role in making new leaves the next spring; insuf-ficient sugar in the winter store will weaken the trees ability to survive the coming summer. The full range of the impacts and long term carry-over effects of extreme drought are emerging from studies of wood anatomy. 2003 has taught us a lot, about ecosystems, and the damage and mortality caused by extreme events, but has also shown up big gaps in our knowledge.

CarboEurope-IP studies of 2003 have emphasised that drought has the potential to become one of the most damaging extreme events in nature, not only because of its immediate impact, but also because ecosystems that are currently carbon sinks could turn into carbon sourc-es, creating a positive feedback and amplifying climate change. This prospect makes the ability and readiness to study of extreme events, such as the drought of 2003, an urgent research priority for the future.

Fig. IV.38: Forest fire. This fire occurred in Siberia, where fire is a natural re-orc-curring event. However, recent investigations show, that more than 90% of fores in the boreal region are caused by humans and not by flashes. (Photo: E.-D. Schulze)

Fig. IV.39: Insect damage at the National Park Bayerischer Wald, Germany. All trees up to the horizon are dead. (Photo: T. Stephan)

Around 50% of carbon in temperate forest ecosystems is stored as soil organic carbon in the organic layer (forest floor) and in the mineral soil. The knowing the susceptibility of this carbon to disruption is fundamental to understanding possible negative feedbacks with the climate. Increased frequencies of windthrow may unlock carbon from the soil which ends up as greenhouse gases in the atmosphere. After a windthrow event in the High Tatras in November 2004 (**Fig. IV.40**) carbon was mainly lost from the upper organic layers (**Fig. IV.41**). Soil carbon stocks (organic layer and upper mineral soil) decreased to a minimum in the cleared windthrow but even increased at the un-cleared windthrow site.

Fig. IV.40: In November 2004, a storm with wind speeds up to 180 km/h destroyed a forest strip of 50 km length and up to 5 km wide in the Tatras National Park, Slovakia. (Photo: E.-D. Schulze)
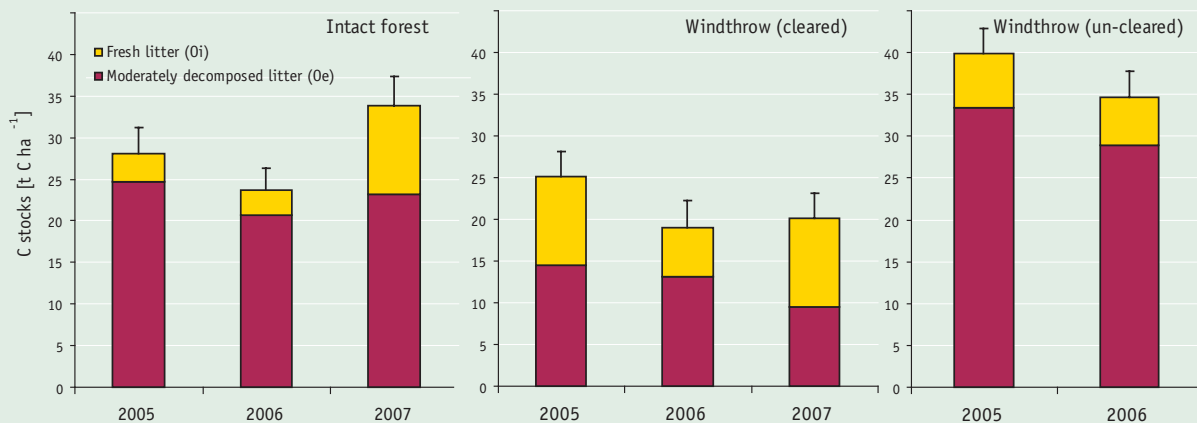
Fig. IV.41: Soil carbon was lost from the organic layers (Oi and Oe) at the cleared windthrow site and at the un-cleared windthrow left for natural succession. (Don et al., unpublished)

Robust findings:

In the drought of 2003 the continent's land surface became a source of CO_2. 1 year of drought was equivalent to 5 years of carbon assimilation.

The effects of drought one year may be felt the following year, through changes in the plant physiology and ecosytem nutrient stores.

Model predictions compared well with the data collected in the extreme conditions of 2003.

Key questions:

What are the carry-over effects of extreme drought and storm?

What are the feedbacks with climate and the carbon cycle that may result from extreme drought and storm?

Where are the tipping points that will cause irreversible ecosystem change to result from extreme conditions?

What are additional climate change agents?

The integration of the site-specific process information gained in CarboEurope-IP for the estimation of the continental-wide carbon balance of Europe necessitates the use of ecosystem models. In CarboEurope a spectrum of modeling approaches is used: On one end of the spectrum are diagnostic models which are calibrated at local field sites, and which use satellite data (FPAR), vegetation distribution and meteorological data for up-scaling to the continent based. These include an artificial neural network modeling approach (NETWORK-ANN), a canopy flux/growth model (PIXGRO) and a semi- empirical radiation-use efficiency based model (MOD17+). On the other end of the model spectrum are fully prognostic process-based biogeochemical models which attempt to compute the cycling of carbon through ecosystems given the prevailing vegetation distribution, soil properties, land use and climate conditions (models: ORCHIDEE, LPJmL, Biome-BGC, JULES) (Vetter et al., 2008). All models have been extensively evaluated at the individual measurement sites (**Fig. IV.25**).

Using a common continental "Eurogrid" with resolution 0.25° latitude by 0.25° longitude, the models were run over the historical period 1958-2005. As an example, **Figure IV.42a** shows computed maps of carbon sinks and sources during the four seasons for the European continent. It is clear that the seasonal cycle is dominated in the northern part of the European conti-

nent by the temperature, with maximum uptake during the summer months. On the other hand, in the Mediterranean region the carbon balance is governed by the availability of moisture, leading to maximum uptake in spring. During the growing season, European ecosystems in the EU-25 region sequester almost 400 Tg carbon, of which a large fraction is released again during the dormant vegetation season.

The spatial pattern of the European ecosystem carbon sink as calculated by the CarboEurope-IP biogeochemical models is shown in **Fig. IV.42b**. The continental sink pattern is dominated by uptake in the forested areas of the Alps, Scandinavia, Eastern Europe and European Russia. These simulations take into account the changing climate and the increasing atmospheric CO_2 concentration, but do not yet include the history of land-use change and management. The calculated sink strength (EU-25: 80 ± 25 Tg C yr^{-1}) is therefore an underestimate.

The calculated imprint of the drought and heat event of the summer of 2003 is shown in **Fig. IV.42c**, which can be directly compared to the decadal average summer fluxmap shown in **Fig. IV.42a**. The widespread reduction of carbon uptake over large parts of southern, western and central Europe is clearly visible, effectively reducing the June to August CO_2 uptake over the EU-25 region by 156 Tg carbon.
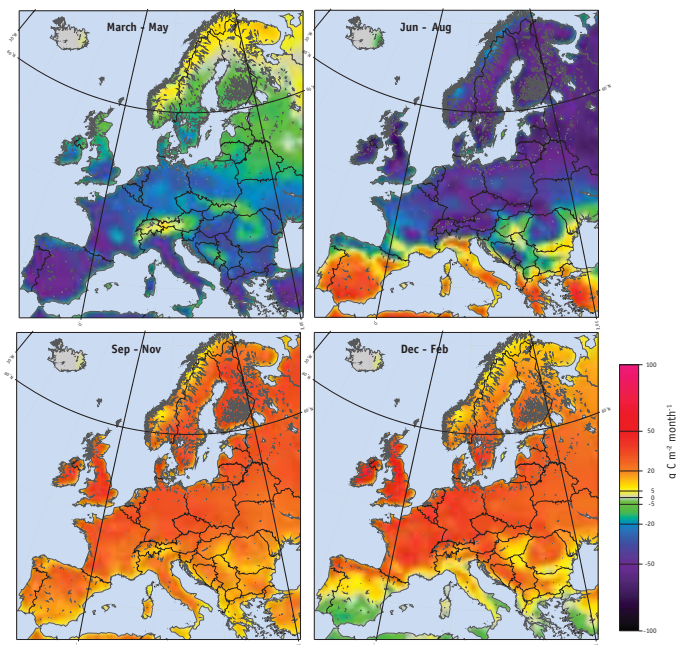
Fig. IV.42a: Seasonal cycle of carbon uptake and release by European ecosystems as computed by the CarboEurope-IP biogeochemical models (multimodel average). Each panel shows the three-month seasonally averaged net flux between the atmosphere and the ecosystems. Negative values (green and blue colours} indicate uptake, positive values (yellow and red colours) a release of CO_2. (Data: Vetter et al., 2008; Figure: M. Heimann)
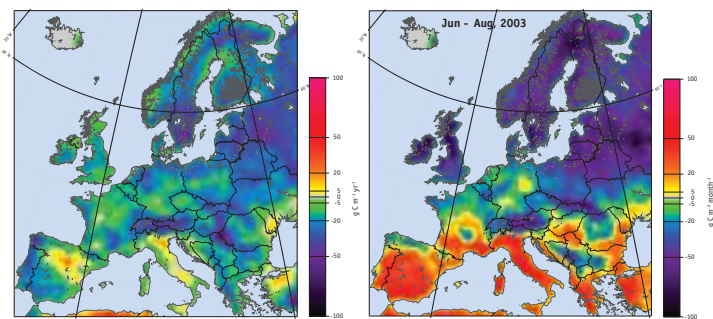
Fig. IV.42b: Decadal average (1996-2005) carbon uptake by European ecosystems calculated by the CarboEurope-IP biogeochemical models (multimodel average). Negative values (green and blue colours} indicate uptake, positive values (yellow and red colours) a release of CO_2. This map can directly be compared with the mean summer carbon flux field depicted in Figure IV.42a (Jun-Aug panel). (Data: Vetter et al., 2008; Figure: M. Heimann)

Fig. IV.42c: Carbon flux in the summer (June-August) of 2003 during the large drought and heat wave in Europe as simulated by the CarboEurope-IP biogeochemical models (multimodel average). This map can directly be compared with the mean summer carbon flux field depicted in Figure IV.42a (Jun-Aug panel). (Data: Vetter et al., 2008; Figure: M. Heimann)

7.2 Regional carbon budgets

The typical European landscape comprises a mosaic of land covers each with its own individual carbon balance. CarboEurope-IP is putting a major effort into sampling the fluxes of these different land covers using observation sites on the ground. These "flux tower" sites (**see Page 32**) give measurements at a scale of a few hundred metres to a few kilometres. At the other end of the spectrum, continental flux is estimated using the inverse modelling technique (**see Page 51**), which combines meteorological models with concentration measurements, at a scale of thousands of kilometres. There is an obvious gap between the scales of these two techniques, that currently blocks progress in understanding how the biosphere interacts with the overlying atmosphere. Filling the gap is important because it covers the regional to national scale, the scale at which community action can be taken: progress can be monitored, and the landscape managed to enhance carbon uptake, mitigating the effect of carbon emissions from burning fossil fuel. Having a method to measure the land surface carbon balance at this scale is an essential complement to the measurement techniques being developed by CarboEurope-IP in the Rhine valley. There, carbon dioxide emission from burning fossil fuel is being monitored at the regional scale using carbon monoxide as a surrogate gas (**see Page 54**).

The techniques of regional scale carbon estimation are being developed using data collected during three intensive, four to six-week measurement campaigns, one in 2005 and one each in the spring and autumn of 2007. The experiment was held in southwest France, in an area roughly 250 x 150 km, bounded to the west by the Atlantic coast (**Fig. IV.43**). This is a rural area with Les Landes forest in the west, and "mixed agriculture farms" and vineyards in the east. There is a low population density and very little emission of CO_2 from burning fossil fuel. A dense network of CO_2 surface fluxes and concentration measurements were combined with extensive measurements through the atmosphere using balloons and aircraft.

Observational campaigns of the size and complexity of the CarboEurope Regional Experiment cannot be achieved by institutions, or even nations, working alone; the observational team was comprised of sixteen teams coming from six nations, a co-ordinated effort only feasible within a large, centrally-funded programme like CarboEurope-IP IP. Han Dolman of VU University, Amsterdam is leading the project. He explained, 'The CarboEurope Regional Experiment was designed to meet the major challenge of quantifying the carbon balance at the missing regional scale. We need to find out how to combine the plot scale data, from flux measurement and carbon inventories, with the observed CO_2 concentration fields, and how these relate to the predictions down-scaled from continental-scale models. The breakthrough will come when we can understand the role of the regional meteorology and land management in controlling the fluxes from land to atmosphere. The high-intensity experimental campaigns provide the essential foundation of real data at the appropriate scale.'

Fig. IV.44: Les Landes Regional Experiment in the south-west region of France: land cover map at 250-m resolution showing the different location of summer and winter agricultural crops. Also shown are the locations of the ground-based observation sites of surface fluxes and flight paths of the aircraft used to sample the fluxes in the atmosphere on 27 May, 2005. (Sarrat et al., 2007)
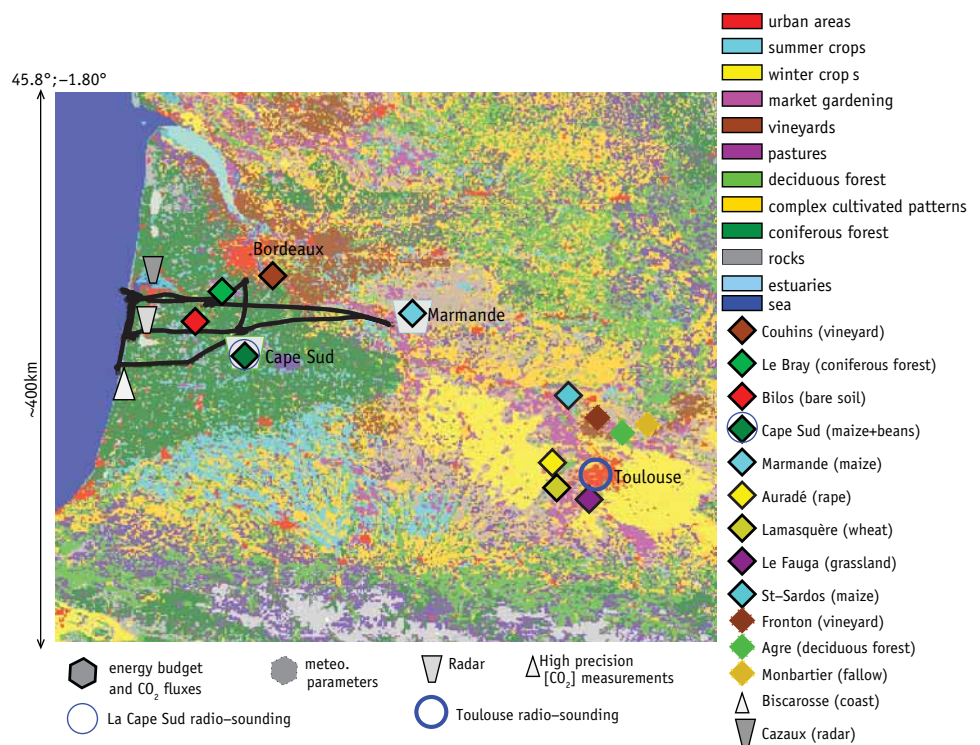
7.2 The CarboEurope Regional Experiment

The objective of the CarboEurope Regional Experiment was to provide the necessary data to ensure that the development of regional carbon balance estimation can proceed on the basis of sound, measurement-based analysis and model development. Although the interpretation of the data is complicated by the sea breeze circulations which result from the proximity of the Atlantic Ocean, it is clear that the variability in the land surface results in a surprisingly high spatial variability of CO_2 (**Fig. IV.44**). This makes a one-dimensional approach to interpreting concentration measurements inappropriate. Only when a three-dimensional approach is used do the observations make sense. Yet, the measurements themselves have shown that interaction of three dimensional air flows with the surface is quite complex above heterogeneous surfaces. The finding that one needs such a full three-dimensional picture of the flux and concentrations at mesoscales, i.e. horizontal scales less than 10 km, has important implications for the use of concentration observations above the land. Their interpretation in large-scale inversion models may only yield meaningful results if this three-dimensional regional context is taken into account.

Atmospheric regional-scale models are in routine use for short term weather forecasting, and they include packages for modelling evaporation and the land surface energy balance. In the project these models were extended to estimating carbon fluxes using a network of concentration measurements as the driving data. Almost certainly the network of air sampling stations will be inadequate over most of Europe, but the dense network used in the CarboEurope-IP experiment is allowing us to find out what density of observations will give an acceptably accurate answer. The technique might then be applied routinely. As Joel Noilhan, of Météo France, Toulouse explains, 'Our ultimate objective is to be issuing the equivalent of weather forecasts for carbon. If we could produce regional maps identifying the sinks and sources we would be able to add these over time to give the accumulated regional carbon balance. Just as we can now give the climatological-averages of temperature and rainfall for any location – so in the future we want to be able to give the climatological-average carbon balance and, most important, how it is changing with time.'

These average fluxes of carbon would not just be for scientific interest - they would be an important tool for verifying progress towards meeting international carbon targets and for guiding policy. Han Dolman said, 'If we are to mitigate CO_2 build up in the atmosphere by land management we need to know where interventions will be most effective. Combining regional networks of accurate CO_2 concentration measurements with regional-scale meteorological models is the way forward.'

The CarboEurope Regional Experiment has created a powerful data set which is providing new insights into how the very mixed landscape of Europe interacts with the atmosphere. Measurements have shown that the CO_2 concentration can be highly variable in space and time, and responds to a complex combination of surface-atmosphere interactions.
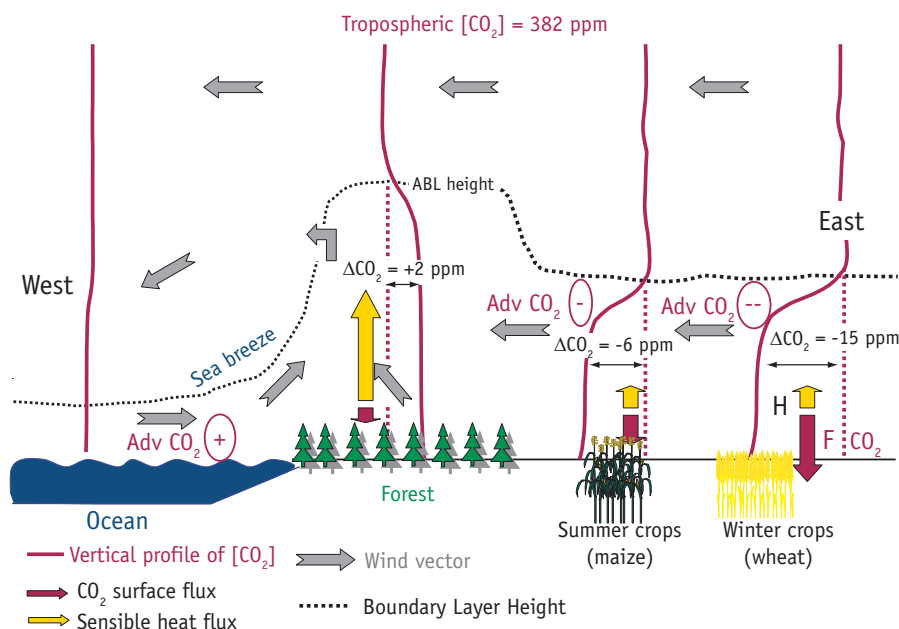
Fig. IV.44: Schematic description of the main physical processes along a vertical west-east cross section on 27 May around 14:00 Universal Time (UTC): the higher Atmospheric Boundary Layer (ABL) above the pine forest is due to a greater sensible heat flux. The CO_2 concentration slightly increases in the ABL due to advection of CO_2 by the sea breeze and because of a small CO_2 surface flux into the surface. The ABL height decreases over the eastern crops where the sensible heat is weak. The CO_2 concentration in the ABL decreases remarkably over the winter crops area characterized by a high assimilation rate. Over the summer crops, despite a relatively small assimilation rate, the CO_2 concentration remains low due to horizontal advection of a CO_2 poor air mass from the southeast. (Sarrat et al., 2007)

Research aircraft

The CarboEurope Regional Experiment made extensive use of research aircraft (**Fig. IV.45**). Light aircraft are ideally suited to the regional scale of measurement and the data they collected gave new insight into how the CO_2 fluxes at the surface are related to the concentration of CO_2 in the air above.

Aircraft were fitted out with new equipment which can make high precision measurements of CO_2 concentration in situ, either along transects or as the aircraft spirals up through the boundary layer. At the same time samples of air were taken for later high-precision analysis of its composition in terms of trace gases such as nitrous oxide (N_2O), methane (CH_4) and carbon monoxide (CO), and their isotopic composition.

Fig. IV.45: SkyArrow: An aircraft operated to measure fluxes between the atmosphere and land surfaces for CarboEurope-IP. (Photo: M. Schumacher)

Stationary measurements from flux towers are continuous in time, but sample only a relatively small area of vegetation. In contrast, when similar instruments are mounted on low flying aircraft, flying through the turbulence, the aircraft can take a "snap-shot" of the fluxes from a large area of upwind vegetation. A first for the CarboEurope Regional Experiment was to fly two aircraft in parallel trajectories one above the other, with the lowest only 50 to 100 metres above the surface. This gives more accurate simulations of the surface flux as account can be taken of the changes in CO_2 concentration with height (**Fig. IV.46**).

This simultaneous measurement of surface fluxes and vertical concentration profiles revealed that the air above any particular patch of vegetation cannot be simply related to the flux at the surface. The measurements of concentration reflect the complex history of air movement over the landscape. The implications of this finding are profound: the regional scale meteorology is complex and the simple one-dimensional models in common use are not appropriate. New thinking and new tools must be developed.
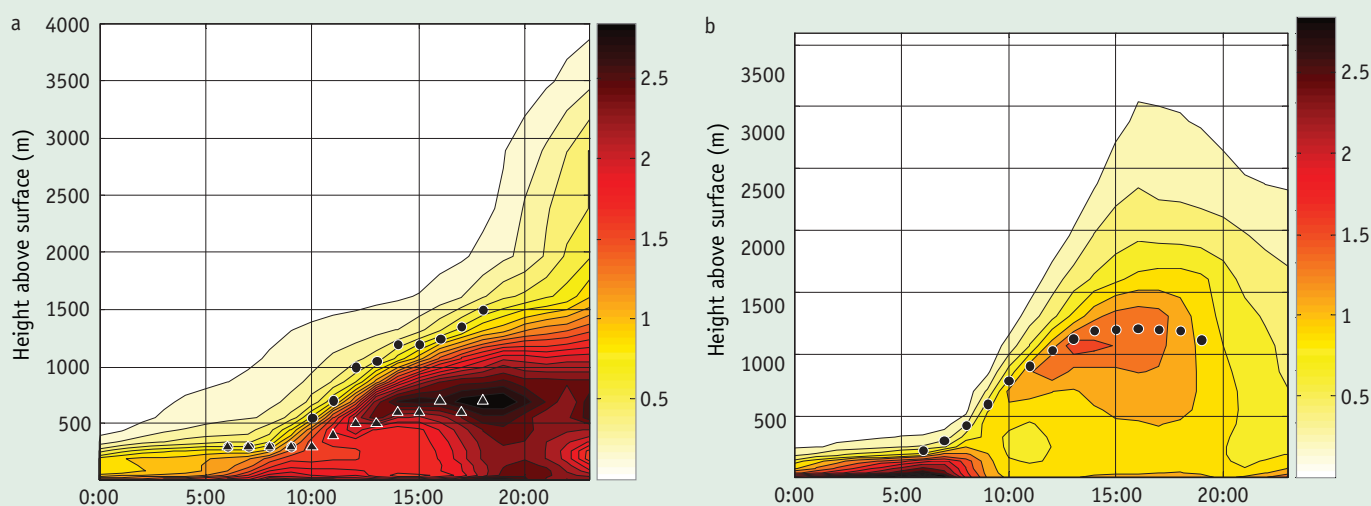
Fig. IV.46: Variations of the representation errors in ppm on 27 May 2005 (a) and 6 June 2005 (b) with time and altitude. The representation errors are averaged over the area north of 44.16oN. The circles in a. indicate the height of the boundary layer in the convergence zone and the triangles the main boundary layer height over the rest of the land area at 27 May, in b. the circles represent the more homogeneous main boundary layer height over the land on 6 June. (Tolk et al., 2008)

7.2 The CarboEurope Regional Experiment

The strong influence of the land surface on the variability of the regional CO_2 budget was dramatically illustrated by data collected during the CarboEurope Regional Experiment in May 2005. Aircraft flying across the experimental domain found a remarkable difference in CO_2 concentration between the air above the pine forest of Les Landes and the air above the agricultural area to the east (**Fig. IV.44**). The difference, of 10 ppm, was consistent with the difference in flux measurements made at the surface. At that time of year, the agricultural crops, particularly the winter-sown cereals, were growing fast and drawing down a large flux of CO_2 as they photosynthesise. In contrast, for the forest photosynthesis and respiration were more closely matched: less CO_2 was drawn down from the atmosphere and the concentration was therefore higher. The difference was amplified by the fact that the well-mixed, convective boundary layer above the crops was relatively shallow and the CO_2 being used by the crops was therefore being drawn from a smaller volume of air than that available to the forest.

A high-resolution three-dimensional meteorological model, with CO_2 flux estimation capability, predicted the observed behaviour well and was able to demonstrate the complex influence of the land surface on the CO_2 budget over the whole region. The model showed how the markedly different fluxes from forest, winter-sown and summer-sown crops, interacted with the local atmospheric circulation such as the sea breeze, caused by differences in the atmospheric convection over the sea, the forest and the agricultural land.

In a critical trial of the inverse modelling approach (**see Page 48**), an atmospheric scalar transport model was used to track the movement of CO_2 across the experimental domain. The best fit of the model to the CO_2 concentration data observed on tall towers (>200m tall TV-towers equipped with CarboEurope-IP measuring systems, **see Page 50**), produced a large correction to be applied to the original model estimates of the fluxes, but the resultant values were closer to the observations over agricultural, forest, and urban areas. Independent validation was done using aircraft-observed concentration differences across the region. The resulting improved regional carbon budget quantification demonstrates the value of the combined top-down/bottom-up methodology and the validity of the inverse modelling approach at the meso scale.

The Regional Experiment was associated with a proposed satellite mission FLEX. The European Space Agency funded field campaign CEFLES2 brought together a multi-national campaign exploiting the synergies between large scale and concomitant airborne and ground measurements performed in coordination with CERES (CarboEurope Regional Experiment Strategy). Synchronized airborne and ground measurements were acquired in April, June and September 2007 to capture different growth stages of a variety of vegetation types. Airborne measurements comprise carbon, heat and water fluxes, fluorescence and hyper-spectral imagery covering the visible, near-, shortwave- and thermal-infrared wavelengths. The campaign aimed for a complete understanding of the link between carbon uptake and fluorescence emission from the scale of single leaves to the region. First results proved that indeed canopy fluorescence is closely correlated with ecosystem carbon uptake and that fluorescence data improve diurnal model predictions of GPP. On the regional scale the fluorescence signal could be correlated to regional airborne measurements of carbon fluxes. Fluorescence maps (**Fig. IV.47**) are currently being refined to extrapolate and test the improvement of regional carbon and water models on the inclusion of fluorescence
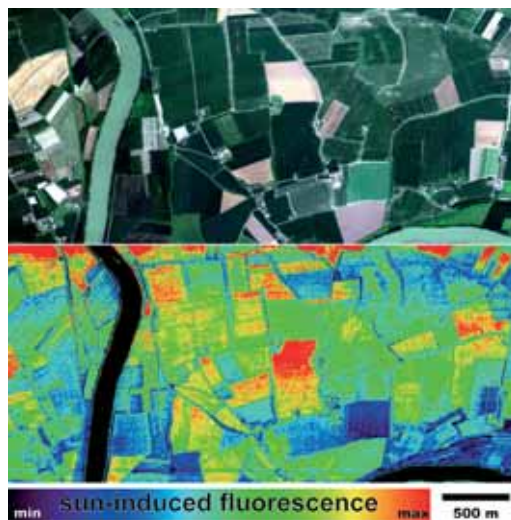
Fig. IV.47: Map of sun-induced fluorescence showing the photosynthetic efficiency of different fields at an agricultural area by Marmande (Southern France). Fluorescence is currently tested to quantify gross primary production. (Source: Forschungszentrum Jülich, ICG-3 and Humboldt-Universität zu Berlin, Geomatics Lab)

Robust findings:

The column of air above any point cannot be simply related to the flux at the surface.

One-dimensional models are not appropriate; three dimensional models are needed to represent complex landscapes.

Regional scale inverse modelling with an atmospheric scalar transport model can reveal how the sources and sinks of carbon are distributed.

Key questions:

How do we relate surface fluxes to atmospheric composition?

What is the minimum monitoring network needed to derive maps of the regional scale carbon balance?

How do we move from research to operations in region scale carbon modelling?

7.3 Atmospheric CO$_2$

The high variability of the European landscape is reflected in an equally spatially variable terrestrial carbon balance, but because the global atmosphere is so well-mixed the effect of different surface fluxes on the atmospheric concentration of CO$_2$ is soon removed. Yet, small systematic differences can be observed: when the wind is blowing from the Atlantic, air in central Europe will typically have CO$_2$ concentrations 2 to 5 ppm greater than air on the west coast (the background level of CO$_2$ is currently about 380 ppm). CarboEurope-IP is measuring this variation in CO$_2$ concentration by making continuous, accurate measurements at about 46 sites across Europe (**Fig. IV.48**). Many of these measurements are made on tall towers (**Fig. IV.49,50**): tall enough (200 to 300 m) to avoid the local effects of small surface heterogeneities, but able to map the change in CO$_2$ concentration as the air moves across the landscape. Inverse modelling (**see Page 51**) can then be used to deduce the most likely field of surface fluxes to have produced this pattern.

9 Tall Tower

24 Aircraft-Flask-Sampling Sites

13 Continuous Sites

Legende

Intensive Aircraft Sounding	Flask Sampling Site	Tall Towers
Non Intensive Aircraft Sound.	Flask Sampling Site (CMDL)	Tall Towers (Regional Project)
Aircraft Sounding	Flask Sampling Site (CSIRO)	Continuous CO$_2$ ^{222}Rn Measurement Site

Map Background
USGS GTOPO30
GISCO Country Borders
0 200 400 600 Kilometers

Fig. IV.48: Atmospheric measurement sites in CarboEurope-IP.

9 Tall Towers

La Muela, ES
Hegyhatsal, HU
Cabauw, NL
Orléans, F
Ochsenkopf, D
Bialystok, PL
Angus/Edinbg., UK
Firenze, I
Norunda, S

25   50   100   150   200   300   400   500   600
(1/1000) * Explained Variance
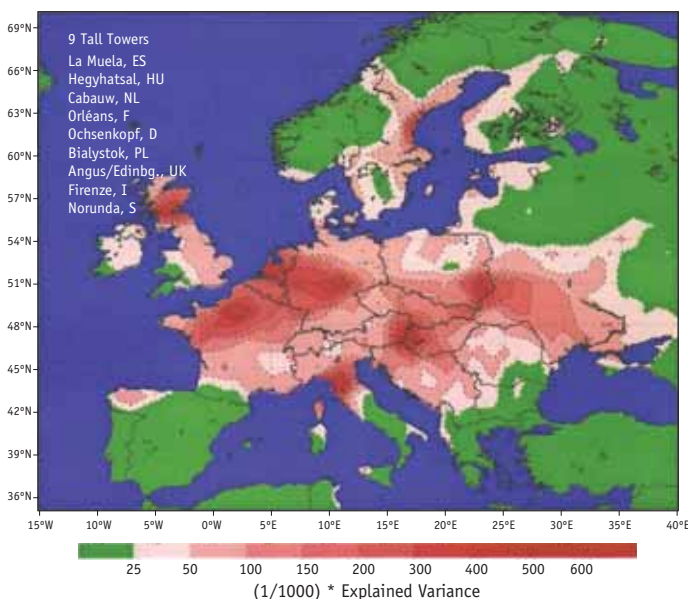
Fig. IV.49: Footprint of the 9 European Tall Towers.

Fig. IV.50: 300m Tall Tower near Bialystok in Eastern Poland, equipped with instruments for continuous measurements of CO$_2$, CH$_4$, CO, N$_2$O, SF$_6$ and O$_2$/ N$_2$ ratio from five heights. (Photo: M. Heimann)

7.3 CO$_2$ Concentration and Fluxes

This inverse modelling technique (**see Box**) has been applied to produce maps of the monthly carbon budget of Europe. All the processes are included: oceanic fluxes, land surface fluxes, fossil fuel burning and wild fires – the maps show the net budget. Two examples shown in the figure illustrate how the carbon budget changes with season (**Fig. IV.51**). In January 2004 the whole continent was a source of CO$_2$, with the carbon balance dominated by respiration as soil microbes continued to break down dead plant material, but low light and short day length inhibited photosynthesis. Fossil fuel burning is also at its greatest at that time of year. In summer the situation is reversed and in June 2004 photosynthesis is dominant over the whole continent. The far northern regions of Scandinavia and Russia have a similar carbon up-take rate to central Europe as the longer day length at high latitudes compensates for the lower levels of solar radiation.

The map in August 2003 is revealing. The drought (**see also Page 42**) has caused the photosynthesis in southern Europe to decrease to the extent that respiration dominates and forest fires add to further emissions of CO$_2$ to the atmosphere.

This inverse modelling methodology is still in its infancy. There are large differences between the estimates of different models and the uncertainty in their calculations of the carbon budget is large. Nevertheless, as CarboEurope-IP measurements challenge these models with real data, they are progressively improving.

CarboEurope-IP scientists see the method moving from the research to the operational level, with the network of concentration and flux measurements becoming routine (**see Page 53**).

As Frédéric Chevallier of the Laboratoire des Sciences du Climat et de l'Environnement, Gif-sur-Yvette said, 'For the future we must integrate the carbon concentration measurements with the flux measurements in a new data system, using satellite data in addition to in situ observations to inform the model about the state of the vegetation and atmosphere. We need to merge all the data available to give the best possible estimate of the carbon balance with the lowest possible uncertainty.'

Inverse modelling: Finding the sources and sinks of carbon

The concentration of CO$_2$ measured at any particular place and time will be the result of the transfer of CO$_2$ into, or out of, the air stream as it has passed over the surface. If the surface is a source, the air will be relatively richer in CO$_2$; if the surface is a sink, the air will be relatively deficient in CO$_2$. This process can be realistically simulated by three-dimensional atmospheric transport models, with the help of weather pattern analyses. Such models therefore establish a link between the pattern of surface CO$_2$ flux to be inferred and the concentrations measured on tall tower, air monitoring stations. From this numerical link, the technique known as 'inverse modelling' explores the space of the plausible flux patterns to best match the measurements. The more measurements of concentration there are, the more accurate will be such a statistical prediction of the flux field which created it.
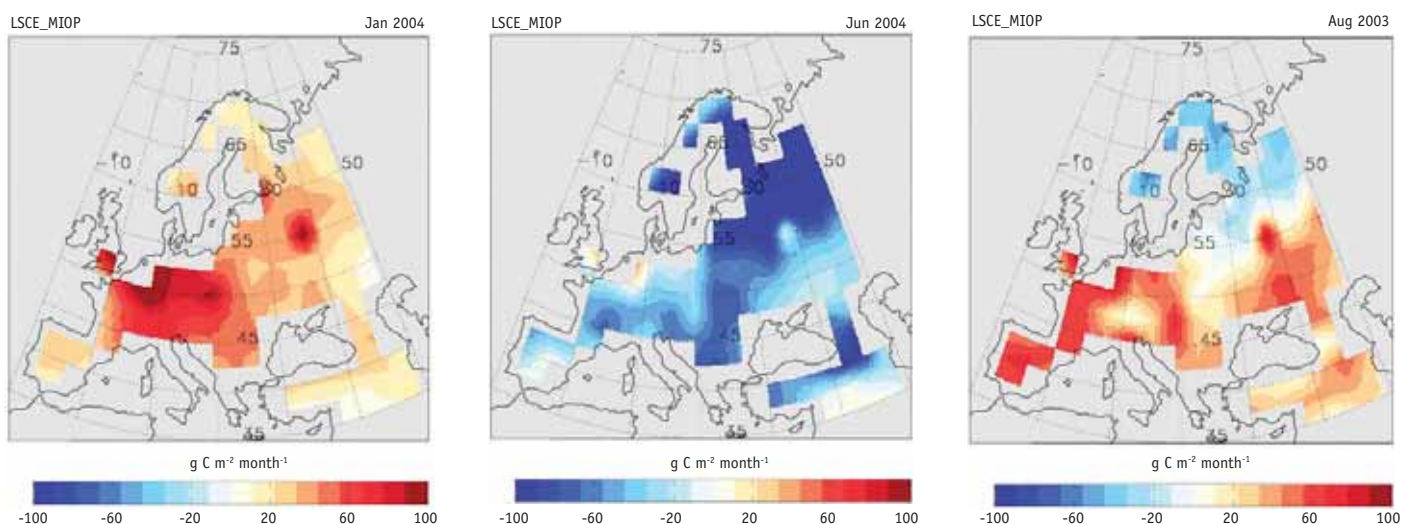
Fig. IV.51: Maps of Europe showing modelled sources and sinks of CO$_2$ as on http://inversions.lsce.ipsl.fr/index.php.
(1) The net carbon flux for the months of January and June 2004. Negative fluxes (blue) indicate up-take of carbon by the surface; positive fluxes (red) indicate emission of carbon. The fluxes are estimated using the inverse modelling method. In January carbon emission dominates; in June the continent is taking in carbon as plants photsynthesise.

(2) The net carbon flux for the month of August 2003. While the north of Europe is blue, indicating photosynthesis is dominating, southern Europe is red, indicating net carbon emission. In the south, photosynthesis has slowed down, because of the drought, and carbon emission from respiration and forest fires is dominant.

An atmospheric signal for changing conditions over Europe

The atmospheric network of CarboEurope-IP monitors the CO$_2$ concentrations at stations along the Atlantic coast, on Atlantic islands, and inland (**Fig. IV.52,53**). The continuous hourly records revealed that for the time period between 1992 and 1999 there was a relatively constant positive West-East difference of atmospheric CO$_2$ across Europe, reflecting the emission of CO$_2$ over the continent (**Fig. IV.54**). However, since about 1999 the difference has been increasing for most inland stations. Obviously something novel is going on. Either, the sink of the land surface has decreased, perhaps due to global warming, or, the emissions over Europe have increased rather than decreased. An alternative explanation is that the circulation patterns of air masses have systematically changed. All three possible causes would be worrying, but more research is needed to fully understand this puzzling observation.

OCEANIC	CONTINENTAL
AZR - Azores	BAL - Baltic Sea (Poland)
IZO - Izana, Teneriffe	BSC - Black Sea Constanta (Rumania)
ICE - Iceland	HH1 - Hegyhatsal (Hungary)
MHD - Mace Head (Ireland)	ORL - Orleans (France)
STM - Ocean Station M (Norway)	PAL - Pallas (France)
	PUY - Puy de Dome (France)
	SCH - Schauinsland (Germany)

Fig. IV.53: Location of key flask monitoring stations

Fig. IV.52: Remote atmospheric station at Mace Head, Ireland. (Photo: M. Ramonet)
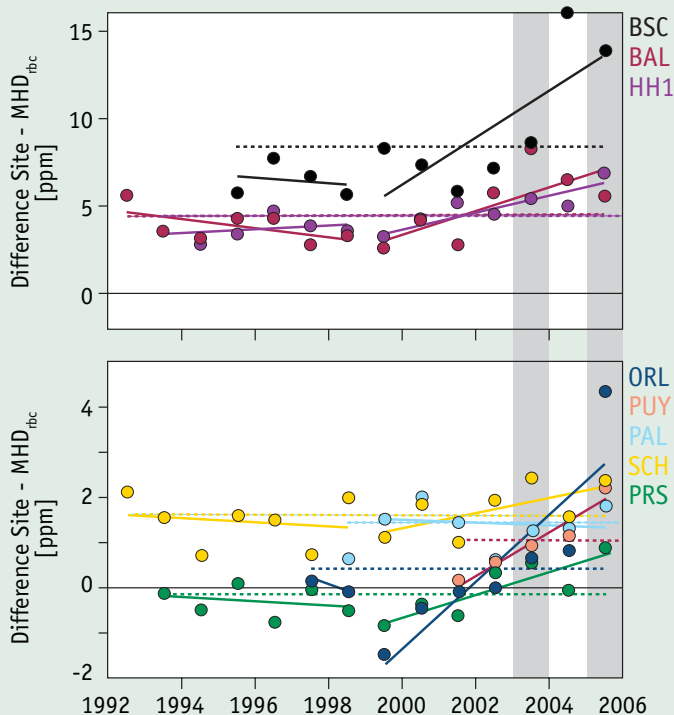
Fig. IV.54: CO$_2$ concentration difference between Mace Head and various continental stations. (Ramonet, unpublished)

ICOS

ICOS, the Integrated Carbon Observing System, is a major EU initiative based on CarboEurope-IP research to establish an operational carbon monitoring network over Europe. ICOS will provide the long-term observations required to assess the effectiveness of carbon sequestration and greenhouse gas reduction activities on levels of atmospheric greenhouse gases. It will also identify sources and sinks of greenhouse gases at the regional and ecosystem level. Monitoring how sinks develop in the future has immediate implications for reduction efforts. More biospheric sinks implies that less severe emission reduction efforts will be required to attain stable levels of CO$_2$.

ICOS is based on the techniques and designs pioneered in CarboEurope-IP with a combination of atmospheric concentration measurements of long-lived greenhouse gases (CO$_2$, CH$_4$, N$_2$O and related isotopic tracers) and measurements of gas, energy and water fluxes from ecosystems, with inventories of carbon and nitrogen stocks and the relevant physical and chemical ecosystem properties. These two types of measurements complement each other because the variations of atmospheric trace gas concentrations are controlled by surface fluxes through atmospheric transport processes.

Atmospheric measurements integrate fluxes over very large regions, while ecosystem measurements represent very small regions. The gap in scale between those two datastreams is bridged using ecosystem models and atmospheric transport models which act as 'intelligent interpolators' for producing the required greenhouse gas sources and sinks distribution.

Although ICOS will be a distributed infrastructure with a multitude of measurement sites, two thematic centres are planned to co-ordinate and standardise the atmospheric and ecological observations (**Fig. IV.55**). A central analytical laboratory will take care of all the necessary analyses (trace gas concentrations and isotope measurements) on flask air samples taken at the various sites. In this way ICOS will implement and maintain a co-ordinated, long-term, high-quality network of atmospheric and ecosystem observations.

Funding is secure for the starting phase but needs to be negotiated with the participating nations thereafter. In any case, ICOS will create a sustainable network that can operate with secured funding for more than 10-20 years, thus assuring the continuity of data that is needed to detect systematic trends and anomalies in the concentrations of the major greenhouse gases.
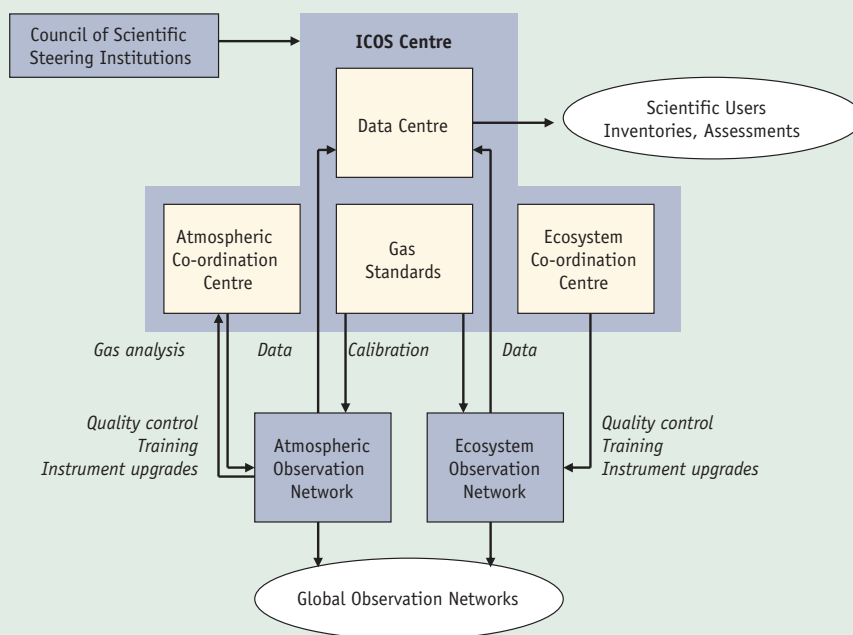
Fig. IV.55: Organization of the ICOS infrastructure, a project originating from CarboEurope-IP research.

Robust findings:

The need for atmospheric measurements is based on the need for verification. There will always be a need for independent monitoring and analysis of the larger scale carbon cycle. This is to (a) verify that reported emissions and claimed sequestration efforts are reflected in the atmospheric total and (b) ensure that there are no surprises in the global carbon cycle that would require policies and reduction targets to be revised.

Key questions:

How do we move the network of concentration and flux measurements from the research to the routine, operational level?

How do we improve the vertical mixing component of transport models in the predicted fields of carbon flux?

How do we merge all the data available to give the best possible estimate of the carbon balance with reasonable uncertainty and spatial resolution?

7.4 Fossil Fuel Emissions

Fossil fuel emissions

Radiocarbon has long been used to date archaeological finds (**see Box**), but a similar technique can also be used to measure the emissions of CO_2 resulting from fossil fuel burning. Because CO_2 generated by fossil fuel burning is free of carbon-14 (radiocarbon or ^{14}C), comparing the high-precision measurements of the background concentration of carbon-14 made high in the atmosphere, with that found near the surface, allows the regional emission of CO_2 from fossil fuel to be detected.

The background level of $^{14}CO_2$ is measured routinely at only two sites in Europe. One, the Jungfraujoch research station, is located high in the Swiss alps, where the air can be taken to represent the unpolluted free atmosphere over Europe. CarboEurope-IP compared measurements from Jungfraujoch with two sets of similar measurements, one made in Heidelberg in the upper Rhine valley in Germany (**Fig. IV.56,57**), typical of a highly populated and polluted region; the other only slightly polluted on the Schauinsland mountain in the Black Forest. The results show that the air at both sites almost always has smaller $^{14}CO_2/CO_2$ ratios than that at the high alpine observatory, because the air becomes diluted with $^{14}CO_2$-free gas released from fossil fuel burning (**Fig. IV.58**). The dilution was found to be eight times greater at the urban site than at the Black Forest site. As expected, the input of CO_2 from fossil fuel burning also varies with the time of year, with the largest difference being found at the urban site in the winter, when electricity and fuel use are greatest.

CarboEurope-IP scientists analysed data from 1986 to 2006 and looked to see how the input of CO_2 generated by fossil fuel burning had changed. Team leader Ingeborg Levin explained 'Radiocarbon measurements are the most direct and accurate method of measuring the impact of fossil fuel CO_2 emissions in the atmosphere, and our precise measurements of carbon-14 dilution would detect any trend in emissions larger than 10% at a site like Heidelberg'. The results showed no significant trend in the generation of CO_2 by fossil fuel burning. Even though Germany has reduced its CO_2 emissions by 18% in this period, the measurements show that the reductions have been made elsewhere, not in Southwest Germany. The regional resolution is important if we intend to share the burden of fossil fuel reductions (**Fig. IV.59**).

Fig. IV.56: Technician preparing $^{14}CO_2$ sample for counting in the Heidelberg Radiocarbon Laboratory. (Photo: B. Kromer)
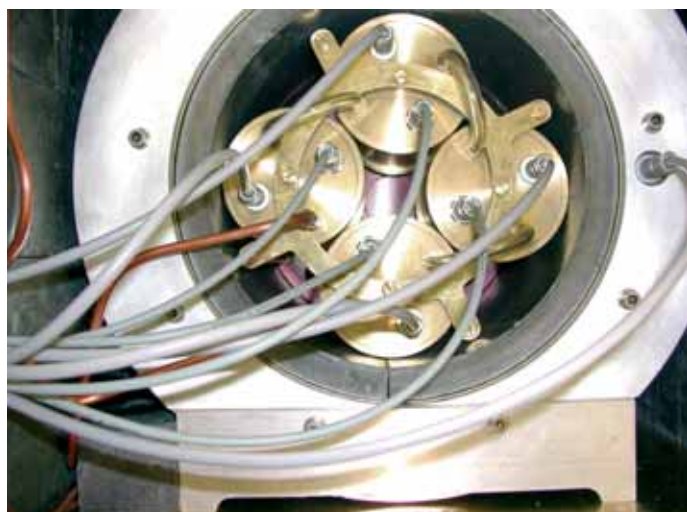
Figure IV.57: $^{14}CO_2$ counting system of the Heidelberg Radiocarbon Laboratory. (Photo: B. Kromer)

Carbon-14

Carbon-14, radiocarbon, or ^{14}C, is the very rare radioactive isotope of the element carbon (the common isotope is carbon-12, or ^{12}C). The two isotopes have the same chemical properties, but the atoms of ^{14}C are heavier. ^{14}C is constantly produced by the action of cosmic rays in the upper atmosphere and combines with oxygen to form a "heavy" carbon dioxide. The ratio of $^{14}CO_2$ to $^{12}CO_2$ in an unpolluted atmosphere is changing slightly, but the rate of production is effectively in equilibrium with the rate of absorption by the oceans and by plants. But ^{14}C is unstable and over thousands of years slowly decays: CO_2 captured today in biological material will have the same ratio of ^{14}C to ^{12}C as found in the atmosphere, but as this ratio slowly declines over time, ancient artefacts made from biological material have a lower ratio. This process, radioactive decay, is used to date finds from archaeological sites. Fossil fuels were originally living organisms, but because they are millions of years old now contain no ^{14}C. Burning fossil fuel therefore releases ^{14}C-free carbon dioxide that dilutes the natural $^{14}CO_2/^{12}CO_2$ ratio in the atmosphere and effectively labels the air by its lack of ^{14}C.

7.4 Fossil Fuel Emissions

Fig. IV.58: Monthly mean $^{14}CO_2/^{12}CO_2$ ratio measurements in Heidelberg and at Schauinsland station in comparison to the continental reference level over Europe as derived from observations at Jungfraujoch (upper panel). Fossil fuel CO_2 component at Schauinsland and Heidelberg as calculated from the respective difference in $^{14}CO_2/^{12}CO_2$ ratios from the reference level (second panel). Note that the fossil fuel CO_2 component shows a strong seasonality in Heidelberg due to changing source influence and variations in atmospheric mixing between summer and winter. The lower two panels show the long-term trends of the annual mean fossil fuel CO_2 levels at Schauinsland and Heidelberg which do not reveal any trend yet, but show inter-annual variations largely caused by varying meteorological conditions. (Levin and Rödenbeck 2008; Levin et al., 2008)
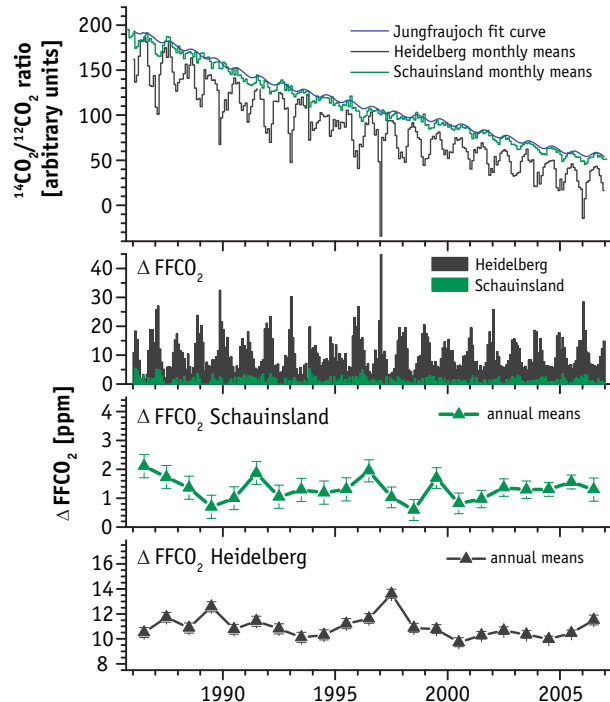
Fig. IV.59: European distribution of the annual fossil fuel CO_2 emissions compiled on spatial grid with 5' latitude by 5' longitude resolution. Logarithmic colorscale with brighter colors indicating higher emission rates. The total emissions over geographical Europe (including Turkey) are 1.6 Pg C/a (for comparison: the contribution by the EU25 countries: 1.06 Pg C/a in 2005). Data compiled by the Institut für Energiewirtschaft und Rationelle Energieanwendung (IER) of the University of Stuttgart. Figure: M. Heimann
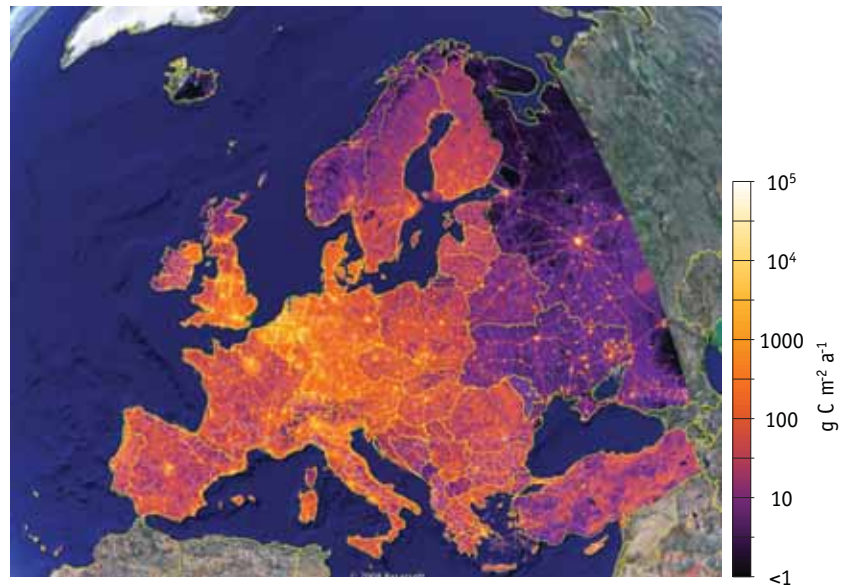
Robust findings:

Monitoring radiocarbon in atmospheric CO_2 is the only quantitative measure of fossil fuel CO_2 in the atmosphere. High-resolution fossil fuel CO_2 records can be derived by concurrent carbon monoxide monitoring as surrogate for the more expensive $^{14}CO_2$ measurements, if properly calibrated.

Key questions:

How can we separate human from natural signals? At the level of terrestrial ecosystems, there is not yet a simple method available to disentangling natural and man-made influences.

Carbon monoxide as a tracer for fossil fuel CO_2

CarboEurope-IP has developed a new method of deriving continuous estimates of the regional carbon dioxide created by burning fossil fuel. The method uses a simple observational approach, combining the accurate, but sparse, network of carbon-14 measurements, with more widely available and less expensive measurements of carbon monoxide concentrations.

Carbon-14 analysis (**see page 54**) currently gives the most direct and accurate estimates of regional CO_2 emission from fossil fuel burning. But these measurements are expensive and slow, and are therefore limited to only a few sites, which provide data only at monthly or, at best, weekly intervals.

Carbon monoxide, CO, is also produced when fossil fuels are burnt, and it may also be possible to deduce the amount of fuel burnt and therefore CO_2 emission from the concentration of CO in the atmosphere. Although CO is relatively easy to measure, unfortunately it is a reactive gas with many sources and sinks. The ratio of CO to CO_2 formed during combustion also depends on the process, for example more CO is produced by petrol engines than by diesels. The ratio of CO to CO_2 is thus highly variable, creating a problem in using the level of CO to accurately estimate fossil fuel CO_2.

Nevertheless, this problem can be avoided by using an observation-based approach whereby a single sample of gas accumulated over a week is analysed in total for $^{14}CO_2$, but the data are then combined with continuous observations of CO.

By making the simple assumption that the average ratio of CO to CO_2 emission from fossil fuel burning is constant over the weekly period, the continuous CO record can be used to give hourly estimates of the CO_2 being emitted from burning fossil fuel. The method was tested during a series of two-week long sampling campaigns held in parallel to the routine $^{14}CO_2$ measurements made in Heidelberg. There was good agreement between the indirect CO-based estimates and those derived directly from ^{14}C analysis.

The ratio of CO to fossil fuel CO_2 varies over the year by about plus or minus 20%, reflecting the change in use of different energy needs, such as domestic heating, electricity generation and transport. Frequent calibration of the ratio is therefore necessary. Interestingly, the ratio measured at Heidelberg has already been observed to change by 20% over the past 5 years. This could be a consequence of the introduction of more stringent European CO emission standards during this period.

Calibration of continuous CO measurements opens up the possibility of creating hourly resolution maps of fossil fuel use for the whole of Europe, based on observations of the atmosphere itself. 'These results demonstrate that we now have the ability to monitor our regional CO_2 emissions', said Annette Freibauer, CarboEurope-IP scientific coordinator. 'This technique allows individual regions to take ownership of their greenhouse gas emissions and monitor their progress in meeting emission reduction targets'.
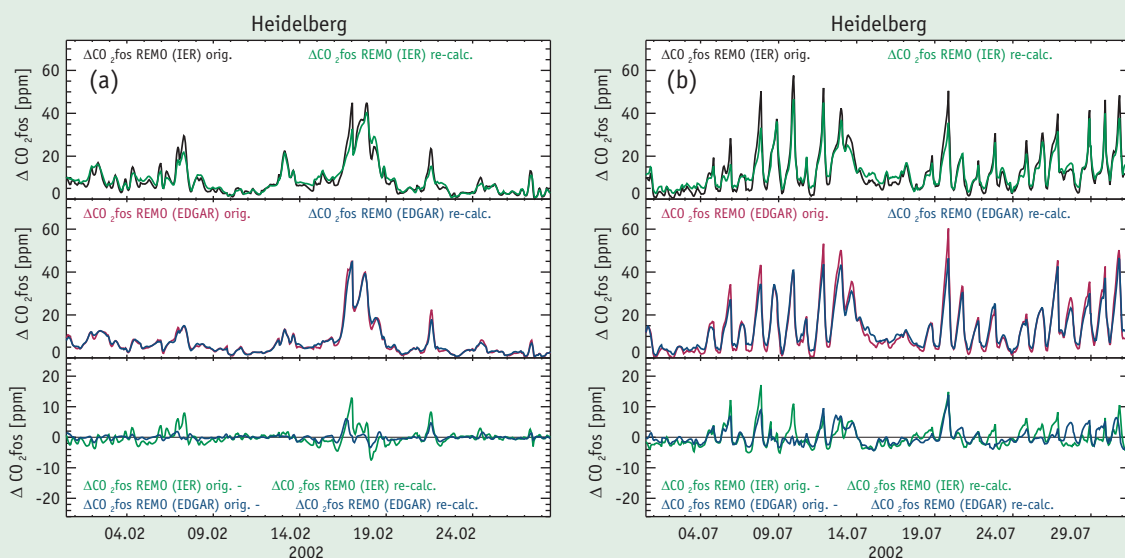
Fig. IV.60: Sensitivity tests with REgeional Model (REMO) of the uncertainty of CO-based fossil fuel-CO_2 estimates: Upper two panels: $\Delta CO_2(foss)$ estimated from "atmospheric" ΔCO records and weekly mean $\Delta CO/\Delta CO_2(foss)$ ratios calculated from original "atmospheric" results and from $CO/\Delta CO_2(foss)$ emissions ratios directly in comparison to original "atmospheric" $\Delta CO_2(foss)$ records, left for a winter and right for a summer month (plotted for IER and EDGAR inventories separately). Lower two panels: respective differences. (Levin and Karstens, 2007)

8. The Carbon Balance of Europe

The baseline was published in Science in 2003 (Janssens et al., 2003), when a review of available knowledge revealed a net carbon sink for CO_2 over Europe of some 205 (top-down predictions) or 135 (bottom-up predictions) Tg C yr^{-1}. The uncertainties in these estimates were large, about 250%. In the most recent estimates the predicted carbon sink has increased to 329 (top-down) and 288 (bottom-up) Tg C yr^{-1} (average: 309 TgCyr^{-1}). However, including the greenhouse warming potential of non-CO_2 greenhouse gases (methane, CH_4, and nitrous oxide, N_2O) as carbon-equivalents reduces the top-down GHG-balance to 140 Tg C-CO_2eq yr^{-1} and the bottom-up balance to 44 Tg C-CO_2eq yr^{-1} (100yr horizon) averaging 92 Tg C-CO_2eq yr^{-1}. The carbon-equivalent emissions of CH_4 and N_2O increased the carbon emissions of fossil fuels by 13%. About 50% of the continental CH_4 and N_2O emissions originate from agriculture, but for the EU-25 the agricultural fraction rises to 62%. About 80% of the continental fossil fuel emissions and about 90% of the EU-25 fossil fuel emissions remain in the atmosphere, to be taken up by the ocean or contribute to global warming. The mitigation potential of the terrestrial vegetation is thus not realised because of the greenhouse gas emissions by intensive agriculture.

These numbers should be regarded as "best estimates", made using all available data and the best models available. As Ivan Janssens from the University of Antwerp said: 'I guess numbers will continue to fluctuate for a couple more years as the analyses become more realistic and complete. For now, we should support our new best numbers.'

A comparative assessment of the main land-use types is best achieved by showing the flow of carbon through these ecosystems (**Fig. IV.61**). For this, we need to compare the carbon input (gross primary productivity: GPP), the respiration of plants (Ra), the biomass growth rates (net primary productivity: NPP), the rates of harvest and other disturbances (fire), the inputs to the soil by litter and manure, and the losses by microbial respiration (heterotrophic respiration: Rh) and organic carbon dissolved in water draining from the soil (DOC). The result of this balance is the net biome productivity (NBP) of the CO_2 carbon-cycle. This NBP appears as changes in the permanent biomass of forests ($NPB_{biomass}$) and as changes in soil carbon ($NBP_{CO2\ soil}$). These changes can either be positive, which would be a carbon sink, or negative, which would indicate a carbon source.

Land-management also leads to emissions of non-CO_2 greenhouse gases. The warming potential of these other gases can be expressed as a CO_2-equivalent, which must then be subtracted from the NBP_{CO2} balance. The resultant balance is termed NBP_{GHG}.

Comparing forests (**Fig. IV.61a**), grasslands (**Fig. IV.61b**) and croplands (**Fig. IV.61c**), it emerges that as a European average, the carbon input (GPP) is about 20% higher in grasslands than
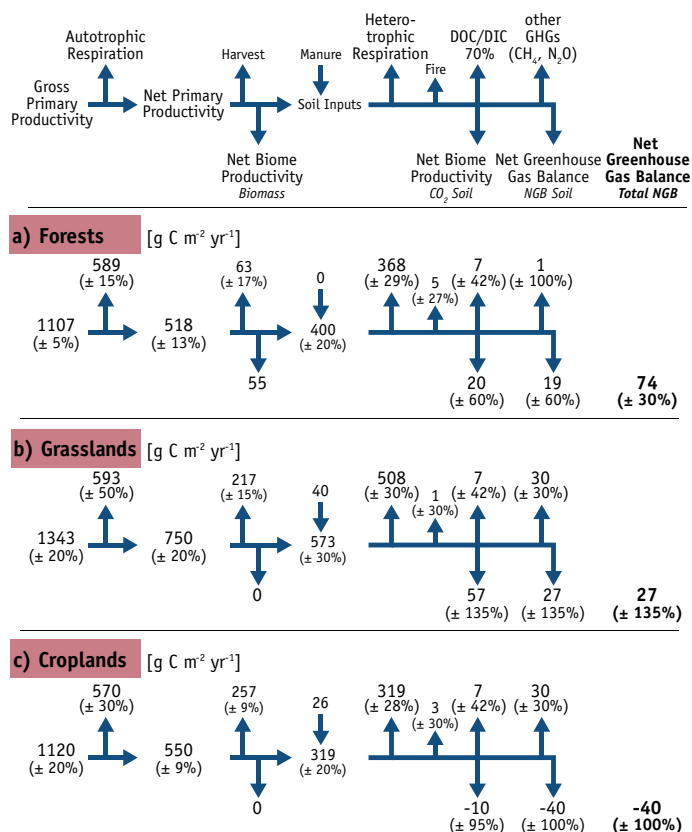
Fig. IV.61: Carbon flow through major land-use types from CO_2 fixation (Gross Primary Productivity) to long-term sequestered carbon (Net Biome Productivity). The data show European averages ± variation coefficient. Results of the Jena annual meeting.
(Janssens, Ciais, Luyssaert and Schulze, unpublished)

in crops and forests. Crops and forests have surprisingly similar GPP despite the fact that croplands grow in more favourable climatic regions and on better soils than forests. Grasslands and crops also receive fertilisers, which are not applied to forests.

The carbon needed for plant respiration also differs between land-use types, with croplands having the highest level of plant respiration. Comparing growth of biomass, as expressed by NPP, grasslands are the winners, with average biomass NPP being about 30% higher in grasslands than in forests and in crops. But, because most of the aboveground biomass is harvested in crops and grasslands, only in forests do we observe an increase in the standing biomass ($NBP_{biomass}$). In crops and grasslands the un-harvested residues and roots enter the soil. In addition, grasslands and crops receive extra carbon from manure. The total carbon input into soils is largest in grasslands, in part due to the high growth rate of roots. Most of this soil carbon input is decomposed by microbes, but the small fraction which remains, generally known as humus, increases the soil carbon content. The formation of humus is the ultimate long-term sink in the carbon cycle. It is likely to be highest in grasslands. The rate of soil carbon sequestration by forests is only one third of that

which grasslands achieve. Croplands emerge as a small carbon source, depleting the soil carbon which has been accumulated over the past millennia. However, including the non-CO_2 carbon gases (methane and volatile organic compounds) changes the effective balance, with the emissions from crops increasing further. The non-CO_2 carbon emissions from grasslands eat up most of their positive CO_2 balance, with their overall carbon-equivalent warming potential becoming about the same as forests. Only forests emit minute amounts of non-CO_2 gases. The effect of N_2O emissions is not included in the diagram of the ecosystem carbon flow.

In summary, NBP is highest in forests and negative in croplands. However, the main part of this forest-NBP accumulates in above-ground biomass which is vulnerable to future harvest.

The data shown in **Fig. IV.61** are the basis for the development of the bottom-up carbon budget for the whole of Europe. It should be made clear, that while the ecosystem data take into account variations in soil fertility, management intensity and crop types, they assume that the mix of soil fertility and management types is constant across Europe. We recognise that this is unlikely to be true. The uncertainty in this assumption is probably largest in croplands, because the model was developed using data from western Europe, where most croplands are managed more intensively than in eastern Europe. However, in future this difference may reduce if levels of fertiliser application in eastern Europe rise to the levels currently applied in western Europe.

Table 2 summarises the European carbon balance, comparing estimates based on separate and independent assessments (i) of atmospheric measurements and inverse modelling, and (ii) of land surface measurements and inventories of the main land-use types of forest, grassland and cropland. The atmospheric top-down estimates are based on a mass balance, assuming that: fossil fuel emissions and trade are balanced by change in the atmosphere and in ecosystems.

In this context, and for the purpose of the comparison with the bottom-up approach, the calculated terrestrial sinks are expressed as positive numbers. **Figure IV.62** shows the distribution of this CO_2-sink across Europe. **Table 2** also includes the climate forcing by CO_2-equivalents of C-containing and non-CO_2 greenhouse gases. We present only a qualitative estimate of the uncertainty because it was impossible to propagate all errors across methods.

Using current knowledge, the average terrestrial CO_2 sink estimated for continental Europe in CarboEurope-IP appears larger in 2008 than that published in 2003 (300 versus 170 Tg yr^{-1}). At the same time, the uncertainty has decreased. The fact that both the top-down as well as the bottom-up estimates indicate an increased CO_2 sink might suggest that this is a real increase. More likely it is only a result of an increased understanding of the carbon cycle. Lateral transport in the atmosphere and in surface waters, trade, land-use change, and non-CO_2 gases are new processes which were not included in the 2003 balance.

The European carbon balance sheet	Continental Europe	Continental Europe Old estimate by Janssens et al. 2003		Continental Europe New estimate by CarboEurope-IP		EU-25	EU-25 New estimate by CarboEurope-IP	
	Area (Million km²)	NBP (Tg C yr^{-1})	Relative uncertainty	NBP (Tg C yr^{-1})	Relative uncertainty	Area (Million km²)	NBP (Tg C yr^{-1})	Relative uncertainty
Top-down CO_2-C fluxes								
Net inversions CO_2-C flux		-1665	*	-1272	**		-947	**
Fossil fuel CO_2-C emissions		-1870		-1600	**		-1060	**
Carbon trade balance				-20	**		-24	**
Carbon exports by rivers to ocean				26	**		10	**
Top-down ecosystem CO_2-C flux		**205**	*	**322**	*		**127**	*
Top-down CH_4 C-CO_2eq + other C gases (1, 2)				-76	**		-32	**
Top-down N_2O flux (1, 2)				-113	**		-90	**
Top-down ecosystem GHG sink (CO_2+CH_4+N_2O)				**133**	*		**5**	*

	Continental Europe	Continental Europe Old estimate by Janssens et al. 2003		Continental Europe New estimate by CarboEurope-IP		EU-25	EU-25 New estimate by CarboEurope-IP	
	Area (Million km²)	NBP (Tg C yr⁻¹)	Relative uncertainty	NBP (Tg C yr⁻¹)	Relative uncertainty	Area (Million km²)	NBP (Tg C yr⁻¹)	Relative uncertainty
Bottom-up CO_2-C fluxes								
Forest biomass	3.39	363	**	157	**		80	**
soil				47	**	1.45	29	**
Other wooded land	0.50	14	**	16	**	0.16	5	**
Grassland	1.51	101	**	85	*	0.57	32	*
Cropland (2)	3.26	-300	*	-33	*	1.08	-11	*
Peat undisturbed	0.39	13	**	7	*	0.09	3	*
drained	0.16	-30	**	-24	*	0.15	-13	*
extracted		-50	**	-50	**		-7	**
Land use change (3)				60	**		20	**
Products and landfills		24	**	24	**		3	**
Volcanic and geothermal CO_2 (4)				-10	n.a.		-10	n.a.
Bottom-up ecosystem CO_2-C flux	**9.21**	**135**	*	**278**	**	**3.50**	**131**	**
Bottom-up CH_4 and N_2O fluxes								
CH_4 agriculture (1, 5)				-38	n.a.		-28	n.a.
industry (1, 5)				-103	n.a.		-46	n.a.
geological (1, 5)				-6	n.a.		-3	n.a.
N_2O agriculture (1, 5)				-87	n.a.		-70	n.a.
industry (1, 5)				-16	n.a.		-12	n.a.
Bottom-up ecosystem GHG sink (CO_2, CH_4, N_2O)				**29**	*		**-28**	*
Average top-down & bottom-up CO_2-C sink	**170**		*	**300**	*		**129**	*
Average top-down & bottom-up GHG sink				**81**	*		**-11**	*

*Table 2: Yellow: the continental carbon balance as estimated by Janssens et al., 2003. Red: the continental greenhouse gas balance as estimated in 2005. Green: the greenhouse gas balance of EU-25 in 2005. Positive values indicate sinks. The uptake by the atmosphere is expressed as negative value by convention. Negative values indicate emissions to the atmosphere. Uncertainties are presented in relative terms: * coefficient of variation >50%, **CV 10% to 50%, ***CV<10%. Land area: according to FAO (http://faostat.fao.org/site/567/default.aspx#ancor). Carbon export by rivers to ocean: Ciais et al., 2008. Terrestrial CH_4 and N_2O flux: UNFCCC national reports. Atmospheric CH_4 flux: Bousquet et al., 2006. Atmospheric N_2O flux: Manning et al., 2003; Huang et al., 2008; Messanger et al., in press. Terrestrial CO_2 fluxes: Ciais et al., in press; Luyssaert et al., in press. Net atmospheric flux inversion: Roedenbeck et al., 2003; Peylin et al., 2005; Peters et al., 2007. Change in human biomass: 0,004 Tg C yr[1], not included. Footnotes: (1) CH_4 and N_2O fluxes are expressed as carbon in CO_2-equivalents with a GWP of 100 year horizon. (2) including erosion re-deposition and burial to deeper horizons. (3) not accounting for urbanization related emissions. (4) geological emissions: Etiope et al., 2007, excluding off-shore sources and Azerbaijan. (5) Russian Federation corrected for Siberia according to area.*

8. The Carbon Balance of Europe

The bottom-up figures show major changes in the contribution of different land-use types since 2003. The estimated forest sink has decreased. At the same time the large losses from croplands could not be confirmed. Forests remain as the main carbon sink in Europe, mainly due to the continuing accumulation of standing biomass. The effects of land-use changes, which appear to increase the total sink, are rather uncertain.

The magnitude of the CO_2-sink estimated from atmospheric measurements is very close to that estimated by ground-based measurements. Compared to the 2003 estimate, the difference between the two approaches has become smaller. Almost 60% of the European CO_2 carbon sink is located in eastern Europe, mainly in the forests of European Russia. However, peat mining contributes substantially to carbon losses in Eastern Europe. When including non-CO_2 greenhouse gases, the total continental sink (100%) is located in eastern Europe.

Including the non-CO_2 greenhouse gases methane, CH_4, and nitrous oxide, N_2O, into the balance changes the total sink of radiative forcing substantially. We define NGB as the resultant Net Greenhouse Balance. NGB was determined from atmospheric measurements, NBG_{at}, and from ecosystem measurements, NGB_{ec}. The difference is probably due to oxidation of methane in the atmosphere. Methane and N_2O reduce the continental CO_2 sink by about 60% (top-down) and about 90% (bottom-up). The resultant NGB of continental Europe is very small (average 81; top-down: 133; bottom-up: 29 Tg C-CO_2eq yr^{-1},100 yr horizon). Including CH_4 and N_2O makes the EU-25 land surface carbon-neutral or even slightly negative. The non-CO_2 gases act as the equivalent of a "toll" taken by the nitrogen cycle on the productivity of biomes. In this case the "toll" is as high as the productivity.

The average terrestrial CO_2-sink is small compared to the total fossil fuel emissions. It compensates for about 20% of the fossil fuel use in continental Europe and 13% of fossil fuel emissions in the EU-25. The lower fossil fuel use in eastern Europe as compared to the EU-25, and a relatively high terrestrial CO_2-sink, improves the eastern European balance. Compared to the total emission of greenhouse gases (fossil fuel plus CH_4 and N_2O carbon-equivalents) the terrestrial CO_2-sink is even smaller (about 17% for continental Europe; 11% for the EU-25).

The high uncertainty of these estimates appears to be an inherent property of the system. The technical uncertainties have been reduced by standardisation of methodologies. Nevertheless, the heterogeneity of the European landscape and the diversity of soils and habitats remain as a source of inherent variation. Even with 100 flux towers this variation is not fully covered. Obviously inventories, models, flux towers and atmospheric measurements are all needed to derive the continental carbon balance.

CarboEurope has successfully pioneered the simultaneous application of the bottom-up and the top-down approaches at the continental scale for CO_2 and non-CO_2-gases. The close match found between the two estimates gives major confidence to the result. It also points at the urgent need for an Integrated Carbon Observing System, ICOS, across Europe (**see Page 53**).

8. The Carbon Balance of Europe

Robust findings:

Continental Europe is a CO_2-carbon sink averaging 300 Tg C yr^{-1} (322 Tg C yr^{-1} based on the top-down approach and 278 Tg C yr^{-1} based on the bottom-up approach). About 80% of the continental fossil fuel emissions and about 90% of the EU-25 fossil fuel emissions remain in the atmosphere to be taken up by the ocean or contribute to global warming. The mitigation potential of the terrestrial vegetation is not realised because of the greenhouse gas emissions by intensive agriculture.

Including non-CO_2 greenhouse gases reduces the continental terrestrial sink by about 70% to 81 Tg C-CO_2eq yr^{-1}, 100yr horizon. The EU-25 carbon-equivalent greenhouse gas balance is even slightly negative. The non-CO_2 gases act as the equivalent of a "toll" taken on the productivity of the biomes. In this case the "toll" is as high as the productivity.

The non-CO_2 gas emissions increase the greenhouse gas emissions compared to fossil fuels about 10% (1600 Tg C yr^{-1} of fossil fuel emission in 2005; 1700 Tg C-CO_2eq yr^{-1} carbon-equivalent greenhouse gas emissions plus fossil fuel).

Agriculture causes about 50% of the continental total carbon-equivalent emissions of CH_4 and N_2O and 62% of the carbon-equivalent GHG emissions in the EU-25.

Almost 60% of the European CO_2-carbon sink is located in Russian forests and grasslands. Including non-CO_2 greenhouse gases, the entire continental sink (100%) is located in Eastern Europe. The EU-25 is carbon neutral.

The average continental terrestrial CO_2-carbon sink is 20% of the fossil fuel emissions in 2005, and only 13% of the fossil fuel emissions of EU-25. The terrestrial CO_2 sink is only 17% of the continental total greenhouse gas emissions (300 of 1700 Tg C yr^{-1}), and only 11% of the EU-25 total greenhouse gas emissions (129 of 1116 Tg C yr^{-1}).

The estimated size of the CO_2-sink appears to have increased since 2003, as estimated by both the atmospheric-based and the ground-based approaches. The increase is mainly due to better representation of the processes. The forest sink has decreased. The large CO_2 losses from agriculture could not be confirmed, but the large non-CO_2 emissions from agriculture were not recognised in the 2003 balance.

The forest sink results from an increase in biomass (70% of the effect) and in the soil organic matter (30% of the effect). This increment is closely coupled to the age-class distribution and to nitrogen deposition. One remarkable finding is that the carbon-equivalent N_2O emissions of agriculture are of similar magnitude to the forest CO_2 carbon sink.

Future estimates of the carbon balance may still change these values as additional data become available, but the estimates appear to be becoming increasingly reliable.

Key questions:

What is the contribution of non-CO_2 greenhouse gases? A better estimate is crucial.

Would a continuous model of European land-use reduce the uncertainties? Such a land-use model is still missing.

What is the role of land-use changes and the associated non-CO_2 emissions? Knowledge of this contribution remains inadequate.

9. International Perspective

Pep Canadell

The Global Carbon Project coordinates international research, seeking to develop a complete picture of the global carbon cycle, including both its biophysical and human dimensions, together with the interactions and feedbacks between them. 'CarboEurope-IP is one of the best examples of the new collaborative and multidisciplinary research approach that is needed to study human modification of planet Earth,' said Pep Canadell, Executive Director of the Global Carbon Project.

'I wish we had one CarboEurope-IP-like project in each major region of the world. If we did, we could put together the total picture of the global carbon balance and its interactions with climate. We could then explore the full potential of managing carbon sinks and sources across the globe for climate mitigation, as now Europe is in a position to do.'

Dennis Baldocchi

Dennis Baldocchi is Professor of Biometeorology at the University of California, Berkeley, and co-initiator of "Fluxnet", the world-wide network of CO_2 flux measuring groups. He is also a member of the CarboEurope-IP External Advisory Panel. Dennis said 'CarboEurope-IP is viewed by scientists across the globe as the premier regional program tackling the multi-faceted problem of the carbon cycle. The project uses a range of measurement techniques (eddy covariance, remote sensing, inversion modelling) to produce a highly integrated assessment of net carbon exchange across a vast range of time and space scales. And this information is coupled with state of art models at the patch to regional scale that are used to interpret and project fluxes into the future. The Project has already had many heralded successes: one example is analysis of the impact of some very important case studies, like the role of the 2003 European Heat Wave and Drought, and major wind storms, on ecosystem structure and function.'

Kevin Noone

Kevin Noone is Executive Director of the International Geosphere-Biosphere Programme, whose agenda emphasises the importance of regarding the Earth as a system, where biological, physical and human processes interact. Kevin has been following CarboEurope-IP's progress and its impact on the international debate on climate change. Kevin Noone said, 'The international community has set itself a very challenging goal: negotiating a new climate agreement by the end of 2009. The success of these negotiations requires having the best possible knowledge of how carbon cycles between the atmosphere, land and marine ecosystems. CarboEurope-IP is an excellent example of how this basic knowledge can be developed and made useful for decision support on adaptation and mitigation issues. CarboEurope-IP's work to produce a carbon balance for Europe, link observations with models, and detect the results of international agreements is a benchmark for other international efforts. It has raised the bar in terms of how basic research for decision support can be done.'

Andrew Mitchell

The Global Canopy Programme promotes forest canopy research, education and conservation with a special focus on the role of forests in climate change. It is committed to exploring the range and economic value of forest ecosystem services and to sharing the findings with decision-makers in Government and finance. Director, Andrew Mitchell said 'CarboEurope-IP is showing us the vital role played by forests in removing carbon from the atmosphere and storing it away - an ecosystem service which is of enormous economic benefit globally. The data that is coming out of CarboEurope-IP demonstrates the urgent need to manage Europe´s forests, and maximise their capacity to act as carbon sinks. Recognising this vital ecosystem service that forests provide, most importantly in the tropics, in all the world's carbon markets, could provide a major economic incentive to protect forests and mitigate climate change efficiently.'

10. Demonstration, Training and Young Scientists
10.1 Demonstration Activities

Regional demonstration activities were established in CarboEurope-IP with the German Thuringian State Institute for Forestry, Game and Fishery (Gotha). The demonstration activities included

- the investigation of the wood product pool resulting from timber harvested in Thuringia´s state forests and considerations of how the life-time in the product pool is influenced by forest management
- considerations of how the forest cover and species composition will change under different climate change scenarios.
- the installation of a data base in combination with an empirical, spatially explicit model which allows for a continuous record of carbon stocks in Thuringia´s state forests
- organisation of joint workshops to transfer the knowledge on climate change into the forest management community
- to transfer recent research results on forestry
- climate interactions to local and regional multipliers, schools, consumers and decision makers by workshops, public presentations and an internet portal (**Fig. IV.62**)

Fig. IV.62: Logo of the internet portal "Forest & Climate" via http://www.waldundklima.net

Most importantly for the forest management community was the investigation of the wood product pool resulting from tree harvests in Thuringia´s state forests (Profft et al., EJFR, in press). This study presents for the first time real carbon inputs of a defined forest management unit to the wood-product sector by linking data on raw timber production, timber sales and wood processing companies (**Fig. IV.63**). The partitioning of wood into certain wood categories depends strongly on the stem diameter. Short lived precuts dominate the small diameters, but long-lived products saturate with modern wood-cutting technologies at about 20 cm diameter, which is equivalent to about 60 years of growth in spruce and beech. Interestingly, the price for this product mix saturates at a diameter of 20 cm, which would be an incentive to harvest wood at that dimension and age. About 47% of annual total timber harvest enters into short-lived wood products with a mean residence time (MRT) less than 25 years. 31% of the total harvest enters into wood products with a MRT of 25-43 years, and only 22% are used in the construction industry, the product class with the longest MRT (50 years). The average MRT of carbon in harvested wood products of Thuringia was 20 years, and thus, approaches that of dead wood in the forests (28 years). The MRT of wood products from Thuringian forests were two times higher than estimates that would result from a forest carbon model (CO2FIX, Nabuurs et al., 2001), which can be ascribed to the relatively high production of large-dimensioned timber and its direct sale to international saw-wood processing companies in Thuringia.

The MRT of wood products can be increased by management from 18 to 22 years by thinning from (harvesting suppressed trees). However, the mean age and volume of forests is likely to decrease in the future, because new wood technologies will allow for an effective production of relatively valuable and long-living wood products from small, but homogenous timber types and the associated price structure.

Carbon stocks in Thuringia´s forest ecosystems and their development over the last 15 years are highly controlled by an unequal age distribution of forest stands and the dominance of instable, overstocked pure coniferous forests resulting from historical political frameworks. Thus, the suggested carbon management strategy for Thuringia is the transfer of the even-aged, mono-species forests to uneven-aged, mixed forests producing predominantly large, valuable timber.
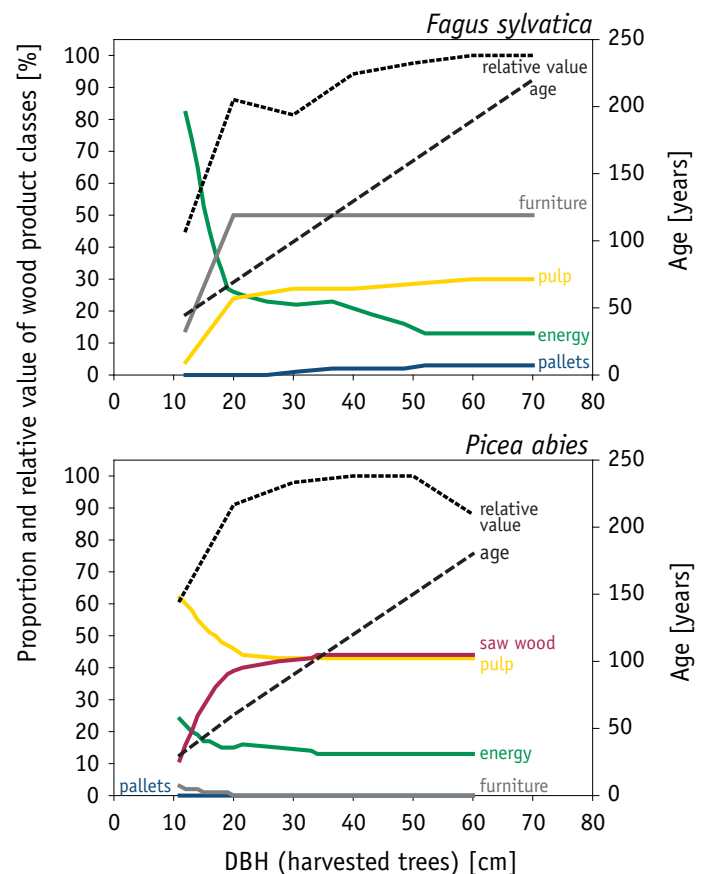
Fig IV.63: Assignment of wood product classes to the diameter at breast height (DBH) of harvested timber. For spruce timber with a DBH below 25 cm the standard tables for wood products of Schoepfer and Stoehr (1991) were used, for all other cases the tables of Schoepfer and Dauber (1985). Parquet wood is not listed in the tables; wood that would fit into this class is added to the product class "saw wood". (Profft et al., accepted)

10.1 Demonstration Activities

Beech (*Fagus sylvatica*)

Legend:
- high (grey)
- low (red)
- climate for Thuringia (1971-2000) (green square)
- climate for Thuringia, scneario B2 (2021-2050) (blue circle)

Spruce (*Picea abies*)

Legend:
- high (grey)
- low (red)
- climate for Thuringia (1971-2000) (green square)
- climate for Thuringia, scneario B2 (2021-2050) (blue circle)
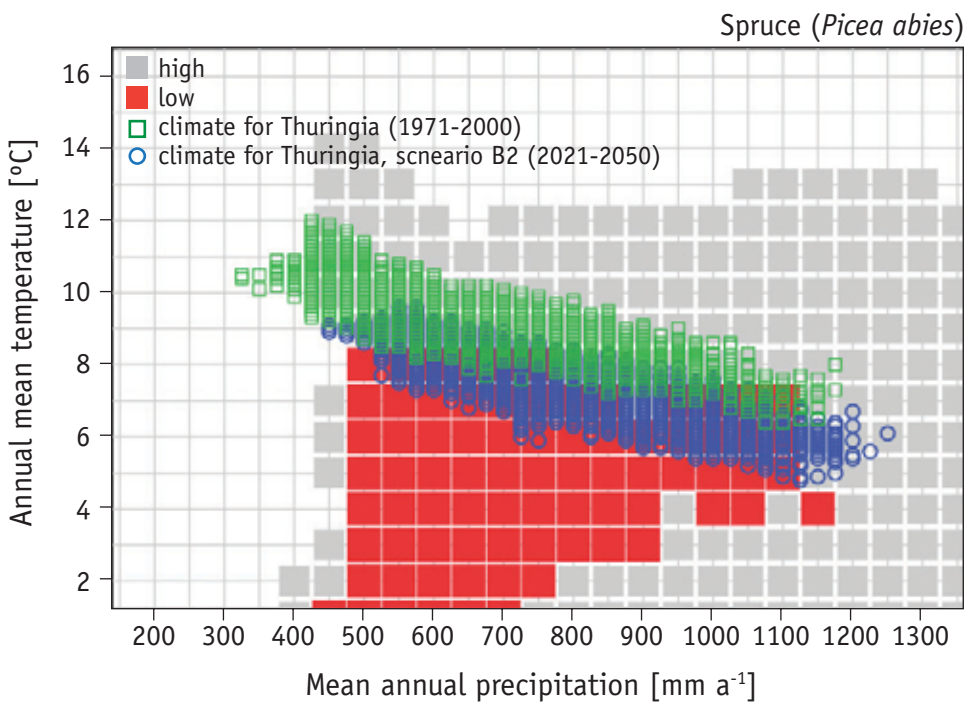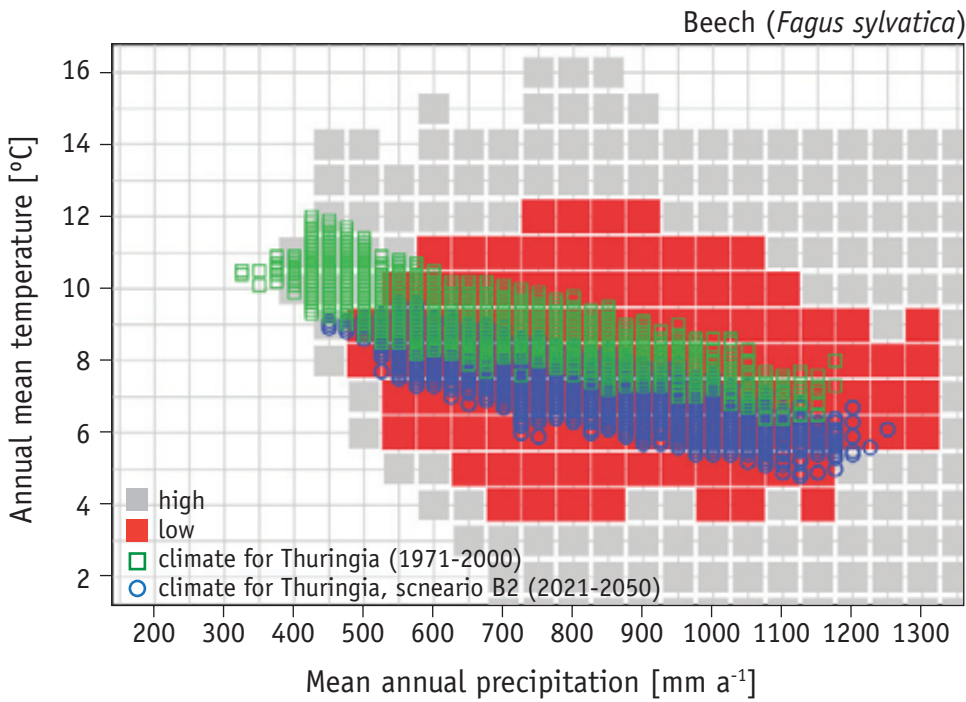
Fig. IV.64: Climate envelope for beech and spruce nach Kölling (2007) modified for present climate conditions (1971-2000, blue) and future conditions according to the IPCC scenario B2 (2021-2050, green) for Thuringia. Red areas indicate temperature-percipitation-combination with high presence according to the nature species distribution in Europe, grey colored combination indicate sporadic appearance within the natural distribution (5% percentil).

Climate change will impact the distribution of main forest species and the vitality and productivity of forest ecosystems in the temperature-precipitation space of Thuringia. Mainly affected will be spruce (Picea abies) (**Fig. IV.64**), which might further disappear from lower elevations and suffer serious problems in the East of Thuringia (**Fig. IV.65**). Based on current spruce distribution and soil conditions in Thuringia in combination with regionalised climate data for the period 1971 to 2000 classified by macroclimatic units, distinct areas were identified with a high propor¬tion of spruce stands that are vulnerable to expected climate change (**Fig. IV.64**). These results were supported by monitoring data on damage caused by bark beetle infestations during the last two decades (Profft et al. 2008).

Tree species were recommended for regeneration in Thuringia according to these findings.

The transfer of knowledge has been a major task for the demonstration project. Additionally to direct education activities, the internet portal "Forest & Climate" was developed in 2004 and launched in 2005 under the internet domain www.waldundklima. net. The portal covers the whole issue of climate change and forestry including carbon aspects. It should serve as an open platform for other institutions, associations and groups working in the field of forestry, ecosystem research, timber use and climate change, where they can present their work and results in a popular scientific manner. Currently more than 200 articles of about 35 different institutions are online and permanent extensions as well as updates with latest news will ensure a sustainable transfer of recent research findings. The portal has also a strong link to the CarboSchool initiative of CarboEurope-IP, and supports local education projects.
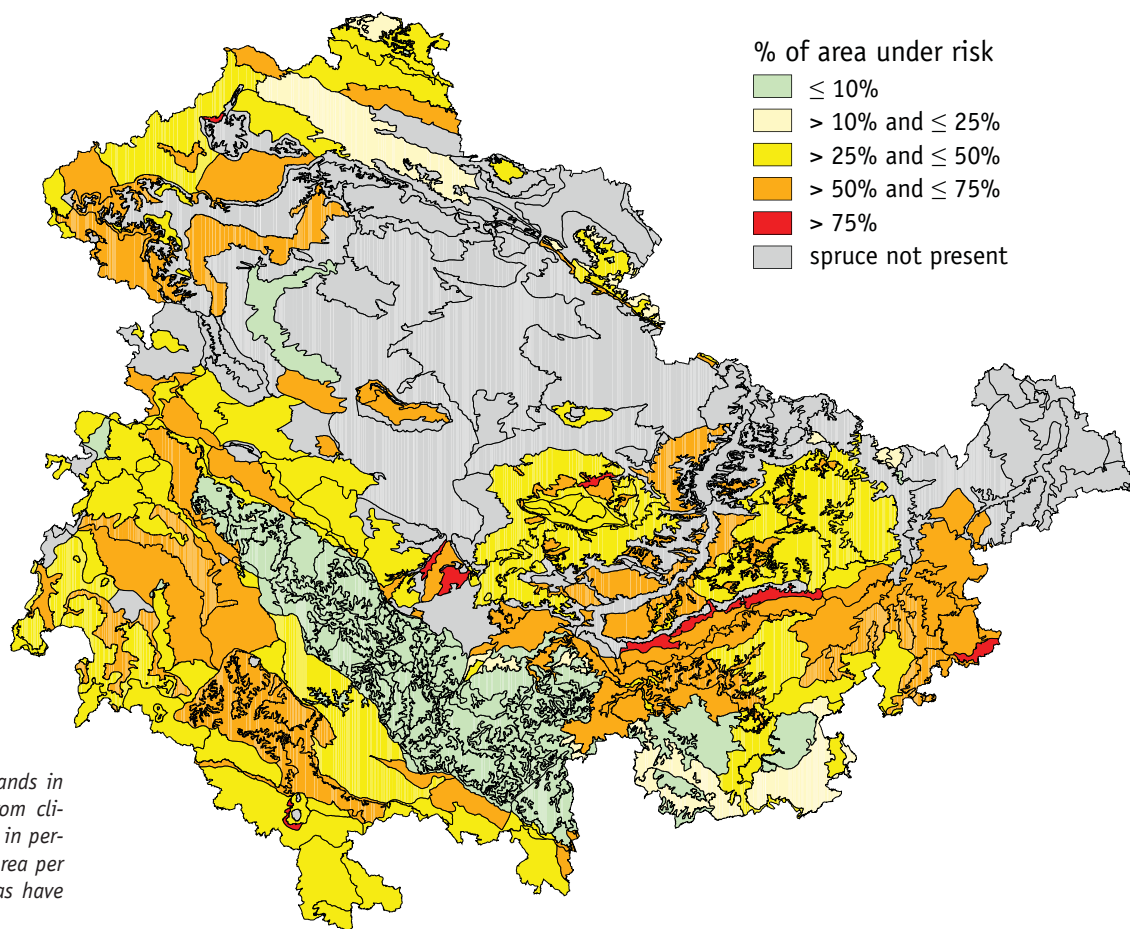
Fig. IV.65: Present spruce stands in Thuringia at potential risk rom climate change. Data are given in percentage of the total spruce area per macroclimatic unit. Grey areas have nearly no spruce stands.

% of area under risk

- ≤ 10%
- > 10% and ≤ 25%
- > 25% and ≤ 50%
- > 50% and ≤ 75%
- > 75%
- spruce not present

Robust findings

The production of large, valuable sawn timber in combination with thinning from above results in higher carbon stocks in the forest ecosystem and higher mean residence times of wood products than a forest management regime that focuses on high mass production within short rotation periods and with a high proportion of pulpwood production.

In Thuringia the largest management effect on carbon stocks in the forest ecosystem is associated with the age distribution of the forest stands and the intensity and way in which the even-aged forests will be harvested and transferred to even-aged young forests with low biomass stocks or to un-even-aged forest of medium to high biomass stocks in the future.

Climate change will impact the distribution of main forest species in the temperature-precipitation space of the demonstration region Thuringia. Spruce will be most badly affected and might disappear from lower elevations.

Key questions

What are the effects of an increasing demand for energy wood, the development of the second regeneration of biofuels, and ongoing changes in wood technology on the greenhouse gas budget of forest ecosystems and the carbon balance of the wood product sector including substitution effects?

What are the effects of weather extremes on the annual and decennial carbon budget of managed forest ecosystems and the entire forestry sector?

How can changes of weather extremes be included in regional risk assessments?

Can markets and consumer decisions be regulated or optimised to converge towards a carbon neutral society?

Young people must live with the impacts of the environmental actions we take today and it is not surprising, that they are impatient to contribute to the public debate on climate change and the action needed to protect the global environment. Schools have the responsibility of equipping the young with the understanding they need to participate in this debate in an informed way and giving them the knowledge to make choices about how we should be managing the environment to build a sustainable future.

Recognising this responsibility, CarboEurope-IP has joined with its sister project CarboOcean-IP in an initiative to raise young people's awareness of the global carbon balance and the research that is going on to find the sources and sinks of carbon on land and sea. This initiative, CarboSchools, is engaging with schoolteachers and pupils by connecting them to scientists and making them aware of the whole process of research. Not just teaching what we know, but equally making young people aware of what we don't know: the limitations of our knowledge and the way we go about building new knowledge. The emphasis is on project-based teaching, learning by doing, encouraging hands-on experience in up-to-date research. This approach helps to bring pupils first-hand knowledge and enhances their understanding of the problems being addressed (**Fig. IV.66a-e**).

Although the main role of CarboSchools is to act as a catalyst involving CarboEurope-IP scientists in school projects, recognising that the number of scientists is limited, CarboSchools is also using the internet to provide materials to all teachers and pupils. Marc Jamous of the Laboratoire des Sciences du Climat et de l'Environnement, Gif-sur-Yvette gives an example 'we have set up an internet site on the carbon cycle and its impacts on global change. There is a "visitors' space" for the general public and school children, "a teachers' space", to provide materials for teachers and a "researchers' space" to help the scientists to be better prepared in communicating their work to schools.'

Philippe Saugier, coordinator of CarboSchools, says 'the changes that are happening to our planet challenge our way of thinking and making decisions. The Earth system is a complex web of interacting, interdependent forces, which demands new thinking, not just from scientists but decision-makers at all levels. Young people are always receptive to new ideas and they will be the pacemakers in the race to deliver the solutions to the problems of global change. Solutions must be built on an appreciation of the complexity and interdisciplinary nature of the problem and the links between decisions at all levels, from international treaties to everyday individual

Fig IV.66a: Pupils from Lycée Max Linder (Libourne, France) discover CarboEurope-IP research with INRA scientists in the Cestas forest, near Bordeaux. (Photo: S. Hayes)

Fig IV.66b: Students at Benevento's agricultural secondary school IPSAA "Vetrone" experiment sod-seeding techniques without tillage with CNR-IBIMET researchers. (Photo: D. Marandola)

choices.' In the future, CarboSchools will also have to teach the interaction between the Carbon Cycle and land management, which supports our daily life.

As part of the EU Science in Society programme, a new phase to CarboSchools has been funded for the period 2008-2010. This second phase will extend the programme with a target of more than 100 schools being directly partnered with research institutions across Europe.

10.2 Training and Outreach

Fig IV.66c: Students test soil samples for calcium content during the Girls' Day 2008 at Max-Planck-Institute for Biogeochemistry, Jena. (Photo: B. Michel)

Fig IV.66d: With an endoscope students and staff from Max-Planck-Institute for Biogeochemistry, Jena explore soil life in earthworm tunnels. (Photo: B. Michel)

Fig IV.66e: Students learn how to measure respiration from their soil samples at Max-Planck-Institute for Biogeochemistry, Jena. (Photo: B. Michel)

Schools' experiment: SchoolCO2web

One of the objectives in the new phase of CarboSchools beginning in 2008 is to create a pan-European schools' experiment known as "SchoolCO2web". The experiment builds on a pilot project in the Netherlands, being run by the University of Groningen. In that experiment, pupils from secondary schools get hands-on experience with real CO_2 measuring instruments installed at their schools. The data are brought together on a website where they can be seen and shared.

The great asset of this experience is that it provides pupils with an opportunity to really "see" the invisible CO_2 gas, to perform real measurements of their own, to compare data from different locations and to discuss their results and share their impressions with each other.

The Groningen model will be extended in the Netherlands, and to the European level, by involving another 10 to 20 schools in other countries. Research groups experienced in performing CO_2 measurements will collaborate with near-by schools, acting as the "local support lab". Adding schools to the network is then straightforward: instruments will be installed at the schools, their maintenance explained, teachers trained and the schools registered in the web-database.

10.3 Young Scientist Award

CarboEurope-IP Young Scientist Award

CarboEurope-IP takes a long term view and training early career scientists is thus a priority; they will have the responsibility of moving the work forward in the future. Young scientists are encouraged to attend spring and summer schools, and special workshops. These have covered training in methods and integration, on method intercomparison, and modelling. They are held in cooperation with other European scientific and training programmes

Every year two young scientists (PhD students and young Postdocs as first author) are awarded with the CarboEurope-IP young scientist award for outstanding publications. The criteria for this award is that the research decribed must be applicable across multiple parts of carbon cycle science, be innovative and give new insight. The awards are selected by the external members of the Advisory Panel.

Sucessful Scientists:

2004

Carrara A, Janssens IA, Yuste JC, Ceulemans R (2004) Seasonal changes in photosynthesis, respiration and NEE of a mixed temperate forest. Agricultural and Forest Meteorology 126: 15-31

Subke J-A, Hahn V, Battipaglia G, Linder S, Buchmann N, Cotrufo MF (2004) Feedback interactions between needle litter decomposition and rhizosphere activity. Oecologia, 139: 551-559

2005

Reichstein M, Falge E , Baldocchi D, Papale D , Aubinet M, Berbigier P, Bernhofer C, Buchmann N, Gilmanov T, Granier A, Grünwald T, Havrankova K, Ilvesniemi H, Janous D, Knohl A, Laurila T, Lohila A, Loustau D, Matteucci G, Meyers T, Miglietta F, Ourcival J-M, Pumpanen J, Rambal S, Rotenberg E, Sanz MJ, Tenhunen J, Seufert G, Vaccari F, Vesala T, Yakir D, Valentini R (2005) On the separation of net eocsystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Global Change Biology 11(9): 1424-1439

Vetter M, Wirth C, Böttcher H, Churkina G, Schulze E-D, Wutzler T, Weber G (2005) Partitioning direct and indirect human-induced effects on carbon sequestration of managed coniferous forests using model simulations and forest inventories. Global Change Biology 11: 810-827

2006

Davi H, Bouriaud O, Dufrêne E, Soudani K, Pontailler JY, Le Maire G, François C, Bréda N, Granier A, Le Dandec V (2006) Effect of aggregating spatial parameters on modelling forest carbon and water fluxes. Agricultural and Forest Meteorology 139(3-4): 269-287

Pérez-Landa G, Ciais P, Gangoiti G, Palau JL, Carrara A, Gioli B, Miglietta F, Schumacher M, Millán MM, Sanz MJ (2007) Mesoscale circulations over complex terrain in the Valencia coastal region, Spain - Part 2: Modeling CO_2 transport using idealized surface fluxes. Atmospheric Chemistry and Physics 7(7): 1851-1868

2007

Sarrat C, Noilhan J, Lacarrere P, Donier S, Lac C, Calvet J-C, Dolman H, Gerbig C, Neininger B, Ciais P, Paris J-D, Boumard F, Ramonet M, Butet A (2007) Atmospheric CO_2 modeling at the regional scale: Application to the CarboEurope Regional Experiment. Journal of Geophysical Research-Atmospheres 112(D12): 12105

Owen KE, Tenhunen J, Reichstein M, Wang Q, Falge E, Geyer R, Xiao X, Stoy P, Ammann C, Arain A, Aubinet M, Aurela M, Bernhofer C, Chojnicki BH, Granier A, Gruenwald T, Hadley J, Heinesch B, Hollinger D, Knohl A, Kutsch W, Lohila A, Meyers T, Moors E, Moureaux C, Pilegaard K, Saigusa N, Verma S, Vesala T, Vogel C (2007) Linking flux network measurements to continental scale simulations: ecosystem CO_2 exchange capacity under non-water-stressed conditions. Global Change Biology 13(4): 734-760

2008

Göckede M, Foken T, Aubinet M, Aurela M, Banza J, Bernhofer Ch, Bonnefond JM, Brunet Y, Carrara A, Clement R, Dellwik E, Elbers J, Eugster W, Fuhrer J, Granier A, Grünwald T, Heinesch B, Janssens IA, Knohl A, Koeble R, Laurila T, Longdoz B, Manca G, Marek M, Markkanen T, Mateus J, Matteucci G, Mauder M, Migliavacca M, Minerbi S, Moncrieff J, Montagnani L, Moors E, Ourcival J-M, Papale D, Pereira J, Pilegaard K, Pita G, Rambal S, Rebmann C, Rodrigues A, Rotenberg E, Sanz MJ, Sedlak P, Seufert G, Siebicke L, Soussana J-F, Valentini R, Vesala T, Verbeeck H, Yakir D (2008) Quality control of CarboEurope flux data – Part I: Footprint analyses to evaluate sites in forest ecosystems. Biogeosciences 5(2): 433-450

Wutzler T, Reichstein M (2008) Colimitation of decomposition by substrate and decomposers – a comparison of model formulations. Biogeosciences 5(3): 749-759

11. Strategy and Future Priorities

In assessing the future priorities for research and monitoring we see the overarching, ultimate goal of Europe as a sustainably managed continent, in which the landscape acts as component of a carbon-neutral economy.

In this context, the purpose of future research is to learn how to manage the landscape as a carbon sink; and to monitor our progress towards meeting that objective. This requires a thorough understanding of ecosystem carbon response to disturbance, human management and climate change, and the feedbacks involved.

CarboEurope-IP has identified the following research priorities to implement this strategy and address the following key issues and questions.

1. Attribution of regional changes in the carbon budget from 1990 to 2012 to human and natural drivers

Ecosystem, atmospheric and ancillary observations and models should be used to quantify the annual to decadal changes in the carbon and greenhouse gas budget of Europe, from 1990 to 2012. This initiative should be driven by data on climate and atmospheric composition, fossil fuel emissions, and land use. Observations should be expanded to under-sampled regions and to cover CO_2, CH_4, N_2O, and lateral carbon fluxes from local to continental scale. The research should emphasise the European continent as a whole and focus on critical European regions with rapid socio-economic and/or climate-driven changes. Data assimilation systems and advanced biosphere and earth system models need to be further developed to include more realism in land use and management. Methods need to be improved to quantify and verify patterns and changes in anthropogenic greenhouse gas emissions.

The key questions are:

How has the European carbon balance evolved over the last decades, and how is it changing at the moment?

To what extent, and for how long can Europe rely on the terrestrial carbon sink?

Have the promised emission reductions in Europe really taken place, have the climate policies been effective?

2. Maintaining, improving and integrating in situ observations on land, atmosphere and ocean

A robust, quality-controlled, long-term system of in-situ observations is needed to improve the knowledge basis for making and monitoring emission-reduction goals, to maintain Europe's international credibility and to maintain ownership over its carbon balance estimates.

The existing network of continuous, in situ observations needs to be sustained for the coming 4-5 years before it can be moved from research into more operational mode under the proposed ICOS infrastructure (**see Page 51**). We must explore whether uniting the existing networks of atmosphere, land and ocean observations of carbon and greenhouse gases would improve the provision of data needed during the first Kyoto commitment period (for example through verification, or expansion to under-sampled regions). Methodological improvement needs to be made to bridge the gap between the existing observational scales and to improve the link between in situ and satellite based observations. We should explore the viability of linking with other already established networks, such as those for monitoring nitrogen and air pollution.

The key question is:

What are the trends and decadal ecosystem response to climate stress and changes in land management?

3. The terrestrial carbon cycle in other regions of the globe, especially Africa

The CarboAfrica pilot study should be continued and intensified. There are huge expectations from African researchers and we have a moral obligation to continue this research and the scientific capacity building which it initiated. Compared to the other continents, there has been very little research into the carbon balance of Africa, making it a high priority research area. Disturbance on the African continent explains a large part of the global interannual variability of the net land carbon uptake. This flux needs to be further constrained. The expected call for a project on the impact of deforestation is seen as very useful. However, the challenge for Africa is not simply land use change, but land degradation and the consequent impacts on plant and soil processes. Soil degradation is globally the most important terrestrial carbon source, but has so far been largely neglected. This challenge requires more research.

The key questions are:

What is the role of other land masses in the global carbon balance?

What are the processes controlling the soil carbon balance in other climates?

What is the impact of land and soil degradation on continental carbon budgets?

4. Focused research to understand coupling between the carbon and water cycles and the carbon and nutrient cycles

Our capacity to predict the terrestrial carbon cycle is limited by the unknown coupling and feedbacks between the major global cycles. Small to medium research projects are need to quantify and understand the coupling between the carbon and water cycle and the carbon and other nutrient cycles, in particular the water and nitrogen cycle. Using experiments, observations and models, research should elucidate the fundamental coupling mechanisms from the process level to the scale of regional carbon-climate feedbacks. Vulnerable or hotspot regions require special attention.

The key question is:

What are the interactions and feedbacks between the major global cycles, especially of water and nitrogen?

5. Managing adaptation and mitigation.

Research should quantify climate change impacts, and adaptation and mitigation options at the local to regional level. Observations, economic, biophysical and climate models need to be linked to develop region-specific solutions, especially in view of a global food shortage.

The key questions are:

What action should we take at the regional level in response to climate change?

How can we solve the global food shortage?

6. Land – atmosphere – ocean integration

Synthesis between land and ocean is being addressed by the COCOS Concerted Action – bringing observations together. At present, land and ocean science have very different uncertainties and research needs, so the core land and ocean research should continue to move in parallel. However collaboration should be encouraged in areas of overlap, such as the research needed to quantify the carbon exchange at the interface between land and ocean. Improvement of coupled land – ocean – atmosphere models and atmospheric inversions could also be included within the Climate Part of the Environment Theme. Collaboration between the land and ocean communities should also be encouraged where there is potential to produce synergy, such as in technological development of sensors, and data transfer and management.

The key questions are:

What are the carbon fluxes at the land-ocean interface?

How does the total Earth system behave now and in the future?

How can ocean-atmosphere-land observation be improved by new common technologies?

7. Integration and synthesis of the terrestrial carbon cycle

Past and ongoing research projects at national and European level have produced a wealth of data and knowledge to be synthesised and analysed in synergy with parallel research programmes in other world regions. In FP6, CarboEurope-IP has successfully operated as a platform to integrate research and to stimulate synthesis activities beyond the formal project boundaries. The anticipated smaller partnerships and sizes of European projects under FP7, creates the danger that the critical mass and dynamics will be lost. This creates the need for a co-ordination project for terrestrial carbon that will act as a platform for the interchange of new ideas, and will maintain the integration of the research community and continue to produce new synthesis. This platform should also link to programmes in other world regions. To keep up the momentum and prevent fragmentation of the research teams, a co-ordination action should start very soon after the end of CarboEurope-IP. A project starting in 2009 would be best.

> **Summary of research priorities**
>
> 1. Attribution of regional changes in the carbon budget from 1990 to 2012 to human and natural drivers.
>
> 2. Maintaining, improving and integrating in situ observations on land, atmosphere and ocean.
>
> 3. Researching the carbon balance and the role of land degradation on the global carbon cycle on other continents.
>
> 4. Focused research to understand coupling between the carbon and water cycles, and the carbon and nutrient cycles.
>
> 5. Developing regional options for adaptation and mitigation.
>
> 6. Collaborative research on land-ocean interactions and technological development.
>
> 7. Synthesising the results of the many past and ongoing terrestrial projects (e.g., through a Concerted Action).

11. Strategy and Future Priorities

Cross-cutting future research themes

The priority issues call for a number of common research themes which will need to be expanded as generic areas of development.

Soil carbon:

In the long term soil is the most important terrestrial carbon store and we need to learn more about processes, soil reactions and how to model the soil carbon balance. We must also research changes in soil carbon stocks. There are questions which need to be resolved about the carbon balances of cropland and pasture soils, and unmanaged, climax forest. We have laid the foundations, but soil changes are slow and relatively small against a large variable background. Soil research requires a long term approach.

Inverse modelling:

The techniques of inverse modelling are being developed with the objective of making them operational, but equally inverse modelling is a powerful technique which increasingly will be used to give insight into the functioning of ecosystems at a range of scales and under a variety of stresses.

Regional scale modelling:

The complex spatio-temporal patterns in land use and atmospheric mixing at the regional scale, call for improved modelling capacity. The region scale is increasingly becoming the focus both of carbon accounting and our efforts to respond to climate change. Monitoring of carbon sources and sinks, assessing the impacts of extreme events, and land use and land management change all require development of more comprehensive and integrated meso-scale models.

The multiple constraint approach:

CarboEurope-IP has successfully pioneered the integrative multiple constraint approach. We need to continue developing this research philosophy, moving beyond observations to combining data with detailed process-studies, manipulations and research in regions undergoing massive change.

Data access and assimilation:

CarboEurope-IP has been successful in bringing together observational scientists with modellers. The free movement of data has played a significant role in this and it is important to maintain this movement through well-organised and easily accessible databases. New initiatives such as inverse modelling will require full integration of all available data streams into the models and data assimilation is the key to improving model estimates. Data management and data assimilation are increasingly ubiquitous and important areas which need their own specific funding.

12. CarboEurope-IP History

Carbon Cycle research emerged from research into acid rain. In the 1980s forest decline was a major concern across Europe. A large, coordinated research effort identified acid deposition and SO_2 as causes. The European conference 1983 at Karlsruhe on "Acid deposition, a challenge for Europe" initiated Concerted Actions (COST 611 and COST 612) to identify further actions.

In 1987 the Symposium at Genoble on "Air Pollution and Ecosystems" (P. Mathy, ed.) further substantiated the acid rain effects and extended the focus towards climate and nitrogen interactions. In the 1st and 2nd Framework Program (FP) the projects CLIMEX (Climate experiments), CORE (reciprocal exchange of soil cores), ENCORE (European catchment studies), EPOCH (Atmospheric constituents), EXMAN (experimental ecosystem manipulations), NITREX (nitrogen saturation experiments), and FERN (Forest Ecosystem Research Network) were initiated. In 1990 the Edinburgh workshop on Acid Deposition (Last and Watling, eds) gave an ultimate summary of the acid rain research epoch.

With the 1991 Florence Symposium on "Responses of forest ecosystems to Environmental change" (Teller, Mathy, Jeffers, eds.) climate change became increasingly important. In the 3rd (1993-1995) and 4th (1997 – 1999) FP projects started (1) with Ecosystem focus: NIPHYS (nitrogen physiology of ecosystems), CANIF (Carbon-nitrogen interactions), (2) with Canopy focus: FLUXNET, EUROFLUXNET and MEDIFLUX, (3) with atmospheric focus: ESCOBA and ESCOBA II studying carbon in the ocean, the biosphere and the atmosphere, and (4) studies were extended beyond Europe (EUROSIBERIAN CARBON FLUX).

During this period the Kyoto Protocol (1993) was negotiated which foresees an accounting of biological sinks in balance of fossil fuel emissions. Also, the need for a stronger focus on "climate change" was underlined by the 1996 IPCC report, which stated that "the balance of evidence suggests a discernible human influence on global climate".

In 1998 an expert meeting in Brussels discussed the "Greenhouse gas sink approach of the Kyoto Protocol". This meeting was the final turning point were the emphasis shifted from nitrogen and air pollution towards greenhouse gases and carbon cycle, and it was the Orvieto workshop of the ESCOBA II project in which (24 June 1998) an interdisciplinary project "CARBON-EUROPE" was proposed, in order to combine atmospheric, ecosystem and soils based research. Already in 2000 at COP6 (The Hague) the CarboEurope cluster forwarded the proposal for "Full Carbon Accounting". The political reply was, that this vision came too early. Nevertheless, the EU summarized its research at the 2000 Lisbon workshop on "Terrestrial carbon research and observations" as part of the IGBP "Global Carbon Plan". This research was in concert with the international efforts to clarify the global biogeochemical cycles in the IGBP-projects

GCTE, BAHC and IGAC. The 2001 Stockholm meeting on "the carbon sink: Absorption capacity of the European Biosphere" was an additional cornerstone in this process.

The 5th Framework Programme of the EU significantly increased the efforts on carbon cycle research. About 22 projects were established (1) in Ecosystems (e.g.: CAMELS - Carbon assimilation and modeling; CARBO-AGE – Age-related forest dynamics; CARBOINVENT – Forest inventories; CARBOMONT – Carbon fluxes in Mountains; FORCAST – Forest carbon-nitrogen trajectories; GREENGRAS – Greenhouse gases from managed grasslands), (2) of canopy fluxes (e.g. CARBOEUROFLUX, CARBODATA), (3) of atmospheric processes (AEROCARB – airborne regional observation; CHIOTTO – Continuous high-precision tall tower observations; RECAB – Regional assessments of the European carbon balance; TACOS-INFRASTRUCTURE – Terrestrial and atmospheric carbon observation system; CarboEurope-GHG – Synthesis of European greenhouse gas budgets) and (4) of global observations outside Europe (e.g. TCOS-Siberia, LBA-CARBONSINK, SIBERIA II). Most of the carbon-related projects were at that time combined under the "umbrella" of the CarboEurope-Cluster. The 2002 CarboEurope Press event at Valencia summarized this research.

The 2001 IPCC summary emphasised the need for further carbon cycle research "Emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that are expected to affect the climate". Thus, in the 6th Framework Programme large integrated projects were introduced. Thus CarboEurope-IP was established in 2003. This research effort was further supported by integrated projects outside Europe, mainly CarboAfrica-IP, CarboNorth-IP and the PAN-Amazonia project. In addition, the need to further understand the interactions of the carbon and nitrogen cycles was emphasised by the establishment of NitroEurope-IP.

Knowledge from CarboEurope research had also entered the IPCC process, which summarized in the Forth Assessment Report that "the understanding of anthropogenic warming and cooling influences on climate has improved since the TAR, leading to *very high confidence* that the global average net effect of human activities since 1750 has been one of warming". This evidence includes the necessity for future carbon cycle research to further reduce the uncertainties and to give evidence of the effects of carbon policies during the Kyoto commitment period until 2013, and to give scientific guidance to the post Kyoto process.

Carbon Cycle Research in the EU has been administered over the past 25 years through the major efforts of the scientific officers of the European Commission: Giovanni Angeletti, Claus Brüning, Panagiotis Balabanis, Mario Catizzone, Anver Ghazi, Anastasios Kentarchos, and Pierre Mathy. The success of CarboEurope owes much to the skill and commitment of this team of the scientific officers.

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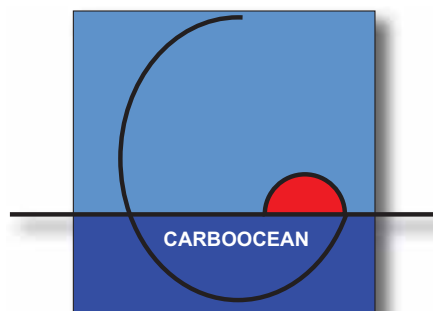
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Personal Notes

Part V:

Scientific Assessment of Marine Carbon Cycle Research in Europe

CarboOcean-IP

edited by

Christoph Heinze (coordinator), and Andrea Volbers

Bergen, 2008

1. CarboOcean-IP - Background
1.1 The Ocean as a CO_2 buffer system

1. Background

The atmospheric CO_2 concentration has been rising from a pre-industrial level of 280 parts per million (ppm) to over 390 ppm today. However, the atmospheric CO_2 content would be even higher if it were not for the fact that at present around 55% of the anthropogenic CO_2 emissions have been taken up by the land and the oceans. The ocean in particular has the most important potential as a long-term sink for anthropogenic CO_2. Latest results from the CarboOcean-IP project record the North Atlantic and the Southern Ocean showing a decrease in uptake strength for anthropogenic CO_2 compared to what was expected. Air-sea fluxes of CO_2 show high temporal (seasonal, interannual) and spatial variation as a result of variability in climate, biological activity and ocean circulation. Temporal and spatial details of the ocean sinks need to be more accurately quantified and marine physical, chemical, and biological feedbacks to climate change and rising CO_2 have to become more accurately determined. The European CarboOcean-IP project has built up worldwide links to approach these issues through a combination of field observations, process studies, and modelling in order to identify and predict changes in the oceanic sink for CO_2.
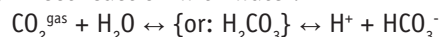
Marine carbon cycle research is of immediate relevance to informing decisions on energy production and consumption (e.g. "how quickly does the ocean buffer CO_2 from the atmosphere?"). The variability in the ocean carbon sink needs to be quantified and the growing number of highly controversial mitigation technological options for greenhouse gas geo-engineering, such as artificial ocean fertilisation, need to be critically evaluated.

1.1 The Ocean as a CO_2 buffer system

The ocean is a huge and relatively quickly-overturning reservoir for carbon (mixing times for surface waters are less than a year; intermediate waters to 800 m depth, years to decades; deep waters, decades to several centuries). The total overturning time for the ocean is approximately 1500 years. Most carbon in the ocean water column is stored as inorganically dissolved carbon (DIC), while only smaller amounts are stored as dissolved organic carbon (DOC) or particulate organic carbon (POC) (the approximate weight ratio is DIC:DOC:POC = 100:2.5:0.1, Degens et al., 1984). Freshwater can usually only hold small amounts of inorganically bound carbon. However, because seawater is slightly alkaline, with pH values around 8.3-7.5, it easily dissociates weak acids such as carbonic acid.

Gaseous CO_2 is exchanged between the surface ocean and the atmosphere according to Henry's law. Higher CO_2 partial pressure in the atmosphere than in the ocean will induce a CO_2 flux into the ocean and vice versa. The solubility of CO_2 and the equilibrium concentration of CO_2 in surface waters are largely determined by the seawater temperature. When gaseous CO_2 enters the ocean, it is partially hydrated to create carbonic acid and dissociated into bicarbonate HCO_3^- and bicarbonate CO_3^{2-}. The three inorganic carbon species in the ocean occur approximately in the following ratio $(CO_2+H_2CO_3):HCO_3^-:CO_3^{2-} = 1:100:10$. The sum of CO_2 and H_2CO_3 is called "free CO_2" and consists mainly of CO_2. The concentration of total dissolved inorganic carbon is determined by the sum of carbon included in $(CO_2+H_2CO_3) + HCO_3^- + CO_3^{2-}$. During the dissociation, the carbonic acid splits off a proton, H^+, and thus decreases the pH value. The following reactions occur after an addition of CO_2 to the water (for details on inorganic sea water carbon chemistry, please see Zeebe and Wolf-Gladrow, 2001):

(1) Direct reaction with water:
$$CO_2^{gas} + H_2O \leftrightarrow \{or: H_2CO_3\} \leftrightarrow H^+ + HCO_3^-$$

(2) Partial neutralisation through carbonate:
$$CO_2^{gas} + H_2O + CO_3^{2-} \leftrightarrow \{or: H_2CO_3 + CO_3^{2-}\} \leftrightarrow 2HCO_3^- \leftrightarrow H^+ + HCO_3^- + CO_3^{2-}$$
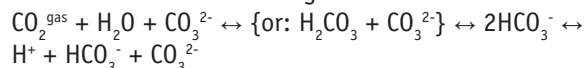
The net effect of the CO_2 dissociation is that the seawater becomes less alkaline when CO_2 is added ("ocean acidification"). From the first of the equations, it can be seen that carbonate ions (CO_3^{2-}) are required to convert free CO_2 into bicarbonate HCO_3^-. These carbonate ions can be delivered through dissolution of calcium carbonate shell material ($CaCO_3$) which has accumulated on the ocean floor. This process is of little help in neutralising fossil fuel CO_2 in the ocean because the ocean has to be mixed through repeatedly, making the timescale very long (several 10,000 years) (Archer, 2005). Because the inorganic seawater carbon chemistry is non-linear, the ability of seawater

1.2 Ultimate CO$_2$ capacity of the ocean versus uptake kinetics

to dissociate and hold additional CO$_2$ decreases with rising CO$_2$ partial pressure. Moreover, the oceanic buffer factor (e.g. Bolin and Eriksson, 1959, Zeebe and Wolf-Gladrow, 2001) varies with temperature and alkalinity. Warm waters in general have a better buffering ability than cold waters due to improved dissociation of carbonic acid with temperature. On the other hand, the solubility of CO$_2$ in seawater decreases with temperature.

The net effect of marine biological activity is to keep the surface ocean CO$_2$ partial pressure up to about 300 ppm lower (Maier-Reimer et al., 1996) than it would be for a lifeless ocean. Also the general three-dimensional distribution of dissolved inorganic carbon in the oceans is caused by biological processes (production of organic carbon at the sea surface, degradation in deeper layers). Natural variations in the carbon cycle and the atmospheric CO$_2$ concentration – especially on glacial-interglacial time scales – may be largely caused by changes in marine nutrient cycling and changes in biological processes. The oceanic uptake of anthropogenic carbon is dominated by the physical-chemical absorption of carbon. However, biological processes significantly modulate this uptake through climatically induced changes to ecosystems. The impact of ocean acidification on marine biota is an active field of research. However, the globally integrated effect on air-sea CO$_2$ fluxes is likely to be relatively small when compared to the effect of anticipated anthropogenic CO$_2$ emissions (Heinze, 2004, Ridgewell et al., 2007; Gehlen et al., 2007). The bottleneck for marine uptake of CO$_2$ is the downward mixing of water which is saturated with respect to human-made excess CO$_2$ (Bolin and Eriksson, 1959).

1.2 Ultimate CO$_2$ capacity of the ocean versus uptake kinetics

Given "long enough time", i.e. several 10,000 years, the ocean has the ability to absorb the major part of all the CO$_2$ previously added to the atmosphere by burning fossil fuel (Bolin and Eriksson, 1959; Archer, 2005). But reaching this new equilibrium between the CO$_2$ in the atmosphere and the oceans would occur long after the human-induced CO$_2$ perturbation of the Earth system. This large "**ultimate CO$_2$ uptake capacity**" is due to the inorganic CO$_2$ buffering in the ocean water column and the dissolution of calcium carbonate (or CaCO$_3$) sediments from the sea floor. The limit of CO$_2$ absorption will be reached when no further CaCO$_3$ can be re-dissolved from the sea floor. This will occur when all CaCO$_3$ that can be mobilised has left the top sediment layer which would then seal off the further potentially reactive layers below a quasi-inert "lid" of clay material (Broecker and Takahashi, 1977). This ultimate uptake capacity indicates that even after several 10,000 years the atmospheric CO$_2$ level will still be higher than the original pre-industrial level if no other mechanisms (such as weathering of silico-carbonates on land) do not very slowly reduce the remaining CO$_2$ anomaly. Further, the anthropogenic CO$_2$ invasion would have completely dissolved the marine CaCO$_3$ sediment, with unknown consequences on ocean ecology and biogeochemical cycling. These long-term effects (including the radiative effect influencing potential future glacial-interglacial cycles, Cochelin et al., 2006) must also be taken into account when considering the overall impact of anthropogenic CO$_2$ emissions to the atmosphere.

Taken as a whole, ocean processes are expected to produce a negative feedback on the elevated CO$_2$ levels from human-made CO$_2$ emissions, i.e. they will reduce these levels and act as a brake on climate change. However, how the strength of this negative feedback changes with time, and the consequent level of human-made CO$_2$ in the atmosphere, will depend on the chemical state of the ocean surface layer and the progress of oceanic mixing. It is of crucial importance to correctly quantify the marine "**CO$_2$ uptake kinetics**", that is to accurately predict how long it will take for the ocean to reach equilibrium with the atmosphere and to understand the relevant processes. Ocean model scenarios have shown, that the build up of anthropogenic CO$_2$ in the atmosphere depends on a combination of the amount and timing of the emissions (Maier-Reimer and Hasselmann, 1987), the rate of oceanic overturning, its temperature, and further biogeochemical feedbacks (Friedlingstein et al., 2006). So far, projections of the climate until the end of the 21st Century show a parallel increase in seawater temperature, increasing CO$_2$ partial pressure, and a slowing down of ocean circulation. The net effect is a slowing down in uptake rates per additional emission made. This is expected to occur as an addition to the existing bottleneck effect with the present ocean circulation. For the timeframe of the next few human generations, it is thus the timing of the marine uptake of anthropogenic CO$_2$ which is the decisive issue.

1.3 Ocean challenges

The challenge for oceanographers is to determine the inventory of anthropogenic carbon in the ocean as well as the regional and global air-sea net CO_2 fluxes, to understand the control mechanisms of the carbon cycle, and to make predictions about potential future developments on carbon re-distributions in the Earth system. What makes it such an extensive task to quantify accurately the oceanic carbon fluxes and budgets?

Compared to the atmosphere, oceanic motion is operating on long time scales and short spatial scales, the counterpart of atmospheric cyclones, the oceanic mesoscale eddies have only length scales of 2-100 km (as compared to 1000 km in the atmosphere) but can persist over several months (rather than the 1-2 weeks found in the atmosphere). In addition, the ocean is difficult to access. Either expensive research cruises are needed, or costly automated measurement equipment has to be deployed and recovered. As a result, the oceans are a highly undersampled Earth system reservoir. Only very few stations exist with long time series of data. Hence, the statistics of carbon transport within the ocean with respect to space and time are largely unknown. However, we do have remarkable new findings which give us a fairly good picture of the possible range of fluctuations in marine carbon fluxes over various time scales. These findings tell us that our picture of air-sea carbon fluxes is still very crude.

Another difficulty is the fact, that the anthropogenic carbon invasion into the ocean started long before the instrumental record of reliable high accuracy, direct measurements of total inorganic carbon and alkalinity began in the early 1990s (one always needs measurements of two carbon state variables in the ocean to fully constrain the various inorganic carbon species and the pH value). Therefore, we have no exact baseline with which to compare modern carbon measurements. The large carbon-uptake capacity of seawater makes it difficult to identify the anthropogenic perturbation of the marine carbon cycle above the natural background carbon concentration. Nevertheless, several different methods have been developed to indirectly determine the inventory of anthropogenic carbon in today's ocean that has built up since the beginning of the industrial revolution. These methods still give differing results in detecting anthropogenic carbon in some critical regions of the world ocean. Model results show that the structure of the anthropogenic carbon in the ocean deviates considerably from the natural structure (i.e. the natural surface ocean has low carbon concentrations due to biological activity, while the anthropogenic carbon concentrations at the ocean surface are highest).

To establish detailed marine carbon fluxes at the transition from continents to the open ocean - from rivers and estuaries through the shelf seas - one has to take the complex boundary conditions and large variability in ecosystem structure into account. Riverine and aeolian inputs of carbon and nutrients must also be included. At certain locations, carbon fluxes per unit area can be very high, but there is large spatial and temporal variability in the underlying processes which control the carbon budget. As yet, these difficulties make it impossible to include the global coastlines and shelf seas in a sufficiently realistic way within global carbon cycle models.

Finally, there are considerable gaps in our knowledge of natural marine carbon cycle climate feedbacks and the relevant biogeochemical processes. The largest natural atmospheric CO_2 variations, which are very well documented through ice core measurements – namely the glacial-interglacial changes in atmospheric CO_2 concentration – are not yet fully understood and the combination of processes causing them is as yet not known. Further, we do not as yet understand how marine particle fluxes and ecosystems will react in a warm and high-CO_2 world. In addition, we do not yet know the precise way in which the ocean circulation will develop in the coming decades and centuries, nor how any changes will influence the buffering of anthropogenic carbon. The lack of observational evidence and lack of process understanding leads to many processes which control the cycling of carbon in current Earth system models being only crudely parameterised. In many cases, semi-empirical formulations are used in our marine carbon cycle models. Although they draw a picture that resembles the current state of the real ocean, they may not be able to reproduce changes in the system, when the models are forced with perturbations, such as the human-induced CO_2 emissions together with other global climate and environmental changes.

The Ocean

- covers 71% of the Earth's surface but is a highly undersampled area compared to the land: It needs continuous and systematic exploration, especially with respect to ocean carbon monitoring!

- reduces significantly the amount of human-produced CO_2 in the atmosphere due to the large uptake capacity of seawater.

- a number of various but not yet fully understood processes in the ocean control the natural carbon cycle variations, e.g. glacial/interglacial changes.

- in addition to the natural amount of CO_2 in seawater, around 50% of the anthropogenic CO_2 emissions have been taken up by the oceans: this leads to ocean acidification and the consequent threats to the marine ecosystem need to be established through high quality measurements.

2. Synthesis of results from CarboOcean-IP so far
2.1 Project and consortium goals

The marine part of this report has a considerable focus on topics and results associated with the CarboOcean-IP-project "Marine carbon sources and sinks assessment" which is the European contribution to the global observation and modelling network on marine carbon. CarboOcean-IP is an FP6 Integrated Project funded over a five year period (2005-2009) with 14.5 million €. It combines the key European experts of 35 contracting partners from 14 countries, including the USA. However, the work of CarboOcean-IP is also intimately liked with marine carbon research activities in other projects. Here, we present CarboOcean-IP as a case study of a successfully working carbon cycle research project, but, of course, not as the only research activity in this field, in Europe or internationally. Explicitly, we would like to mention the US carbon cycle research programme including notably the Ocean Carbon and Biogeochemistry (OCB, http://www.us-ocb.org/) programme, with which CarboOcean-IP has links.

The CarboOcean project

- is the European contribution to the global observation network on marine carbon.

- has built up a worldwide link to the international carbon cycle research communities.

- provides a European-wide integration of latest research results on the marine carbon cycle.

- contributes to guidelines for global change policy, such as the IPCC assessment report.

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2 Synthesis of results from CarboOcean-IP so far

2.1 Project and consortium goals: a concerted effort to reduce uncertainties

CarboOcean-IP is the key FP6 Integrated Project on marine carbon sources and sinks. The project emerged from a suite of previous research projects in earlier framework programmes with the objective of integrating European marine carbon cycle research through a strong, well-organised and coordinated effort. The scientific objective was to provide more reliable numbers on large-scale air-sea CO2 fluxes. In doing this CarboOcean-IP was able to build on previous research projects, such as the internationally well-recognised FP5 studies ORFOIS, IRONAGES, TRACTOR, CAVASSOO, EUROTROPH, OCMIP (Phase 1 and Phase 2), GOSAC, NAOC, and NOCES. These projects were more focused, each specifically targeting a special aspect or discipline of marine carbon cycle research:

ORFOIS – fate of biogenic particle fluxes as well as sedimentation and their relation to carbon cycling,
IRONAGES – role of iron in biogenic carbon cycling,
TRACTOR – tracer transport in northern deep-water production areas,
CAVASSOO – estimate of North Atlantic carbon uptake through voluntary observing ships,
EUROTROPH – nutrient and carbon cycling in coastal seas,
OCMIP – carbon cycle model intercomparison,
GOSAC – modelling the ocean carbon uptake taking into account deliberate carbon storage,
NAOC – remote sensing of bio-optical properties in the ocean,
NOCES – interannual to decadal variability of air-sea CO_2 fluxes.

It was recognised that the results of these successful projects needed exploitation in a concerted effort that would bring the different streams of research together, make their work interoperable, tackle the fragmentation of the European research area on marine carbon research and maintain the international competitiveness of the European research community. In the early years of this decade, the European marine carbon research community was not as well organised as the terrestrial research community in the FP5 CarboEurope Cluster. Pioneering work was needed to coordinate the marine carbon cycle community. The "new instrument" of the FP6 "Integrated Project" proved to be optimally suited for accomplishing just such an integration of marine carbon cycle research. The design of the CarboOcean-IP Integrated Project involved the key research leaders of previous projects, who together created a horizontal project structure with five major "core themes". The project planning started with an experts' meeting at the Royal Dutch Academy of Sciences in Amsterdam, in April 2002. The project started officially on 1 January 2005, and will continue until 31 December 2009. The CarboOcean-IP results cited in this report thus do not represent

the final products of the project, but reveal insight into the very successful on-going work of the CarboOcean-IP consortium.

The main aim of CarboOcean-IP is to reduce the present uncertainties in the quantification of net annual air-sea CO_2 fluxes by a factor of two for the world ocean and by a factor of four for the Atlantic Ocean. The project will deliver description, process-oriented understanding and prediction of the marine carbon sources and sinks with special emphasis on the Atlantic and Southern Oceans on a time scale –200 to +200 years from now.

The specific scientific objectives of the project and current progress are (**Fig. V.1**):

1. Description and quantification of the CO_2 air-sea exchange on a seasonal-to-interannual scale for the Atlantic Ocean and the Southern Ocean:
An observing system for surface marine CO_2 in the Atlantic has been implemented. Methods for diagnosing and predicting the Atlantic and Southern Ocean CO_2 sinks through a combination of in situ measurements, satellite data, and models have been developed.

2. Quantification of decadal-to-centennial large-scale Atlantic and Southern Ocean carbon inventory changes:
The Atlantic and Southern Ocean carbon sink, and its decadal change, are being quantified through highest accuracy measurements of the changing inventories of inorganic carbon and carbon-related tracers. Atlantic and Southern Ocean data have been integrated into a coherent global database. The ability of prognostic models to represent the observed changes for a reliable nowcast is being assessed.

3. Quantification of the carbon sources and sinks at the European regional scale:
The variability of carbon uptake and release, as well as the exchange of marginal seas with both the land and the open Atlantic Ocean, is being determined. A pilot study on establishing a closed carbon budget for Western Europe combining the marine, terrestrial, and atmospheric compartments is under way in cooperation with the CarboEurope IP.

4. Identification and understanding of biogeochemical feedback mechanisms which control marine carbon uptake and release:
The quantitatively important feedbacks between CO_2 partial pressure and other carbon cycle variables are being identified and analysed. Quantitative descriptions that can be used in models have been derived. Key regions for feedback processes have been identified and strategies to monitor the evolution of feedbacks are being developed.

5. Integration of carbon observations into an integrated prognostic modelling framework:
Best possible science-based projections of ocean carbon sink behaviour for scenarios of future energy use and climatic change have been carried out. The initial conditions for the scenarios have been provided through model fields which have been validated with observations. The models include revised formulations of new biogeochemical feedback mechanisms.

A further goal of CarboOcean-IP is to coordinate data collection and modelling, in particular to improve coordination with marine carbon cycle research activities in the US.

CarboOcean-IP is structured into five major "core themes" which directly correspond to the five major goals presented above:

1. North Atlantic and Southern Ocean CO_2 air-sea exchange on a seasonal-to-interannual scale.
2. Detection of decadal-to-centennial Atlantic and Southern Ocean carbon inventory changes.
3. Carbon uptake and release at the European regional scale.
4. Biogeochemical feedbacks on the oceanic carbon sink.
5. Future scenarios for marine carbon sources and sinks.

The CarboOcean-IP consortium was selected to combine the key European research institutions for marine carbon cycle research. The consortium of contractors and associate partners consists of about 200 scientists from Norway, Sweden, Denmark, United Kingdom, Germany, France, Belgium, Switzerland, The Netherlands, Poland, Iceland, Spain, Ireland, Morocco, Canada, and the United States of America. Altogether 50 different groups are working in CarboOcean-IP, including 35 contracting partners. The project is being coordinated by the University of Bergen and the Bjerknes Centre for Climate Research in Bergen, Norway. Theses institutions host the project office with the coordinator, scientific project manager, financial/administrative project manager, and a scientific data manager.
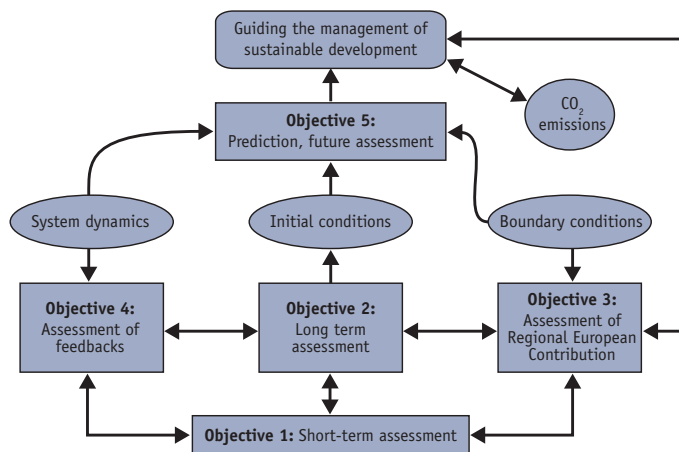
Fig. V.1: Goals/core themes/objectives of CarboOcean-IP (Source: CarboOcean-IP consortium). Core Theme (CT1, objective 1) provides a description and quantification of the CO_2 air-sea exchange on a seasonal-to interannual scale for the Atlantic Ocean and the Southern Ocean which is extended by CT2 to a decadal-to-centennial time-frame also involving the deep ocean (objective 2). A special focus is on the quantification of the carbon sources and sinks at a regional scale (CT3, objective 3). CT4 deals with the identification and understanding of biogeochemical feedback mechanisms which control marine carbon uptake and release (objective 4). Finally, the new data and knowledge will be integrated into CT5 where prognostic modelling with complex climate models is carried out to finally help guide sustainable development management (objective 5: prediction and future assessment).

2.2 Variable sink strength in North Atlantic and Southern Ocean

The key regions of the World Ocean that govern the uptake of anthropogenic carbon are those areas where water is transported downward from the surface to greater depth. In these regions, surface water, that carries high loads of anthropogenic carbon, can reach deeper layers through intermediate and deep-water production mechanisms, while water that is not yet saturated with respect to anthropogenic carbon enters the upper ocean. Because the water column is stably stratified in most parts of the ocean, there is normally little exchange of water between the surface and depth: downward transport of anthropogenic carbon only occurs in the intermediate and deep-water production areas which, acting as a bottleneck, thus play a decisive role in the ocean's uptake kinetics with respect to man-made carbon. Such deep and intermediate water production areas exist in the northern North Atlantic, especially in the Labrador Sea, the Greenland Sea, and the Arctic Ocean margin. They also occur in the Southern Ocean, especially in the Weddell and Ross Seas and at the Sub-Antarctic Front. The North Atlantic and Southern Ocean therefore carry a considerable load of anthropogenic carbon (Sabine et al., 2004). It is particularly important to quantify the carbon sinks in these key areas and to assess potential changes and variability in sink strength.

An accurate assessment of the entire North Atlantic carbon sink is equally important, because it is needed to make reliable quantitative estimates of the air-land CO_2 fluxes for North America and Eurasia. The internationally binding commitments on greenhouse gas reductions require accurate estimates of regional emissions. Without precise knowledge of the oceanic carbon sink, there would be considerable ambiguity associated with estimates of carbon fluxes solely based on air-land flux data.

For the Atlantic Ocean, especially the North Atlantic, a carbon observing system, first implemented in the EU CAVASSOO project (2000-2003), is now fully operational in Core Theme 1 of CarboOcean-IP (2005-2008). Forming the backbone of this observing system are automated measurements of the partial pressure of CO_2 (pCO_2) in sea surface water and marine air, and surface water salinity and temperature. A series of automated systems are installed mainly on commercial ships (voluntary observing ships, "VOS lines", **Fig. V.2**) with a regular and frequent sailing schedule, but also on research vessels (**Table 1**). Notwithstanding the difficulties in the approach, such as the occasional rescheduling of commercial ships, these measurements are providing unprecedented observational data coverage of Atlantic CO_2 surface partial pressures and air-sea pCO_2 differences.

GPS system — Atmospheric sampling tube — Electronics/detector — Seawater system
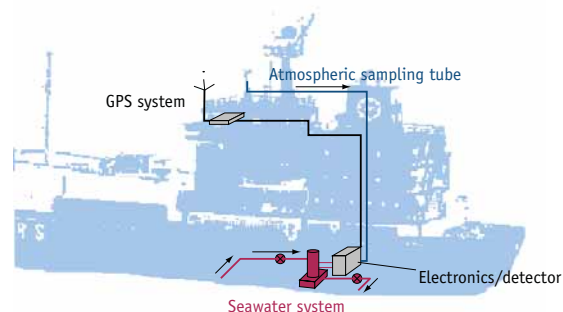
Fig. V.2: The North Atlantic carbon observing system is one of the highlights of the CarboOcean programme. The temperate and sub-polar Atlantic has been investigated with the help of VOS-lines ("voluntary observing ships") to reduce the uncertainty in the North Atlantic sink by providing seasonal and annual regional air-sea CO_2 fluxes with unprecedented accuracy. In order to continue to obtain new data, commercial ships, such as the MV Benguela Stream ("Banana boat" to the left) were also equipped with a pCO_2 measurement system. With the help of these continuous data, scientists can monitor the North Atlantic sink and quantify how the CO_2 uptake changes over time and varies for different latitudes. (Source: T. Steinhoff and U. Schuster)

Ship	Period	Region	Route	Frequency	PI, Institution
Nuka Arctica	2005-2009	North Atlantic	Aalborg (Denmark) – Nuuk (Greenland)	Monthly	A. Olsen, T. Johannessen Bjerkness Center, Bergen, Norway
Skogafoss	1993-	North Atlantic	Iceland – Newfoundland (Canada)	3-4 / year	G. Reverdin, N. Metzl, R. Wanninkhof LOCEAN, Paris, France NOAA, Miami, USA
MV Atlantic Companion	2006-present	North Atlantic	Liverpool (U.K.) – Halifax (Canada)	2 per 5 weeks	A. Körtzinger, D. Wallance IfM-GEOMAR, Kiel, Germany
Explorer of the Seas	2004-present	North Atlantic	Caribbean (winter), Bermuda – Newark- Caribbean (summer)	Weekly	R. Wanninkhof NOAA, Miami, USA
TransCarrier	2005-present	N. Atlantic and North Sea	Amsterdam (NL) – Bergen (Norway)	Weekly	A. Omar, T. Johannessen Bjerkness Center, Bergen, Norway
MV Benguela Stream	1994/95, 2002-present	North Atlantic	Portsmouth (U.K.) – Caribbean	4 weekly return	U. Schuster, A.J. Watson UEA, Norwich, UK
Quima line	2005-present	Atlantic	U.K. – Cape Town (South Africa)	Monthly	M. Gonzalez-Davila U. Las Palmas, Spain
Elisa-B (BOLUDA group)	2007-present	Atlantic, Mediterranean	Canary Islands - Italy	Monthly	M. Gonzalez-Davila U. Las Palmas, Spain
MN Colibri	2006-present	Atlantic	France - Brazil	6 / year	N. Lefèvre LOCEAN, Paris, France
Monte Olivia	2007-present	Atlantic	France - Brazil	6 / year	N. Lefèvre LOCEAN, Paris, France
Las Palmas	2005-present	Atlantic	Cartagena (Spain) – Rio de Janeiro (Brazil) - Ushuaia (Argentina)	2 / year	A. Ríos CSIC-IIM, Vigo, Spain
Marion Dufresne / OISO	1998-present	Indian and Southern Ocean	Reunion – Crozet –Kerguelen – Amsterdam Island	2 / year	N.Metzl LOCEAN, Paris, France

Table 1: Some of the current voluntary observing ships with data collection for pCO_2 or other carbonate parameters, their schedules and the scientific institution responsible. The network is operated by EU CarboOcean-IP investigators and US partners (after IOCCP, 2007). A full list of past and present VOS worldwide is given in the 2007 IOCCP report.
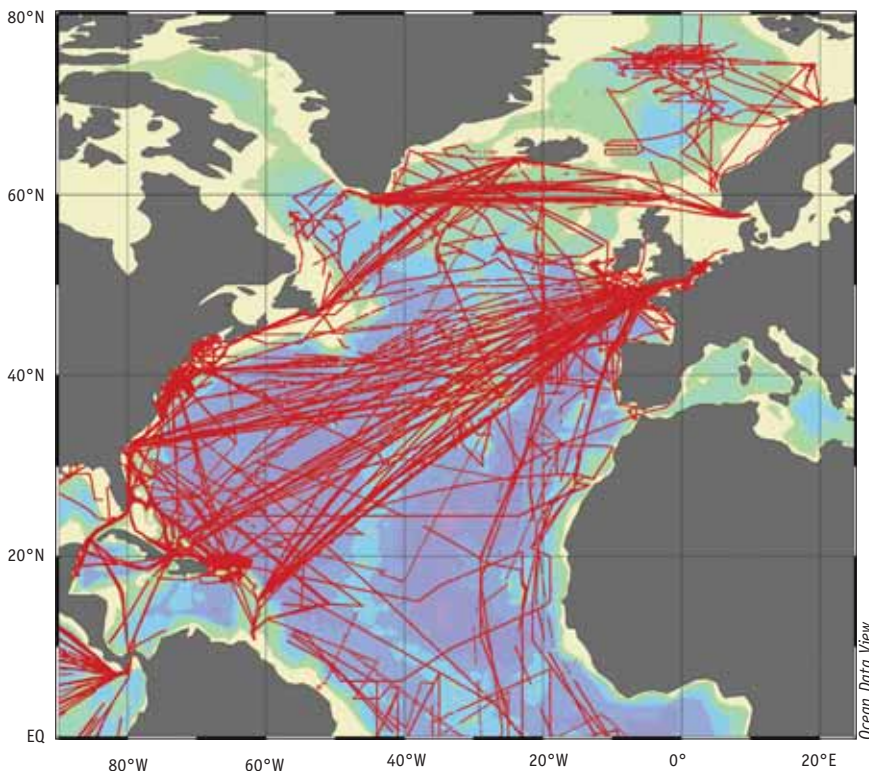
Fig. V.3: The CarboOcean-IP programme not only employs research vessels, but also commercial ships. These volunteer observing ships (VOS) help to efficiently create a large database at rather low cost. This figure shows the cruise tracks of the VOS lines used in the northern Atlantic Ocean. (Source: CarboOcean-IP 2008, 3rd annual report, Andrew Watson and colleagues)

The North Atlantic carbon observing system represents a major achievement for CarboOcean-IP: it is the first ever operational, multi-ship CO_2 observing programme, covering an ocean basin and reporting regularly and rapidly into a database (**Fig. V.3**) (e.g. Lüger et al., 2006; Schuster and Watson, 2007; Olsen et al., 2008). As the observations sample only a small part of the ocean, suitable methods have to be used to interpolate the measurements and to upscale local CO_2 fluxes between air and water to a larger area. This is carried out with a procedure based on the existing in situ data, using interpolation techniques, ocean general circulation models, remote sensing data, and data assimilation methods. Based on the observational sea surface pCO_2 data, pCO_2 maps have been created by a number of methods, including neural networks and multi-linear regression (Olsen et al., 2008; Telszewski et al., 2008). Estimates of North Atlantic sea surface pCO_2 (such as the estimate for 2005 shown in **Figure V.4**) can now be made annually and for most seasons to within a 10% relative error. This is an unprecedented accuracy for basin wide estimates. The overall North Atlantic CO_2 sink has been calculated to be 70 percent of the climatological average. This is substantially less than the "Takahashi climatology" for the region (Takahashi et al., 2002; Takahashi et al., in press). This change reflects our previous conclusion that the flux in the region as a whole has declined over the last decade (Lefèvre et al., 2004; Omar and Olsen, 2006, Corbière et al., 2007, Schuster and Watson, 2007) (**Fig. V.5**).
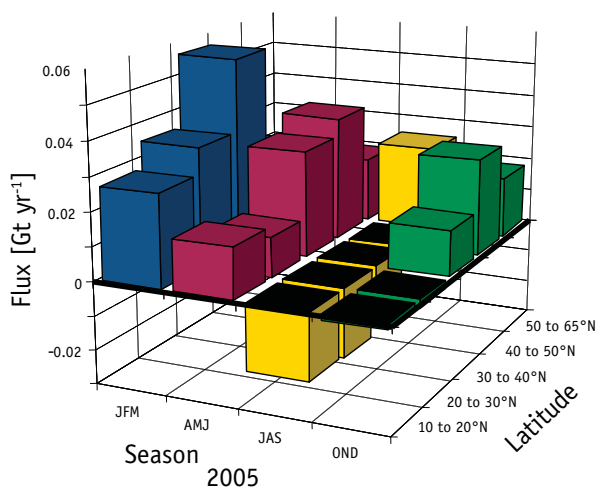

Fig. V.4: From detailed investigation in the North Atlantic region, we know that the North Atlantic carbon sink strength depends on latitude and varies seasonally as shown in this diagram for the year 2005. Fluxes from the atmosphere into the ocean were highest between 30-40 ºN during January to July 2005. High latitude waters took up CO_2 during the whole year, whereas the lower latitude waters took up CO_2 during January to June 2005. However the latter then released some of it again to the atmosphere during the rest of the year, especially during the summer period (July to September). These results are based on data from the CarboOcean-IP observing system. (Source: Andrew Watson)

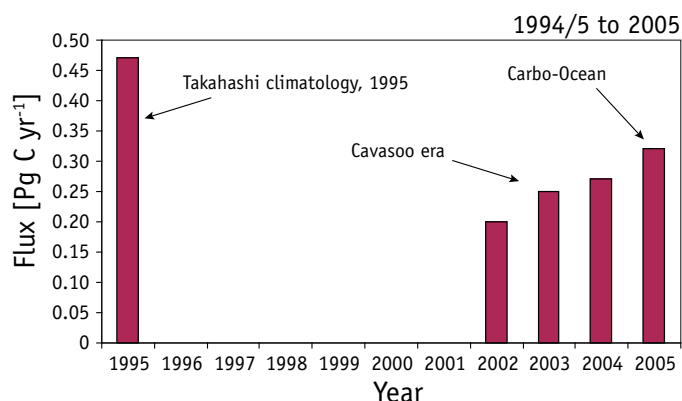*Fig. V.5: Varying North Atlantic sink strength as deduced from a suite of collaborative projects. In the early years of the 21st century the North Atlantic CO_2 sink was only 50% of that in the mid-1990s. Recent data show that the CO_2 sink is slowly recovering. These findings show that the CO_2 sink is highly variable; continuous observations are needed to capture this variability. (Source: Andrew Watson)*

However, evaluation of more recent pCO_2 measurements indicates a partial recovery of the North Atlantic sink in 2006 and 2007 (Schuster and CarboOcean-IP-Team, 2008) (**Fig. V.6**), emphasising the need for sustained long-term observations of air-sea carbon fluxes in key regions of the world ocean (IOCCP, 2007; Metzl et al., 2007). The international context provided by EU funding is ideal for operating such an observational network, as no single country can run more than a few VOS lines.

A series of data assimilation and interpolation procedures for upscaling the measurements to basin wide fluxes has been tested and successfully applied. These techniques, which include neural network and adjoint modelling techniques, also take into account biologically induced variations of sea surface pCO_2 through a combination of process parameterisations in the models, in situ measurements, and chlorophyll data derived from ocean-colour satellite measurements.

To assess Southern Ocean air-sea CO_2 fluxes, a comprehensive observational programme is being carried out; surface water CO_2 observations and process studies in the Atlantic and Indian sectors of the Southern Ocean are already underway. A total of six freely drifting CARIOCA buoys equipped with CO_2 sensors have been deployed in the Southern Ocean. A first estimate based on the CARIOCA measurements indicates 0.8 Pg C yr^{-1} of CO_2

uptake in the sub-Antarctic zone. Analysis of a large ship-database south of Tasmania has revealed locally in the sub-tropical-zone and in the sub-Antarctic-zone very significant inter-annual variability related to the Southern Annular Mode using a purely observational approach (Borges et al. 2008). Locally, large pCO_2 variations due to biological export production have been observed near the Sub-Antarctic Front and the Crozet and Kerguelen Islands (Bakker et al., 2007; Jouandet et al., 2008) by shipboard and buoy measurements, and satellite observations. Ice covered CO_2–rich waters were found to rapidly change to a major CO_2 sink in the Weddell Sea during sea ice melt in early summer (Bakker et al., 2008). Using a combination of forward modelling and data-driven inverse atmospheric simulations, Le Quéré et al. (2007) could attribute a decrease in the CO_2 sink strength for the Southern Ocean from 1992 to 2004 to interannual variation in the climate system. This is in line with direct observations of the sea surface CO_2 partial pressure, which so far at least leads to the conclusion that the sink for atmospheric CO_2 in the Indian Ocean sector of the Southern Ocean has not increased during recent years (though the atmospheric CO_2 continued to rise). Following up this issue is a challenge for the experimental oceanographers because of the low data coverage for the remote Southern Ocean, which few ships visit in the winter months.

A "big-box" view

Trend atmosphere: + 1.7 µatm yr^{-1}
Trend ocean: + 2.1 µatm yr^{-1}

Ocean sink decreases? - 0.4 µatm yr^{-1}
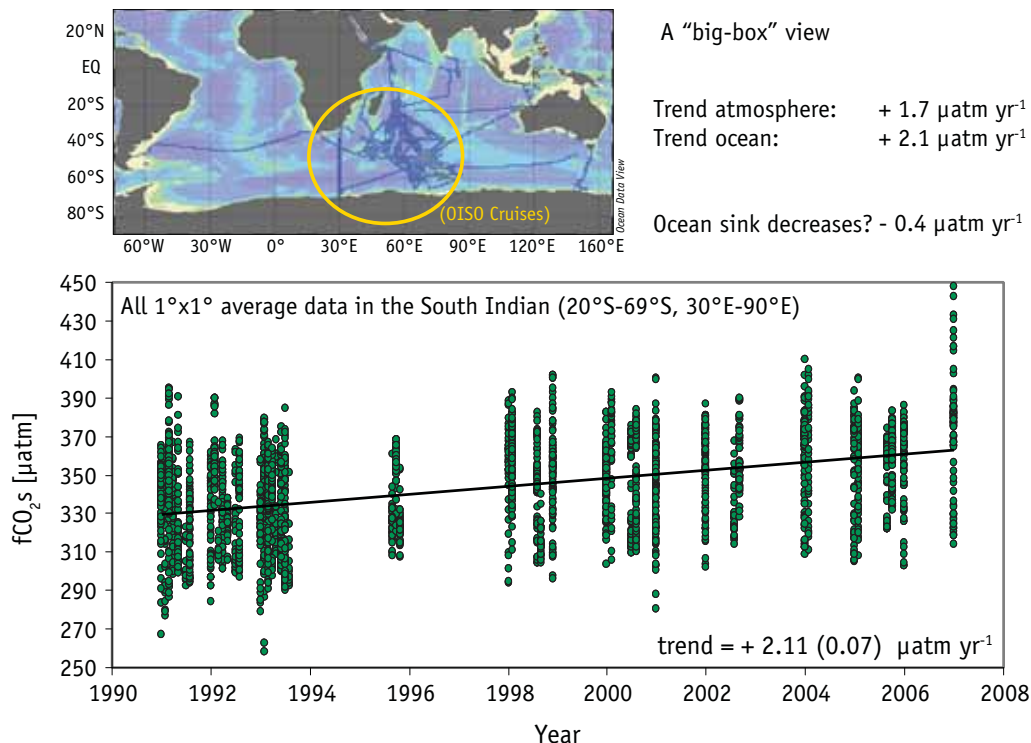
Fig. V.6: Surface ocean CO_2 trend for the Indian Ocean section of the Southern Ocean based on direct in situ measurements. The flux of CO_2 between air and water depends on the difference in CO_2 concentration in the atmosphere and the surface ocean. The surface ocean CO_2 partial pressure appears to rise faster than the atmospheric CO_2 partial pressure indicating the possibility of a decrease in Southern Ocean sink strength for anthropogenic CO_2. The figure is based on data published by Metzl (2008).

2.2 Variable sink strength in North Atlantic and Southern Ocean

Major achievements:

The establishment of an operational CO_2 observation network providing seasonal and annual basin-wide CO_2 flux estimates for the North Atlantic for 2005 to 2008.

Improved understanding of processes (natural iron supply, sea ice cover) driving CO_2 air-sea fluxes in the Southern Ocean.

Robust findings:

North Atlantic and Southern Ocean both show (at least transient) decrease in uptake strength for CO_2.

Air-sea fluxes of CO_2 show a high temporal (seasonal, interannual) and spatial variation as a result of variability in climate, biological activity and ocean circulation. We cannot yet justify giving a single number for the oceanic uptake of anthropogenic CO_2 in the key regions of the North Atlantic and Southern Ocean, but valid flux estimates for selected periods and regions have been successfully calculated.

Key questions:

The data coverage for in situ CO_2 partial pressure measurements needs to be increased. For the North Atlantic a reasonably good coverage has been achieved since 2005 using regular VOS lines, but no funding is available to maintain the observational network after 2008. Regular VOS data collection requires sustained and long-term funding. An international framework is ideal for coordinating Carbon Observing systems.

The CO_2 fluxes in the remote Southern Ocean are poorly known.

The reason for the decrease in CO_2 sink strength is not yet fully understood, in particular we need to unravel the interdependency of physical, large-scale forcing, biological activity, and lateral transport of water with varying degrees of anthropogenic carbon loads. A dense observational network and higher resolution modelling is needed.

2.3 Best estimates of anthropogenic carbon water column loads and their changes

Detecting the current amount of anthropogenic carbon in the ocean is a major research challenge. The sparseness of the available observations, the varying three-dimensional fields in the ocean, the small signal to noise ratio, and the lack of high accuracy data before the 1990s, all make it difficult to establish global-ocean, anthropogenic carbon uptake. In fact, we have no direct data at all from before the industrial revolution, from which to derive the carbon content of the unperturbed ocean. It is even more difficult to establish decadal changes in oceanic water column storage. The best prospect of filling this gap in our knowledge is to use techniques that track backwards in time. These techniques use our knowledge of the thermohaline circulation of the ocean, ocean biological processes, ocean chemistry, sedimentation, climate change and air-sea gas exchange, to reconstruct the past oceans carbon cycles. Similarly, we can then also project the future ocean anthropogenic carbon uptake.

As the net uptake of anthropogenic carbon by the ocean proceeds, there is a corresponding increase in the within-ocean inventory of carbon. This change in the oceanic carbon inventory is quantitatively equivalent to the oceanic carbon sink and reflects the integrated effects of the direct and indirect human perturbations of the carbon cycle. The 3-D carbon analysis within CarboOcean-IP is working to quantify this integrated carbon sink using observations and models of changes in carbon stored within the ocean. The WOCE / JGOFS Global CO2 Survey of the 1990s produced an initial estimate of the anthropogenic CO2 inventory of the World Ocean based on observations, as well as several model runs. So far, the observational estimates have tended to focus on the overall inventory of anthropogenic CO2 (i.e. the "extra" inorganic carbon stored in the ocean since about 1750). Although there is some controversy and disagreement over estimation methods, overall, the uncertainties of such approaches in estimating total inventories of anthropogenic CO2 in the oceans are well recognised. The uncertainties in observational approaches relate to doubtful assumptions; for model realisations, the uncertainties lie with the parameterisation of complex ocean dynamics, including representation of key vertical motions. The Southern Ocean is one particular area where the uncertainties are particularly noticeable and important.

CarboOcean-IP scientists, and international collaborators from other programmes, have carried out an enormous synthesis task in the field of ocean-interior carbon data collection and documentation, producing a consistent, high quality data set for the Atlantic Ocean. Here, CarboOcean-IP scientists are working closely with scientists from all over the world in a global ocean carbon synthesis approach motivated by the following international projects: Surface Ocean Lower Atmosphere Stud-

ies (SOLAS) and Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) Joint Carbon Group, and the International Ocean Carbon Coordination Panel (IOCCP) sponsored by the IGBP, SCOR, WRCP and UNESCO. An enormous collection of previously unavailable carbon, tracer, oxygen, nutrient and hydrographic data from the North Atlantic and sections of the Southern Ocean are now to be found in the CARINA data set. This data set is already publicly available. But the final quality-checked data will be published during the autumn to early winter 2008 and will include all data produced up to 2006.

During the course of this work new routines for correcting data, crossover techniques etc., have been developed. These are now available to all seagoing scientific groups in the world and serve as best practice for data correction and for obtaining consistency between cruises. Applying these common procedures will help to keep consistency between data sets. CarboOcean-IP scientists have made a strong contribution to building up these routines. A series of CarboOcean-IP research cruises have also collected new deep-section carbon datasets of the highest accuracy.

A suite of methods is available for calculating anthropogenic CO_2 content in the ocean. These methods are based on different carbon-related measurements and correct for processes, like biology, that also affect the ocean CO_2 concentration: CFC-shortcut (Thomas and Ittekkot, 2001), TTD transit time distributions (Waugh, 2004, 2006), TroCA (Touratier and Goyet, 2004), IPSL method (Lo Monaco et al., 2005), ΔC^* (Gruber et al., 1996, Matsumoto and Gruber, 2005), eMLRs (Friis et al., 2005) and the Tanhua approach (Tanhua et al., 2007).

The answers provided by these methods still differ. Most of the methods are not very reliable in high latitude environments, but in general, and looking at the globe as a whole, they perform relatively well – especially considering that the low concentration of anthropogenic CO_2 makes it difficult to measure. Some areas, like the sub-polar gyre system in the North Atlantic Ocean, are relatively uncritical because of the high uptake of anthropogenic CO_2 in these areas. We need to assess how deep the anthropogenic CO_2 has penetrated and how far the anthropogenic CO_2 has followed the deep current systems which originate from source waters produced by deep-water formation, but this is a difficult task. Most of the uncertainties stem from lack of measurements and low data coverage in time and space. But still from a global perspective the different approaches give a relatively consistent mean. Nevertheless, improvement is still needed to reduce the uncertainties. In general, there is a strong need to understand the processes related to anthropogenic CO_2 uptake, how they vary in time and space, and how sensitive they are to climate and environmental changes. **Figure V.7** gives an example for the North Atlantic Ocean of the reconstruction of anthropogenic carbon loads in the water column.
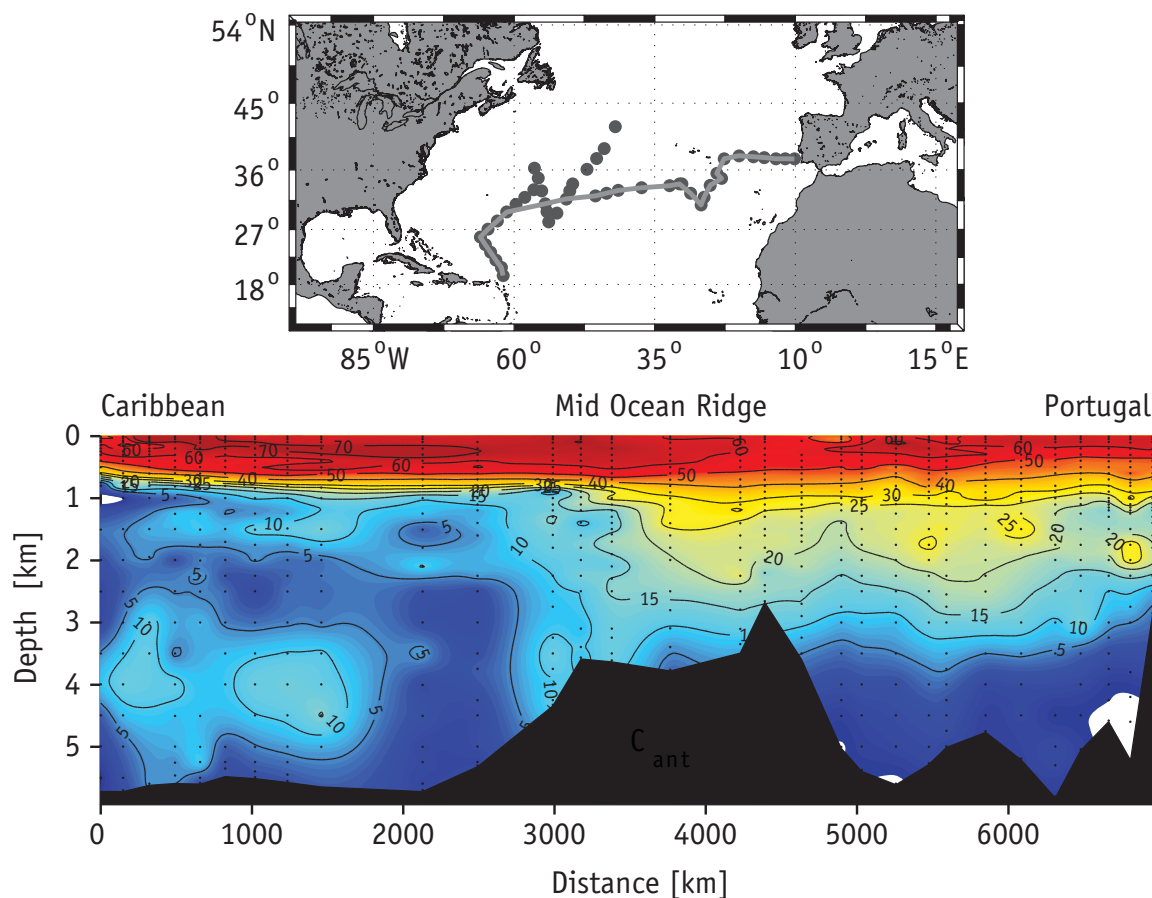
Fig. V.7: Detection of existing anthropogenic carbon (C_{ant}) in the ocean is challenging, as we do not have direct measurements of the oceanic carbon before the industrial revolution. How deep has the anthropogenic CO_2 penetrated and how far has it followed deep current systems which originate from source waters produced by deep-water formation? Here we show anthropogenic carbon (µmol/kg) estimate using extended Multilinear Regression on repeat hydrographic data from the Meteor cruise 60/5 in 2005 and the TTO-NAS data from 1981. The estimates have been scaled to cover the full anthropogenic period. The dots on the map are the stations for the 2004 cruise, and the grey line (upper panel) corresponds to the section shown in the lower panel. Red to yellow: high anthropogenic CO_2 concentrations in the surface and parts of the intermediate waters, light to dark blue: rather low anthropogenic CO_2 concentrations in the deep waters. (Source: T. Tanhua)

In addition to these back calculation methods, forward models as well as inverse methods have been used to estimate the anthropogenic carbon inventory in the oceans and to investigate how it might vary. Five different Earth system models have been forced with anthropogenic CO_2 emissions as compiled by Marland et al. (2007) for the period 1751-2004. The water column anthropogenic CO_2 burdens for all models show the maximum in the North Atlantic, as do the data-derived methods of, e.g., Sabine et al. (2004). However, there are considerable differences between these methods, especially in the Southern and Pacific Oceans. The inverse approach has been presented in papers by e.g. Brewer et al. (1989), Holfort et al. (1998), Alvarez et al. (2003), and, most recently, by Mikaloff Fletcher et al (2007). **Figure V.8** shows a summary of anthropogenic carbon storage and transport estimates across zonal sections taken from a number of published studies. In principle, they estimate the anthropogenic carbon content along East-West going sections.

The transport direction of currents is perpendicular to these sections, and thus oriented North and South. The transport rate and the anthropogenic carbon content in the East-West sections will balance if correct. The change in ocean storage can be seen as the difference in air-to-sea transfer today compared to that 200 years ago – before the industrial revolution. This inversely determined "perturbation flux" cannot be measured directly, but can be a significant component of the air-sea CO_2 flux as estimated by direct sea surface pCO_2 measurements. The two approaches correspond to the 'dual approach' as pursued by the terrestrial CarboEurope community, where the inverse method represents the "top-down" and the direct pCO_2 measurements the "bottom-up" methodology. The backtracking methods used by oceanographers are a similar approach, but here the transfer is estimated from differences between today's and the pre-anthropogenic ocean.
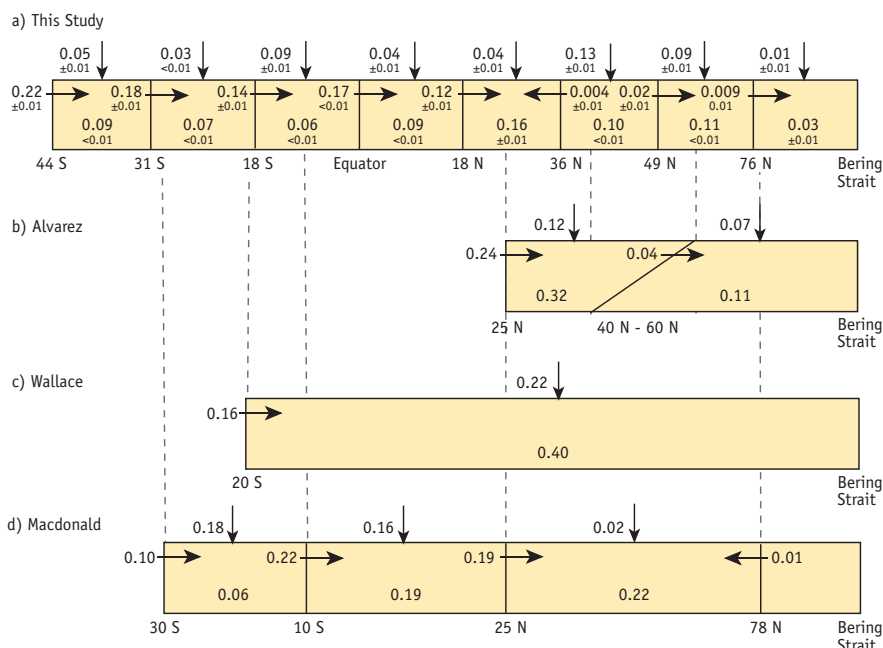
Fig. V.8: Summary of the anthropogenic carbon uptake, storage and transport in the Atlantic Ocean (Gt C yr-1) based on different data analysis studies (panels a, b,c, and d) as given by Mikaloff Fletcher, S.E., N. Gruber, A.R. Jacobson, S. C. Doney, S. Dutkiewicz, M. Gerber, M. Follows, F. Joos, K. Lindsay, D. Menemenlis, A. Mouchet, S. A. Müller, and J. L. Sarmiento, Inverse estimates of anthropogenic CO_2 uptake, transport, and storage by the ocean, Global Biogeochem. Cycles, 20, GB2002, doi:10.1029/2005GB002530. Copyright [2006] American Geophysical Union. Reproduced by permission of American Geophysical Union. The boxes from left to right indicate the different oceanic regions starting in the south and ending in the Arctic Ocean. Horizontal arrows indicate transport with ocean currents, vertical arrows the uptake from the atmosphere. Accurate transport rates are still difficult to quantify due to the sparseness of observations.

Fig. V.9: Oxygen concentration is a carbon-related property that carries valuable information concerning changing ocean carbon levels: It can be measured at high density and used to guide interpolation between sparse inorganic carbon measurements. CarboOcean-IP therefore includes a technology development and application component that seeks to advance our ability to monitor oxygen (and ultimately carbon) inventories from a new generation of profiling floats. This figure introduces an example of such a profiling float: (a) shows an oxygen float track in the Labrador Sea Gyre (positions of weekly surfacing are indicated by symbols). (b) gives examples for measured vertical oxygen profiles, and (c) an oxygen inventory time series in the upper 1400 m and the mixed-layer, as based on 42 weeks of measurements. From Koertzinger, A., Schiemanski, J., Send, U and Wallace, D. (2004). The ocean takes a deep breath. Science Vol 306, 19.11.2004. Reprinted with permission from AAAS.

2.3 Best estimates of anthropogenic carbon water column loads and their changes

As the high quality data set for oceanic inorganic carbon grows, it is becoming possible to estimate the carbon increase directly, from repeated observations. Closely associated with this ability to measure changes in ocean carbon inventories is the increasing ability to sample and measure the ocean interior using autonomous observation techniques. In particular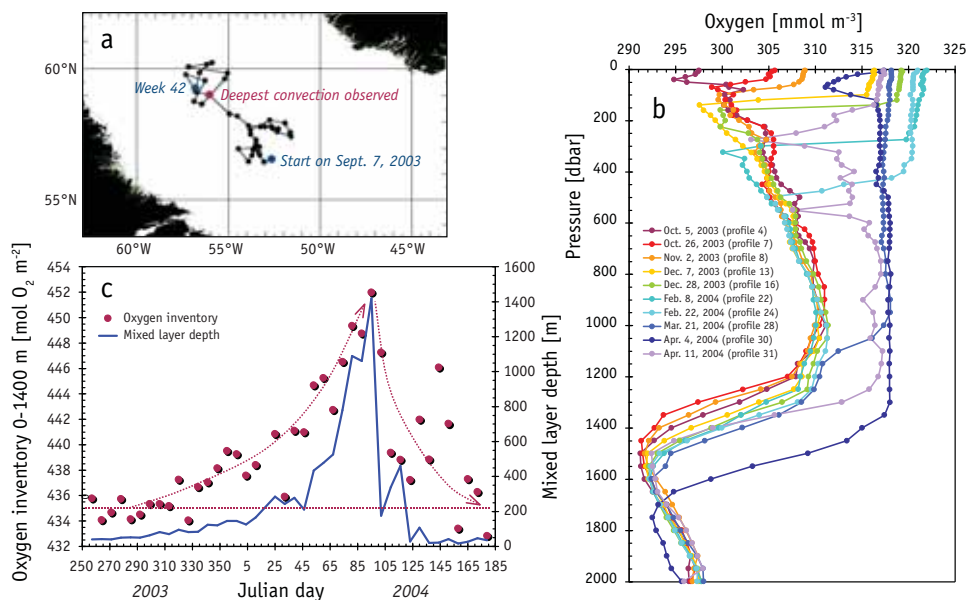, oxygen content is a carbon-related property that carries valuable information concerning changing ocean carbon levels both in the ocean and the atmosphere. Oxygen data are used in almost all anthropogenic carbon estimation approaches: oxygen, O_2, is a tracer of water mass ventilation (or how often, how well, and since when, the water has equilibrated with the atmosphere), which, because it can be measured at high density, can be used to guide interpolation between sparse measurements of inorganic carbon. CarboOcean-IP includes a technology development and application component that is advancing our ability to monitor oxygen (and ultimately carbon) inventories from a new generation of profiling floats. An example of the use of these floats is given in **Figure V.9**.

A new international joint Argo-Oxygen programme is planned to determine, on a global-scale, seasonal to decadal time-scale variations in sub-surface dissolved oxygen concentrations. The technique and its implementation are developed in CarboOcean-IP WP10. The suggested approach is to add dissolved oxygen sensors to the floats of the successful Argo array, thus extending its measurement capabilities. Such a development will provide new measurements of a key quantity for ocean ecology and biogeochemistry, and allow study and quantification of a diverse and crucial set of processes.

These processes include the detection of the oceanic impact of global warming on ocean biogeochemistry and circulation, the addition of unprecedented constraints on the export of biologically formed organic matter, and improved estimates of the oceanic uptake of anthropogenic CO_2. The addition of oxygen to the currently measured suite of temperature and salinity on Argo will represent a revolutionary step in our ability to observe the ocean's evolution over time, integrating biogeochemical and physical observations.

The following issues justify the approach:

- Detect changes in ocean biogeochemistry and climate,
- Improve atmospheric O_2/N_2 constraint on ocean/land partitioning of anthropogenic CO_2 ,
- Determine seasonal to interannual changes in oxygen in sub-mixed layer waters as a proxy for net community production and export production,
- Aid interpretation of variations in ocean circulation/mixing,
- Provide constraints for ocean biogeochemistry models,
- Aid in interpretation of sparse data from repeat hydrographic surveys,
- Determine transport and regional air-sea fluxes of oxygen and finally,
- Prediction and assessment of anoxic or hypoxic events.

Robust findings:

The findings from independent approaches (data analysis, forward, and inverse modelling) seem to converge and lead to the conclusion that:

- the ocean has indeed taken up large amounts of anthropogenic carbon since the pre-industrial era, and

- the maximum for the water column burdens of human-made CO_2 is in the northern North Atlantic close to the areas of deep convection,

- the Southern Ocean also carries significant amounts of anthropogenic carbon.

Key questions:

The data coverage in the Southern Ocean is still small. Interdecadal variations in anthropogenic carbon storage can so far only be determined for the limited regions where there is sufficient data coverage.

Measurements of oxygen and carbon through autonomous floats need to be considerably extended in order to allow better estimates (top-down) of integrated air-sea CO_2 fluxes and carbon storage.

2.4 Carbon fluxes at the transition land- shelf sea - open ocean

2.4 Carbon fluxes at the transition land- shelf sea - open ocean

A comprehensive understanding of the carbon balance at a continental scale must include all the relevant compartments: land, atmosphere as well as coastal and open oceans. Land, atmosphere and coastal ocean maintain a triangular relationship, with exchange of matter and energy between all compartments and in all directions. The coastal ocean is highly variable, with a complex pattern of fluxes, for example: riverine inputs deliver a variety of compounds from the terrestrial to the coastal ocean compartment; the intrusion of salt water into rivers or directly onto land, as regular (e.g. tides) or extreme events, produces transport of matter in the reverse direction; deposition of terrestrial material to the coastal ocean via the atmosphere is another pathway. Airborne and riverine nitrate supply to the coastal ocean, which is often of the same order of magnitude, constitutes a major fuel for marine primary productivity. Similar considerations apply to carbon exchange between land and coastal ocean. The coastal ocean is the only marine area where land and ocean are linked at short time scales through atmospheric deposition and riverine sediments. This rapid linkage creates various feedbacks and biogeochemical interactions. Furthermore, the coastal ocean at the interface between land and open ocean acts as a link, with bi-directional exchange of matter between both compartments.

Despite the high variability and heterogeneity of the coastal ocean at a global scale, there have been several recent attempts to describe and quantify the role of the coastal ocean in the global and marine carbon cycles. These investigations have increased our understanding of coastal oceans at the global scale, but at regional or local scale the diversity and variability of the coastal systems (Borges, 2005, Borges et al., 2006, Ciais et al., 2008; Chen and Borges, 2008) still prevents us from achieving a comprehensive understanding. An example of this is evident in the assessment of the European carbon balance, using bottom-up and top-down approaches. The uncertainties of "known" individual fluxes far exceed the order of magnitude assumed for fluxes involving the coastal ocean, in particular the lateral exchange between land and coastal ocean. Creating the necessary understanding of the role of the coastal ocean in the carbon balance will only be achieved by detailed field studies. Only these will provide the required information to constrain integrative modelling studies.

CarboOcean-IP has a core theme making a carbon sink assessment for regional European seas. This theme will start to link European shelf sea measurements with terrestrial carbon fluxes and open-ocean fluxes. Quantifying the fluxes for these heterogeneous and variable shelf seas presents a special challenge, particularly when drawing up the type of comprehensive assessments such as those aimed for by CarboOcean-IP. CarboOcean-IP decided to focus on those European Seas, which are directly connected to the Atlantic: namely, the North Sea and the Mediterranean Sea. A comprehensive observational and modelling programme is being undertaken, which tackles several key aspects of the problem, for both sea systems. In a joint-venture with CarboEurope-IP (which covers the partial budgets of the atmosphere and the land), CarboOcean-IP will, for the first time ever, quantify all relevant fluxes between sea, land and air. Western Europe is the first case study being pursued with this pioneering, integrated approach,

A considerable amount of new oceanic and atmospheric data has already been collected for both the North Sea and the NW Mediterranean. This new data is added to existing data, creating new datasets that will enable us to unravel the spatial and temporal variability of the systems. The result will be new insight into the carbon balance of these coastal seas, from local to basin-wide and at daily, via seasonal, to multi-annual and decadal time scales.

Pioneering studies on the seasonal variability of the North Sea carbon cycle (Thomas et al., 2004) and how it is controlled, for example by the Baltic Sea runoff, are currently being complemented by high resolution time series observations in the southern North Sea. Combining observations and modelling, these studies provide highly detailed, process-based insight into the land-ocean coupling (Schiettecatte et al., 2005, 2007; Borges et al. 2008; Gypens et al., 2008; Prowe et al. 2008). For example, investigations into the trophic state of the water can provide insight into the effects and magnitude of lateral inputs, which may vary from local to basin wide scales. While the basin-wide biological carbon cycling of the North Sea as a whole is primarily controlled by organic matter input from the Atlantic (Thomas et al., 2005), the Southern Bight in turn is strongly affected by organic matter inputs from land.

There is a clear relationship between the air-sea CO_2 fluxes and the trophic state of the water in the Southern Bight, which thus can be considered as an indicator of lateral carbon exchange between land and coastal ocean – one of the key unknown processes mentioned above. These investigations are being extended to basin-wide scales to research the role of tidal mud flats on the North Sea carbon cycle. There is new evidence that the CO_2 uptake by the North Sea is facilitated to a surprisingly large extend by anaerobic processes within the tidal wetlands and mud flats, which in turn are in partly fuelled by terrestrial supplies (Thomas et al., 2008). These studies are paralleled by investigations on the role of tidal wetlands (**see Page 97**), and the overall North Sea, on atmospheric CO_2 concentrations, based on measurements from a North Sea oil/gas platform "F3", about 300 km north of the Dutch coast, and a measurement tower in the tidal margin of the Wadden Sea (**Fig. V.10**). The fluxes for example from the latter (Klaassen et al., 2007) reveal clear daily and seasonal cycles.

Interestingly, the atmospheric data mirror both the North Sea and Atlantic Ocean signal and can be used to understand the variability of the CO_2 systems in both marine areas at seasonal to decadal time scales (e.g. Schuster and Watson 2007, Thomas et al., 2007a,b).

For the NW Mediterranean a similar structure has been established. For example, more than ten cruises have been carried out in the Strait of Gibraltar to assess the exchange with the Atlantic Ocean. The role of the Mediterranean Sea in absorbing anthropogenic CO_2 has also been evaluated (Aït-Ameur and Goyet, 2006) (**Fig. V.11**). The Mediterranean outflow waters, which lie underneath the Atlantic Ocean water masses (**e.g. Fig. V.11c**) entering the Mediterranean, contribute considerably to the mid-depth water masses of the Atlantic Ocean (high salinity compound) and also carry significant amounts of anthropogenic carbon into the ocean's interior. The oceanic observations and modelling studies are being complemented by a time series of atmospheric observations at the French station DYFMAED, in the Gulf of Lions. These activities in the North Sea and the NW Mediterranean link Core Theme 3 to Core Themes 1 and 5 of CarboOcean-IP.

The atmospheric observations over the marine areas, as well as air-flux estimates for these areas constitute the link to the third branch of CT3, the EUROPEAN integration, which applies top-down and bottom-up modelling approaches to constrain the European Carbon balance. The studies are paralleled by socio-economic assessments of firstly emission scenarios, and then by the evaluation of costs related to potential mitigation scenarios.
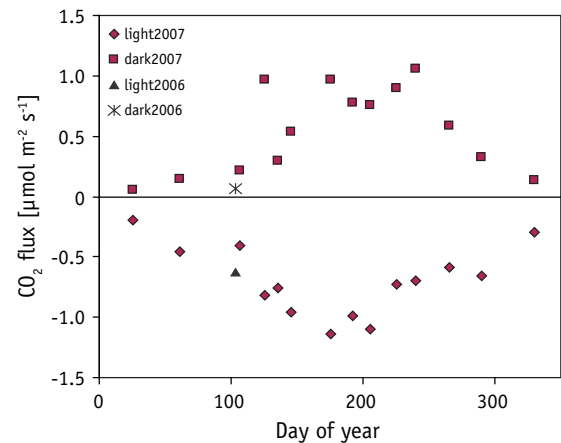
Fig. V.10: CO_2 air-sea fluxes measured above the Dutch Wadden Sea. CO_2 fluxes are generally larger in the summer (days 120-270) and reverse sign over a 24 hour cycle (outgasssing at night, uptake during daylight). The sink may be overestimated due to preferential measuring on bright days. (Source: W. Klaassen)
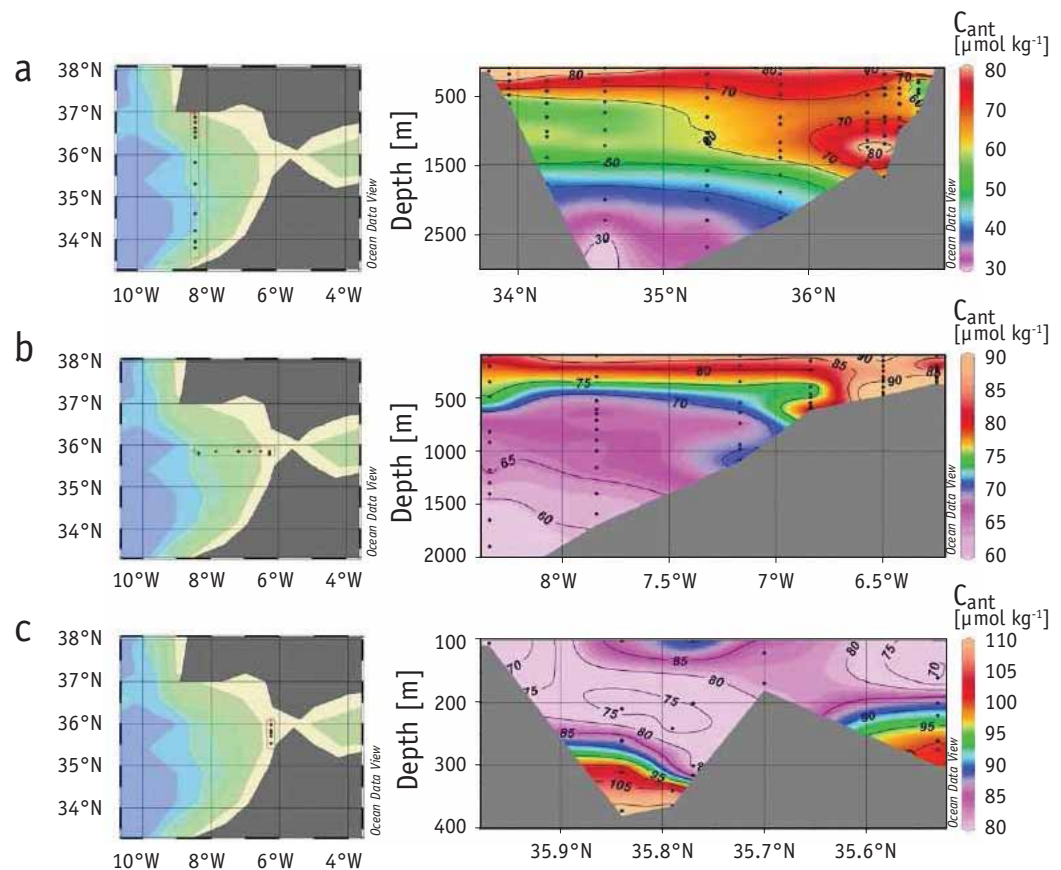
Fig. V.11: This figure illustrates the role of the Mediterranean Sea in absorbing anthropogenic CO_2 and transporting it into the North Atlantic. The figures on the left show the three profiles investigated and the right hand figures the anthropogenic carbon (C_{ant}, μmol kg^{-1}) distribution along the three sections: (A) N–S, (B) E–W section, and (C) the detailed Gibraltar section showing the high anthropogenic carbon load of the Mediterranean outflow (in red) into the Atlantic Ocean (Aït-Ameur and Goyet, 2006). Reprinted from Publication Aït-Ameur N. and C. Goyet (2006). Distribution and transport of natural and anthropogenic CO_2 in the Gulf of Cadiz. Deep-Sea Research, Part II (53): 1329-1344. Copyright (2006), with permission from Elsevier.

Monitoring greenhouse gases from southern Greenland to improve understanding of the role of the Atlantic Ocean carbon sink
by M. Delmotte, P. Ciais, J. Lavric, M. Ramonet

Improving our understanding of the role of greenhouse gases within the carbon cycle is a top priority of climate change research. Human activities release a huge amount of carbon dioxide into the atmosphere (about 9 billion tonnes of carbon per year) of which only 45% stays in the atmosphere. The remaining part is absorbed by natural carbon sinks: the terrestrial vegetation and the oceans. On a global scale both sinks contribute nearly equally to the carbon absorption, but at a regional scale the picture is more complex, demanding a better understanding of the processes involved. In particular, we need to know more about the role of the oceans. Within the framework of the CarboOcean-IP European project, LSCE (CEA-CNRS-UVSQ, France) installed a new monitoring station to continuously follow the atmospheric CO_2 and O_2 concentration throughout the summer of 2007. The dual measurements of CO_2 and O_2 are providing new information that will help us to better constrain the role of the Atlantic Ocean in the North Atlantic region. The station has been set up in Ivittuut, Southern Greenland on the shore of the Arsuk Fjord (**Fig. V.12**). This site was chosen because of its proximity to the Atlantic Ocean at the confluence of air masses coming from either North America or Europe, and because of the logistical facilities pro-

vided by the local Danish naval base in Grønnedal (5 km away from the station). The monitoring station was installed in a field laboratory that we have equipped with a meteorological station and CO_2 and O_2 monitoring instruments. Atmospheric air samples are collected continuously ,through four air inlets installed on a mast. **Figure V.13** shows the scientists at work during the installation of the air inlets and lines on the mast (J.V. Lavric and M. Delmotte).

Air is pumped through the lines and then dried before being injected into the instruments. The moisture is removed from the air in two steps. The air is first cooled down to 1-2°C while passing through water traps placed in a fridge (see **Figure V.14** illustrating the cold traps placed in the fridge of the oxygen analyser) and it is then directed to another water trap placed in an alcohol bath at -90 °C; this ensures that there is no residual moisture in the air. The dry air is then injected into the analyser for measurement. As a further control on the quality of the continuous measurements and to allow us to make complementary analyses of other greenhouse gases (CH_4, N_2O, SF_6, CO, H_2, isotopic composition of the CO_2), we also fill 1 litre air flasks using a sampling unit that has been developed at LSCE. The flasks are sent back to LSCE where they are independently analysed in the central laboratory. **Figure V.15** shows the sampling unit and the sampling flasks during a field test before the final installation in the atmospheric station.

Fig. V.12: Arsuk Fjord, the Danish navel base of Grønnedal can be seen in the foreground. The Arsuk fjord is about 5 km wide and 800 m deep, and 5 km way from the open Atlantic Ocean (Source: M. Delmotte, 2006)

Fig. V.13: Installation of the air lines and inlets on top of the sampling mast by J.-V. Lavric and M. Delmotte
(Source: CEA, C. Morel, Our polar heritage, 2007)

Fig. V.14: J.-V. Lavric adjusting some fittings on the Foxy instrument-O_2 analyser
(Source: CEA, C. Morel, Our polar heritage, 2007)

Fig. V.15: Test of the flask sampling unit. The samples, collected in glass flasks, are used as a quality control on the continuous analysers. The flasks are returned to the central laboratory in France where the samples are also analysed for other greenhouse gases
(Source: CEA, C. Morel, Our polar heritage, 2007)

Carbon dioxide release by a tidal flat
By W. Klaassen

Carbon dioxide was flux measured in the field using small chambers on a tidal flat in the Wadden Sea, just north of the Netherlands. One chamber was transparent for observations in light and the other was opaque and used for observations in darkness. Fluxes in darkness were defined as respiration, while photosynthesis was determined as the difference between respiration and the flux in the light. Photosynthesis and respiration were related to temperature, irradiance and tidal cycle. Respiration increased exponentially with temperature, and photosynthesis increased almost proportionally with irradiance. Fluxes were very low when the flat was flooded but increased gradually during the first three hours after the tide had ebbed to expose the tidal flat. Data of a nearby meteorological tower were used to calculate weekly fluxes. Fluxes were high in summer and low in winter. Year-long respiration (11.4 mol C m^{-2} yr^{-1}) exceeded photosynthesis (6.2 mol C m^{-2} yr^{-1}) so the tidal flat was a source of atmospheric CO_2.

Fig. V.17: Trial of the transparent flux chamber near the coast. Later on measurements were taken at more remote locations that taken as representative of tidal flats in the Wadden Sea.
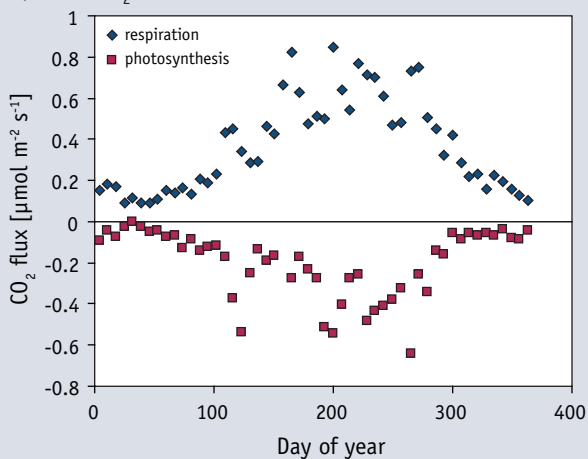
Fig. V.16: Weekly average fluxes of photosynthesis and respiration.

Fig. V.18: Dark and light flux chambers during observations on the tidal flat.

Robust findings:

European regional seas, including enclosed and semi-enclosed seas, play an important role in the carbon budget, e.g. through the Mediterranean Sea outflow into the North Atlantic and the continental shelf pump mechanism of the North Sea. The first measurement stations for atmospheric CO_2 in the Wadden Sea and in the North Sea present a promising outlook for improved continental scale greenhouse gas budgets.

Key questions:

Carbon and greenhouse gas budgets for coastal seas and shelf seas are difficult to establish in detail due to the complex boundary conditions and the heterogeneity of the marine systems. For global greenhouse gas budgets and studies of biogeochemical element cycling, a quantitatively correct simulation of the coastal and shelf ocean on a global basis is needed. Such a simulation will be a major challenge for Earth system modellers in the coming decade. In-situ and satellite measurements will be needed to validate respective model simulations.

2.5 Marine physical and biogeochemical feedbacks and impacts in a high CO$_2$ world

2.5 Marine physical and biogeochemical feedbacks and impacts in a high CO$_2$ world

CarboOcean-IP focuses on processes which are of significance in partitioning CO$_2$ between ocean and atmosphere. Rising atmospheric CO$_2$ levels since the beginning of the industrial revolution and the consequent warming are driving profound changes to the physical and chemical state of the ocean. Temperature driven changes in ocean circulation and stratification lead to large-scale changes in vertical marine carbon and nutrient distributions. As a consequence marine ecosystems are altered in their structure and functioning. All these processes combine to significantly alter physical and biological carbon pumps. They ultimately affect the efficiency with which the ocean can take up carbon and permanently remove it from the atmosphere. At present, we are only just beginning to understand how rising pCO$_2$ will impact marine ecosystems and biogeochemical cycles, and how these changes will feed back on atmospheric pCO$_2$. This hampers our capability to quantify physical and biogeochemical feedback loops and to predict how they will change in the future. The approach of integrating observations and modelling adopted within CarboOcean-IP is designed to further our understanding of the relevant physical and biogeochemical processes and their complex interplay.

The high latitudes are hot spots of global climate change. The effects of changes in the rate of land ice melting, changes in sea-ice cover, marine density stratification and atmospheric forcing conditions are combining to produce rapid climate change. If the global ocean as a whole suffers from undersampling, this is even more true for the high latitudes. Nevertheless, a high quality description of the present status of the system is essential if we are to predict the potential future evolution of high latitude climate.

A series of research cruises in the Arctic Ocean (R/V Oden, 2005, 2002) and the Barents Sea (marginal ice zone, R/V Jan Mayen (2003, 2004, 2005) led to a comprehensive data set of hydrographic and carbonate system measurements. These data are now available via the CarboOcean-IP data portal. Together with data mining, the analysis of this new field data reveals the relationship between physical and biogeochemical regimes, and surface ocean pCO$_2$ in the high latitude region from the North Atlantic inflow to the Nordic Seas, to the Eurasian Basin of the Arctic Ocean. There is a high regional variability in the relative importance of physical (ice cover, hydrography) and biogeochemical processes that dominates the surface CO$_2$ system. The timing and rate of ice melting, and the role of Arctic river runoff and biological productivity has been shown to significantly control both the carbonate system and air-sea CO$_2$ exchange in the marginal ice zone of the Barents Sea and Eurasian Basin of the Arctic Ocean. A first attempt has been made to compile the pCO$_2$ field of the Arctic Ocean and to compute the potential uptake of CO$_2$ by the surface waters (Jutterström et al., in preparation).

This exercise highlights the potential for a substantial uptake of CO$_2$ from the atmosphere in response to a decrease in summer sea ice coverage. Understanding and disentangling the processes shaping the response of the Arctic Ocean to anthropogenic forcing is a central objective of CarboOcean-IP. As part of the efforts to meet this objective, we modelled (Kivimäe et al., submitted) the relative roles of the solubility and biological pumps in preconditioning the carbon biogeochemical signatures of the Barents Sea water masses prior to transport and sequestration in Arctic intermediate and deep waters. Results stress the importance of the Norwegian Atlantic Current in controlling the carbon flux from the Norwegian Sea to the Arctic Ocean, both via Fram Strait and the Barents Sea. The latter is a net exporter of carbon originally coming from the Nordic Seas to the Arctic Ocean with a net DIC export of ~2500 million tonnes of carbon per year, of which ~1800 million tonnes (72%) are in subsurface water masses and thus sequestered from the atmosphere. The majority of this carbon is imported from the Nordic Seas. The net total organic carbon export to the Arctic Ocean is 80 million tonnes of carbon per year of which 20 million are labile.

Southern Ocean simulations with the OPA8-PISCES-T coupled physical-biogeochemical model showed that the Southern Ocean sink for CO$_2$ has weakened, at least since 1980, because of the increase in upwelling caused by the intensification of the southern ocean winds (Le Quéré et al., 2007) (see also the discussion in the above section on the variable sink strength in the Southern Ocean).

A series of key biogeochemical processes were identified which interact with atmospheric CO$_2$. Considerable methodological advances have been made through the use of large scale manipulative or mesocosm experiments, the marine counterpart to FACE (Free Air Carbon Enrichment) experiments for terrestrial ecosystems. Mesocosms are enclosures containing a large volume of seawater, including its biota, within transparent containers or bags (**Fig. V.19**). The first CarboOcean-IP mesocosm experiment was carried out at the Espegrend facility near Bergen (Norway) in 2005.

This experiment investigated the response of dominant phytoplankton groups to CO$_2$ induced changes in carbonate chemistry. A set of parallel mesocosms was set up, each containing the same ecosystem type. The atmospheric CO$_2$ partial pressure was then varied between 350 µatm, 700 µatm, and 1,050 µatm (Riebesell et al., 2008). The experiment lasted for 25 days during which comprehensive biological and biogeochemical measurements were recorded.

2.5 Marine physical and biogeochemical feedbacks and impacts in a high CO$_2$ world
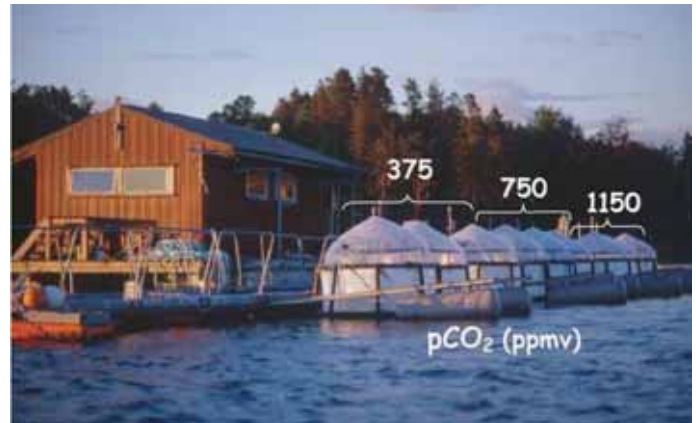

Fig. V.19: How does the oceanic ecosystem react to a doubling of today's atmospheric CO$_2$ concentration? This and other questions were investigated by running the experiment "the first CarboOcean-IP mesocosm CO$_2$ perturbation study" in a Norwegian fjord. The experiment took place in the Raunefjord, 20 km South of Bergen at University of Bergen's Large Scale Mesocosm Facility which was recently designated the National Mesocosm Centre by the Research Council of Norway. The experiment lasted from 15 May to 15 June 2005, with one week prior to this for setting up the mesocosms and aerating the 10 m deep-water column inside the mesocosm bags with CO$_2$ enriched air. The 9 mesocosms, each covered with a polyethylene dome allowing 90% light transmission of the photosynthetically active radiation (including UV-light), were adjusted to initial pCO$_2$ levels of 375, 750 and 1150 ppmv (in triplicate) and were monitored during the development and decline of a phytoplankton spring bloom. The results of this study, involving over 50 scientists from 14 European and North American institutions, are published in a special issue of Biogeosciences (http://www.biogeosciences.net/special_issue38.html). (Source: A. Volbers, U. Riebesell)

Marine calcifiers in a high CO$_2$ world
By U. Riebesell

Calcium carbonate (CaCO$_3$) is one of the most widespread building materials used by marine organisms to form their shells and skeletons. Although the best known calcified structures are probably corals, mollusks and echinoids, the most productive calcifiers on Earth belong to a group of planktonic microalgae, the coccolithophorids (**Fig. V.20a**). As with all calcifying organisms they rely on surface seawater being supersaturated with respect to calcium carbonate. This supersaturation prevents their crystallized CaCO$_3$ from dissolving. Ocean acidification due to anthropogenic CO$_2$ emissions progressively reduces carbonate saturation, a process which will cause large parts of the surface ocean to become subsaturated with respect to calcium carbonate before the end of this century. Subsaturated waters will be corrosive to calcium carbonate, making it impossible for calcifying organisms to maintain their shells and skeletons. But well before the seawater turns subsaturated, organisms will find it increasingly difficult to form their CaCO$_3$ structures. Evidence for this can be found in reduced rates of calcification. In coccolithophorids reduced calcilification also results in a drastic increase in malformations, as shown in the right panel of the figure below (**Fig. V.20b**). Despite much uncertainty about its broader implications for marine life, ocean acidification is likely to cause major shifts in marine biodiversity and ecosystem structure.

Fig. V.20: Scanning electron micrographs of the single-celled coccolithophorid Calcidiscus quadriperforatus grown at present day (V.20a, above) and projected year 2100 CO$_2$ levels (V.20b, below).
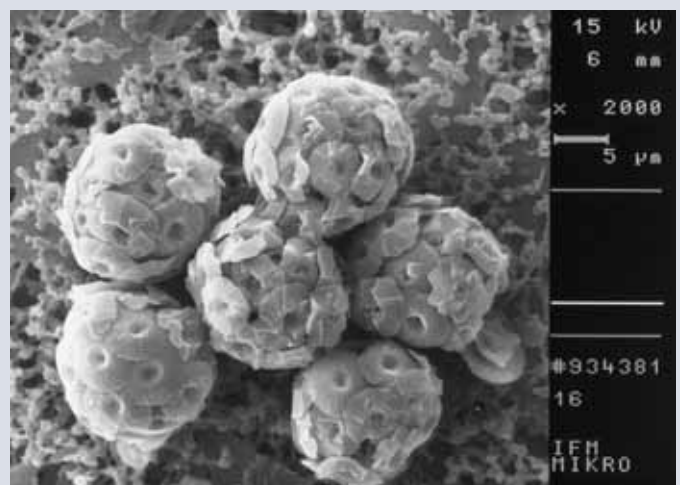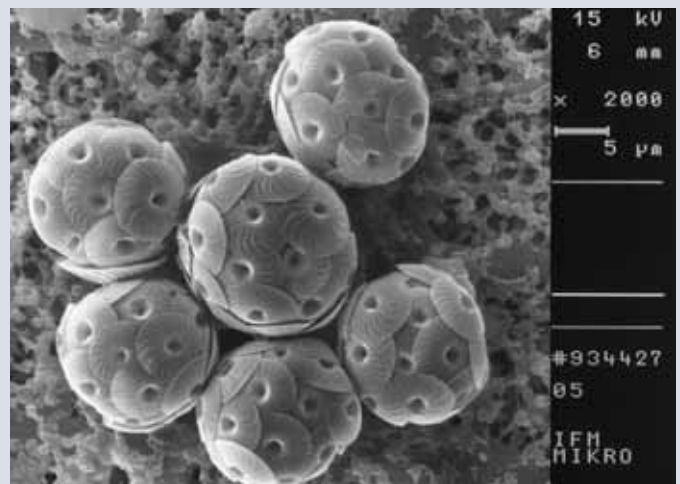
99

In agreement with earlier experiments on "ocean acidification" (Zondervan et al., 2001), the organic carbon production increased slightly under higher CO$_2$ concentrations. Interestingly, the microcosms with high CO$_2$ conditions also showed increased nutrient utilisation efficiency. The detailed analysis of carbon to nitrogen drawdown during the mesocosm experiment revealed an enhanced carbon drawdown at higher than present atmospheric CO$_2$ levels, as well as an increase of the stoichiometric ratio, C:N, from 6 at low, to 8 at high CO$_2$ (Bellerby et al., 2007; Riebesell et al., 2007) (**Fig. V.21**). However, it is not yet clear, whether this result can be extrapolated to other biological regimes. The mesocosm study allowed investigation of potential impacts of rising atmospheric CO$_2$ on ocean biogeochemistry, such as the emissions of the volatile organic gases, methanol, acetone, acetaldehyde, isoprene, DMS and chloroiodomethane, during the development and decline of a phytoplankton bloom. Experimental results suggest that emissions of DMS and chloroiodomethane could increase with increasing atmospheric CO$_2$ and in response to acidification. Further studies are needed to confirm these results and to assess their potential impact on climate, particularly in the case of the increase in DMS production with increasing CO$_2$.
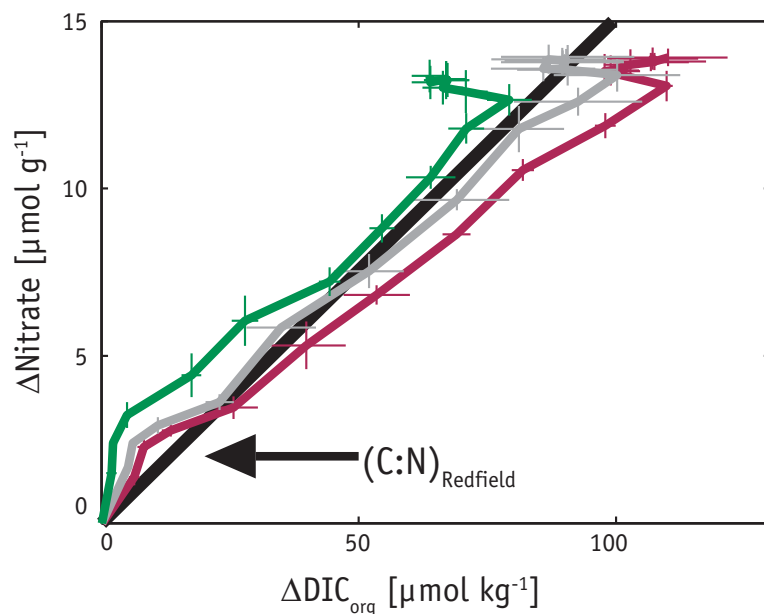
Laboratory experiments have shown that the growth of the cyanobacterium Trichodesmium in semi-continuous batch cultures is affected by CO$_2$ concentrations, with higher rates being found at higher CO$_2$ values. The ability to fix molecular nitrogen was also CO$_2$ sensitive. This might have important implications for future element cycling and ultimately affect the strength of the biological carbon pump and hence atmospheric CO$_2$ (Barcelos e Ramos et al., 2007).

Experiments investigating the temperature dependence of remineralisation of organic matter have confirmed the strong temperature control of the degradation of organic matter. Experiments included water samples collected by the Danish vessel Vædderen while sailing from Antarctica, via the Panama Canal, to Copenhagen, Denmark. In addition, temperature regulated incubation experiments were also carried out on water collected on three cruises in the transition zone between the North Sea and the Baltic Sea. Incubations were made at different temperatures over periods of 30 – 100 days. DOM and POM remineralisation rates show strong temperature dependence.

The database on CaCO$_3$ fluxes recorded by sediment traps and compiled during the FP5 project ORFOIS was used to evaluate the pelagic dissolution rate of carbonate particles. The description of CaCO$_3$ dissolution kinetics was updated in PISCES. The model computes a carbonate budget in line with current estimates. To quantify the coupled calcification/ballast feedback on rising atmospheric CO$_2$, simulations were performed with atmospheric pCO$_2$ increasing at a rate of 1% per year from the pre-industrial level to 4 times this value. Carbonate production (**Fig. V.23**) decreased by 27% in response to the pCO$_2$ increase. Over the same period, export decreased by 29%. The effect of reduced calcification leads to a total increase of the cumulative CO$_2$ uptake of 6 Gt C over time, which is close to negligible in view of current and expected anthropogenic CO$_2$ emissions.

In summary: CarboOcean-IP has been successfully studying physical and biogeochemical feedbacks to increase our limited knowledge of their influence on potential changes in the Earth system due to rising CO$_2$ and changing temperature. However, at this stage it is too early for us to give an accurate quantified description of the physical/biogeochemical feedbacks. However, such a quantified description is needed if we are to predict the future CO$_2$ sink for given emission scenarios.

Fig. V.21: In the Bergen mesocosm experiment not only did the organic carbon production increase slightly under higher CO$_2$ conditions but so did the nutrient utilisation efficiency. The stoichiometric ratio of carbon to nitrogen (C:N) increased from 6 to 8 under high CO$_2$ conditions. This figure shows the change in inorganic carbon taken out of the surface layer of a mesocosm, in relation to change in nutrients taken up by organisms in order to bind the inorganic carbon (after Riebesell et al., 2007). The coloured lines stand for initial pCO$_2$ values of 350 µatm (green), 700 µatm (grey) and 1,050 µatm (red). This finding needs further investigation and may not be applicable to other oceanic regions. Riebesell, U., K. G. Schulz, R.G..J. Bellerby, M. Botros, P. Fritsche, M. Meyerhöfer, C. Neill, G. Nondal, A. Oschlies, J. Wohlers, E. Zöllner, 2007, Enhanced biological carbon consumption in a high CO$_2$ ocean, Nature, doi:10.1038/nature06267

Future changes in bottom-water carbonate chemistry
By M. Gehlen

A model sensitivity study was designed to evaluate the amplitude of changes in bottom-water($) carbonate chemistry in response to an acidification scenario, as well as the potential for dissolution of marine calcium carbonate (CaCO$_3$) sediments on century timescales (Gehlen et al., 2008). A model experiment was carried out according to the standard CMIP scenario of atmospheric pCO$_2$ levels increasing at a rate of 1% per year from 286 to 1144 ppm over a 140 year time period. The uptake of anthropogenic CO$_2$ by the world ocean is the basic cause of a strong decrease in deep water [CO$_3^{2-}$] concentrations (**Fig. V.22a**). The model predicts that the reduction in [CO$_3^{2-}$] would be highest in areas of deep-water formation in the North Atlantic reaching 100 µM, as well as intermediate and mode water formation in the Southern Hemisphere (30°S to 50°S). These regions correspond to those for which the highest contemporary column inventories of anthropogenic CO$_2$ were estimated by Sabine et al. (2004). The reduction in [CO$_3^{2-}$] levels is accompanied by a decrease in calcite saturation state of bottom-waters and drives the dissolution of CaCO$_3$. The model predicts a decrease in CaCO$_3$ content averaged over the top first centimetre by up to 6% over the course of the simulation (**Fig. V.22b**). Experimental evidence of the effects of CO$_2$ on benthic communities is still scarce and mostly limited to shallow water biota (e.g., Shirayama and Thornton, 2005; Turley et al., 2006). Recognizing that the deep benthos has evolved under rather stable environmental settings (Childress and Seibel, 1998) and is reported to be sensitive to even moderate changes in environmental variables, the potential for changes in benthic community structure needs to be highlighted.
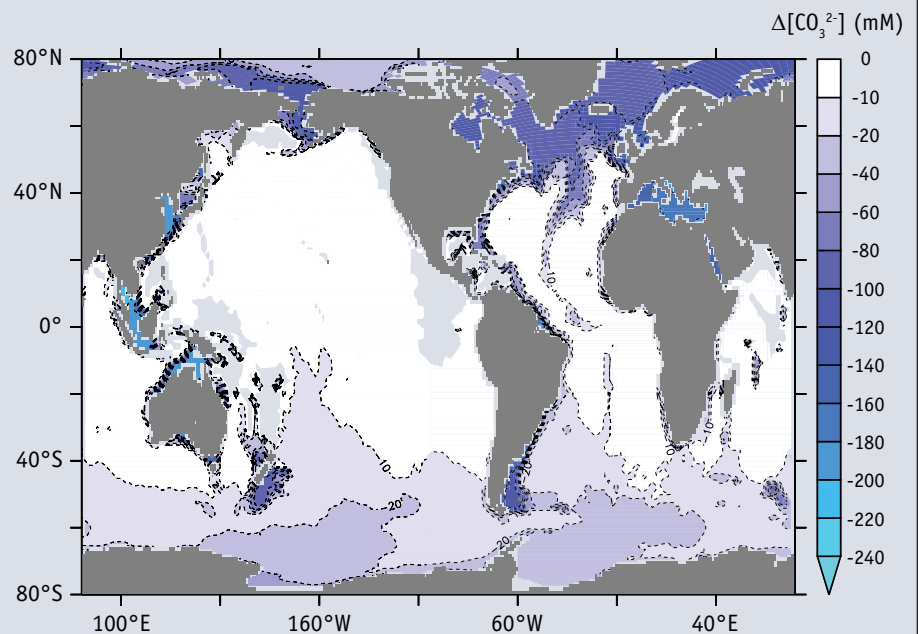
Fig. V.22a: Absolute change in bottom-water carbonate ion concentrations (M) computed as the difference between the initial concentration and the levels reached at the end of the scenario.
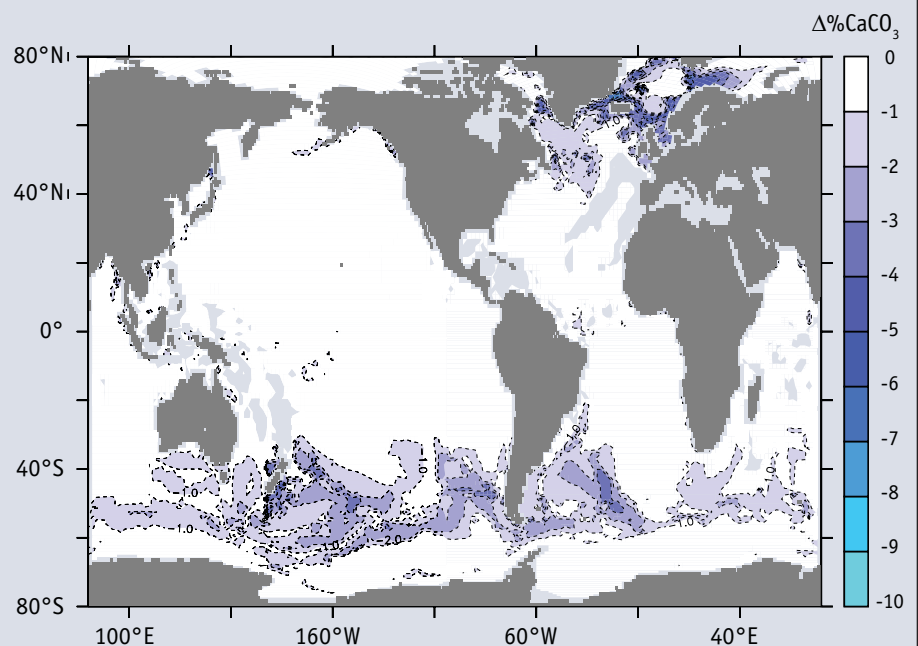
Fig. V.22b: Absolute change in the solid fraction of calcium carbonate (%CaCO$_3$) of deep sea sediments averaged over the top first centimetre.

Footnote:
($)In this context bottom-water does not refer to a particular water mass, but rather to the deep part of the water column in contact withsediments.

net CaCO$_3$ production vert. integr. [gC m^{-2} yr^{-1}]

CaCO$_3$ dissolution vert. integr. [gC m^{-2} yr^{-1}]

1 x pCO$_2$

2 x pCO$_2$ - 1 x pCO$_2$
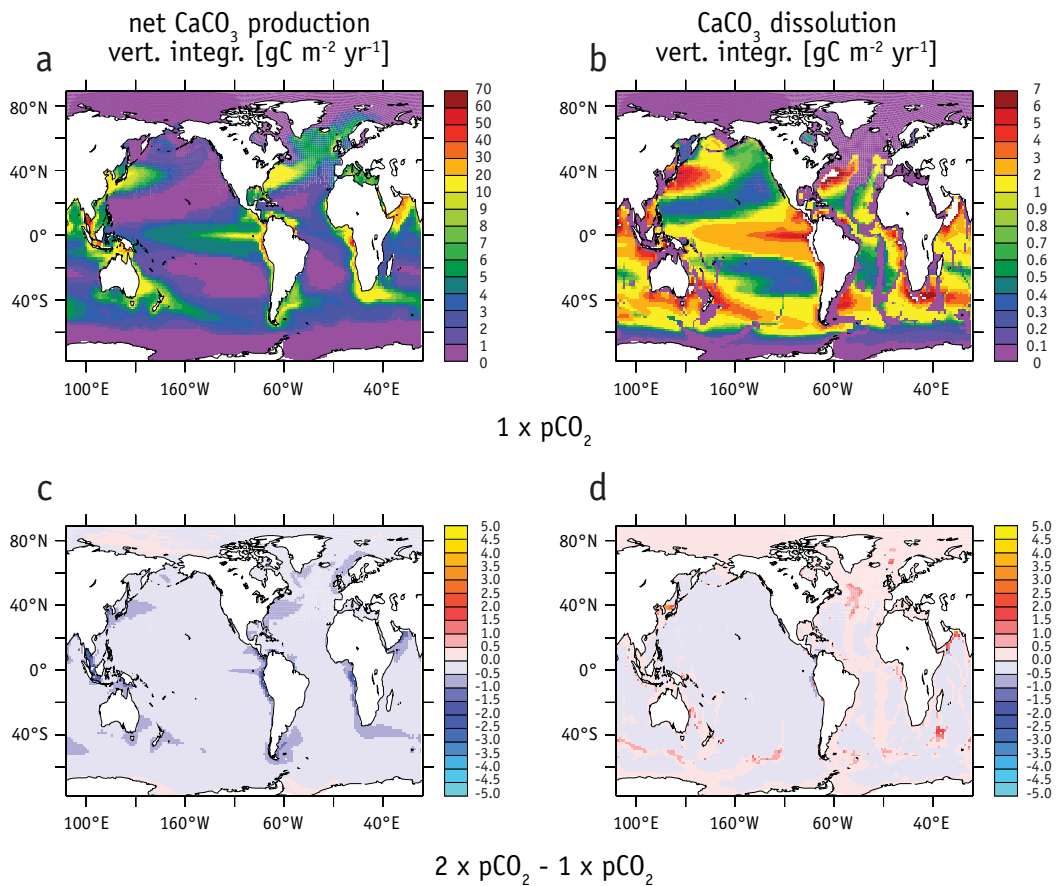
Fig. V.23: How can we upscale local process studies in the large-scale ocean? To answer this question, a model was used to simulate the calcium carbonate production with respect to increased CO$_2$ contents over time. This figure shows the net CaCO$_3$ production and CaCO$_3$ dissolution under different atmospheric CO$_2$ concentrations: (a) Vertically integrated net production of CaCO$_3$ (g C m^{-2} yr^{-1}) at 1×pCO$_2$ (= pre-industrial): 27% less CaCO$_3$ is produced in response to an increase in atmospheric CO$_2$ and (b) difference in net production at 2×pCO$_2$ minus 1×pCO$_2$: 29% of the produced CaCO$_3$ gets dissolved (After Gehlen et al., 2007). In total, this model study predicts a decrease in CaCO$_3$ produced by marine organisms under highly increased CO$_2$ conditions. Gehlen, M. R. Gangstø, B. Schneider, L. Bopp, O. Aumont, and C. Ethe, 2007, The fate of pelagic CaCO$_3$ production in a high CO$_2$ ocean: a model study, Biogeosciences, 4, 505–519.

Robust findings:

Physical and biogeochemical feedbacks to climate change and rising CO$_2$ concentration include a broad spectrum of processes, which can be summarised under changes due to the physical carbon pump (circulation, mixing) and the biological pump (organic carbon production, hard shell production).

The anthropogenic carbon uptake by the oceans is dominated by physical-chemical buffering, but biological and biogeochemical effects cannot be neglected. Ecological impacts may be severe (e.g. through warming and pH changes).

High latitude oceans are particularly sensitive to changes in climate and carbon cycling, and thus can serve as a useful "magnifying glass" for watching ongoing changes in the Earth system.

Key questions:

At this stage, we are only beginning to understand the spectrum of potential changes in the Earth system due to rising CO$_2$ and changing temperature. Many biogeochemical and ecological processes are not yet understood and can only be simulated by empirical approaches. Models based on more stringent "first principles" are needed. Laboratory, mesocosm, and in situ experiments need to be carried out in order to estimate the system response to a warming world with increasing levels of greenhouse gases.

2.6 Development of the marine CO$_2$ sink in the future

Key questions concerning the future development of the oceanic carbon sink include: Is the steep rise in atmospheric CO$_2$ concentration just starting – we assume that the basic signal is governed by the ocean, but is this indeed the case? How can we check whether the feedback processes really work and where are the most sensitive regions, which may hold surprises? How large are the feedbacks in relation to mitigation options and emission reduction plans – do we have to revise emission reduction policies?

We use the latest European coupled carbon cycle climate models in order to make the best possible prediction of the CO$_2$ airborne fraction in the future. These predictions are based on the sources and sinks of CO$_2$ estimated by the ocean modules, but also the terrestrial fluxes estimated by the land modules. For year 2000, the coupled models result in a global oceanic net sink for anthropogenic carbon of around 2.3 GtC/yr. We consider the time frame until year 2100 ("IPCC time frame") and 100 years beyond, until 2200. We are carrying out fully coupled climate/ocean carbon cycle simulations using realistic scenarios for future anthropogenic CO$_2$ emissions, including new process knowledge on biogeochemical feedbacks. These simulations will give the most realistic estimates of future transient CO$_2$ source-sink distributions currently available. The largest increase of the anthropogenic CO$_2$ build up in the atmosphere has occurred over the past few years and the rate of CO$_2$ emissions is expected to continue to increase (Raupach et al., 2007). Changes in the greenhouse effect and climate evolution in the coming decades and centuries will critically depend on human action with respect to emissions. The purpose of the predictive model runs in estimating the repartitioning of carbon, in the coming decades and centuries until 2200, is to make best possible projections of: the overall airborne fraction of CO$_2$ (the ratio of the annual increase in atmospheric CO$_2$ to the combined annual CO$_2$ emissions from fossil fuel burning and cement manufacture combined). To achieve this the model must predict the evolution of the oceanic uptake kinetics, taking into account all climatic and environmental changes in an integrated way, including modelling how the oceanic carbon sink depends on the carbon fluxes to and from the land biosphere. Such a budgeting approach, which is based on best possible process knowledge, can only be carried out with prognostic models. These are models whose framework of mathematical equations can be reliably integrated forward in time on the basis of given initial conditions. As it is difficult to consider regional carbon budgets, because one would have to know all carbon fluxes at all open boundaries, such a modelling approach can only be based on global Earth system models (coupled ocean-atmosphere climate models, that include biogeochemical modules for ocean and land biogeochemistry). Within CarboOcean-IP, modelling future scenarios using Earth system models is an important synthesis-

ing tool, where the results from the data collection, the process determination, and the model performance assessment can all be brought together to make realistic forecasts for a given set of CO$_2$ emission scenarios.

Friedlingstein et al. (2006) published an intercomparison of 11 Earth system models (general circulation models and coupled models of intermediate complexity) for carbon fluxes, land-atmosphere as well as ocean-atmosphere, for the A2 SRES IPCC emission scenario (IPCC, 2000) until year 2100 (C4MIP project). The models revealed a broad range of different time evolutions for the concentration of atmospheric CO$_2$. For the ocean, all models showed a continuous flux of excess CO$_2$ into the ocean. However, this flux decreased as the prevailing CO$_2$ concentration in the atmosphere increased (with the exception of one model). This implies that the oceans will continue to act as a CO$_2$ sink; however, the uptake per additional unit of CO$_2$ emitted will slow down. The result will be an accelerating rate of CO$_2$ build up in the atmosphere. The reason for this change has still to be analysed in detail. The land uptake predicted by many of the models declined to possibly zero in year 2100, while some models even predict that the land will become a CO$_2$ source to the atmosphere after initially acting as an increasing sink due to CO$_2$ fertilisation of the land biosphere.

In CarboOcean-IP, we chose five model systems to further analyse the ocean's role in future CO$_2$ uptake (model systems COSMOS/Max Planck Institute of Meteorology, IPSL-LSCE, Hadley Centre, CCSM NCAR/Bern, BCM). These five model systems include several new developments: for example, in the Bergen Climate Model BCM, the biogeochemical ocean model HAMOCC (Maier-Reimer et al., 2005) was implemented and converted to communicate with the isopycnal ocean model MICOM, resulting in a new model type within the interactive carbon cycle climate models. Further progress beyond the previous state of the art was made through implementation and use of new parameterisations (such as particle dynamics Gehlen et al., 2006). All the Earth system models used show a future reduction in the oceanic sink in response to climate change, but with considerable differences between the models (**Fig. V.24**). These differences can be attributed to changes in mixed layer depth, temperature changes, changes in ocean circulation, and related changes in biogeochemical cycling of carbon, nutrients, and oxygen. In addition to analysis of the reaction of the CO$_2$ airborne fraction to changes in climate and oceanic biogeochemical feedbacks, the ocean acidification due to marine CO$_2$ uptake was also studied.

CarboOcean-IP includes an analysis of the feasibility of deliberate carbon storage in the ocean. It is by no means the goal of CarboOcean-IP to explore this as a realistic means of climate mitigation; rather our aim is to contribute to the discussion with respect to a few key scientific questions. The two primary questions addressed are: what is the dispersion process when

anthropogenic CO$_2$ is injected purposefully into the deep-water column? How does the injected CO$_2$ spread at a larger scale? To address the first question, we carried out a suite of laboratory experiments with a sophisticated high-pressure tank. The results of these experiments show that injected CO$_2$ can relatively quickly rise up to shallower layers because of high droplet rise rates (droplets without hydrate skin) in the water column (Bigalke et al., 2008) (**Fig. V.25**). Modelling has progressed through the further development of a process model, now capable of realistically simulating the spread of directly injected CO$_2$ in all three directions and the simulation of the dispersal of CO$_2$ into the water column out of a "CO$_2$ lake" on the ocean floor. First studies with a high resolution ocean general circulation model indicated that the details of the upwelling in the Southern Ocean critically depend on model resolution and that significant differences for the predicted CO$_2$ injection efficiency can be expected, depending on the resolution used (Lachkar et al., 2007).
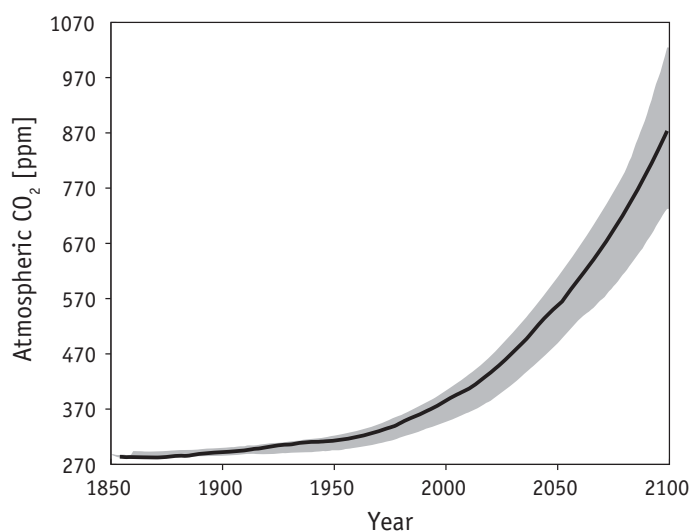
Fig. V.24: We assume that the steep rise in atmospheric CO$_2$ concentration is just starting and that the basic signal is governed by the ocean- but how do we make the best possible predictions of the future atmospheric CO$_2$ concentration? To tackle this problem, five model systems were chosen within CarboOcean-IP to analyse the ocean's role in future CO$_2$ uptake. In this figure, the mean atmospheric CO$_2$ concentration is simulated (black line) by the BCM-C model as compared to the range (grey shading) from other C4MIP (Friedlingstein et al., 2006) models. (Source: Tjiputra et al., in prep.)
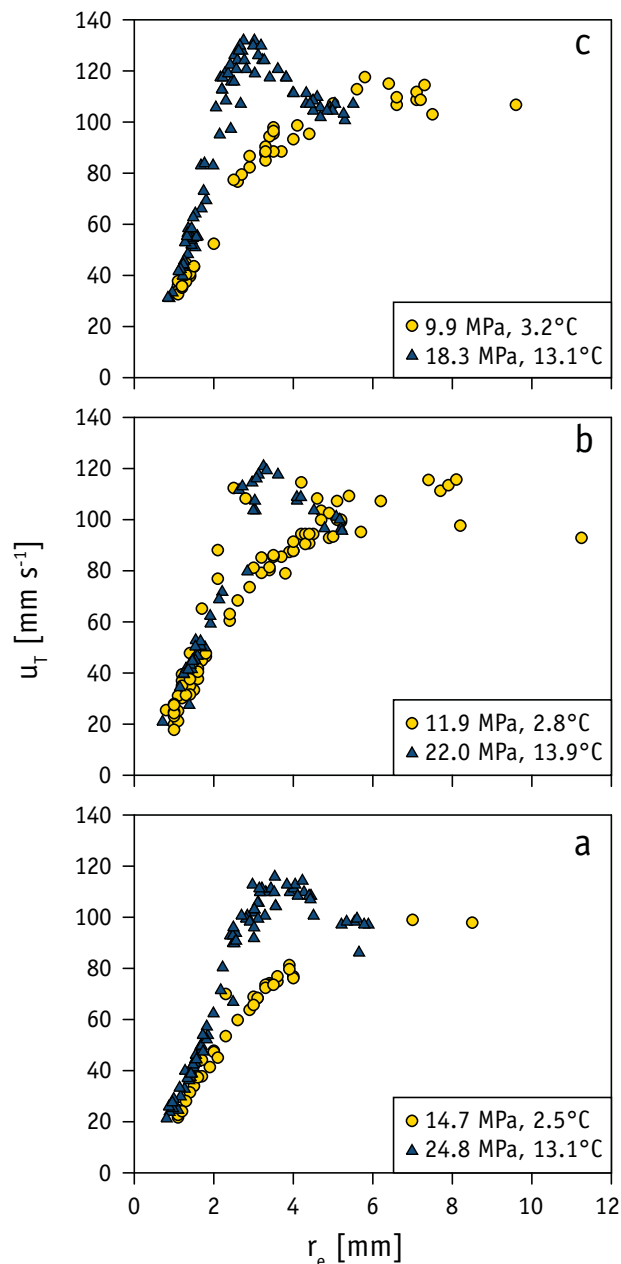
Fig. V.25: Various technological mitigation options are currently under public debate. One example is "storing" CO$_2$ on the ocean floor to keep it out of the atmosphere. CarboOcean-IP includes an analysis of the feasibility of such deliberate carbon storage in the ocean to provide a critical quality check on this proposal. The results of these experiments show that injected CO$_2$ can relatively quickly move to shallower water depths layers. This figure is derived from pressure chamber measurements. It shows the droplet rise rates of liquid CO$_2$ versus droplet radius at pressure and temperature conditions inside and outside the field of hydrate stability of deliberately injected CO$_2$ (Bigalke et al., 2008). Droplets without a hydrate skin (triangles) can rise significantly more quickly through the water column than those with a hydrate skin (circles). Reprinted with permission from Bigalke, N. K.; Rehder, G.; Gust, G. Experimental Investigation of the Rising Behavior of CO2 Droplets in Seawater under Hydrate-Forming Conditions. /Environ. Sci. Technol., (2008) 42 (14), 5241–5246. 10.1021/es800228j. Copyright (2008) American Chemical Society.

2.6 Development of the marine CO_2 sink in the future

Robust findings:

The ocean will continue to respond to further CO_2 additions in the atmosphere by absorbing CO_2. However, climate change and rising CO_2 concentrations in the atmosphere and ocean will gradually reduce the oceans ability to keep up with additional greenhouse gas loads. This will lead to a gradual decrease in the sink efficiency of the ocean and thus a temporary huge increase in the rate of growth of atmospheric CO_2. This increase will depend on the future amount of CO_2 emitted, the change in ocean circulation, and related biogeochemical processes. Climate model runs which account for an interactive carbon cycle show an accelerated climate change as compared with less realistic models which are based on physics only.

Remaining key questions

The science of accurate quantification of the physical and biogeochemical feedback processes to future carbon emissions is in its infancy. Even the reason for the natural positive feedback of the marine carbon cycle to climate change is not yet clear (glacial-interglacial changes). Prognostic Earth system models need to be systematically calibrated to measurements from modern and paleo-times in order to increase their accuracy for future predictions.

2.7 Ocean carbon data syntheses

2.7 Ocean carbon data syntheses

For the surface ocean CO_2 partial pressure database, all publicly available data was harmonised and fCO_2 (fugacity of CO_2) was re-computed from the various carbon dioxide parameters whenever possible. The database contains original data as reported by the scientific team leaders, as well as detailed metadata from the cruise. This database is an ongoing international effort (UNESCO/IOCCP, SOLAS, IMBER) serving the needs of the carbon dioxide research community and contains data from approximately 1400 cruises (from 1968 until 2007), with a total of 4.5 million carbon dioxide measurements – all recomputed to the same standards and available in the same format.

Two different oceanic carbon data sets have been compiled during CarboOcean-IP. These essential data syntheses provide an unprecedented collection of high quality, ocean carbon measurements for direct analysis and validation of model simulations against actual data. The two data sets are: an Atlantic 3-D carbon data set (including related tracer data) based on the original CARINA data set, but with further recent extensions and a 2-D surface ocean CO_2 partial pressure data set of first-level, quality-controlled data (i.e., no gridding to the original data was applied). The respective data coverages are shown in **Figures V.26 and V.27-29.**

Regional groups have now been established to perform a detailed second-level quality control. The accuracy of the final dataset will be approximately 5 µatm. Afterwards the data set will be made available to the community through the CarboOcean-IP data portal and a LAS (live access server). The final data product will be published as a data report and archived at the World Data Center for carbon dioxide (Carbon Dioxide Information Analysis Center, CDIAC, USA).

For 3-D deep-section, marine carbon data, the CARINA collection now includes data and metadata from more than 180 cruises. During a recent workshop in Paris (18 – 19 June 2008) the three CARINA research groups (Arctic, Atlantic and Southern Ocean) completed secondary quality control of the CARINA data set. Secondary quality control is an objective process aimed at identifying and quantifying systematic errors in the reported values. The data biases are then subjectively compared to pre-determined accuracy limits. Special consideration is given to the fact that some of the regions studied are known to have had real temporal change over the time period covered by the various cruises (1982-2007). Obviously, one does not want secondary quality control to "erase" real temporal change. Variables considered include salinity, oxygen, nitrate, phosphate, silicate, alkalinity, total inorganic carbon, pH, CFC-11, CFC-12 and CFC-113. The nature of the quality control procedure is such that various data recording errors are also identified. The Paris meeting completed an extraordinary amount of work: possible largely because of the internet-based software developed specifically for this task, and both the automated and manual methods developed for the required data comparisons.

In spite of the very substantial progress on the CARINA data project, significant work remains. Most of this work must be done sequentially and cannot be distributed. The remaining tasks are outlined below, but it is important to note that while these are being completed, scientific investigation using the data has already begun. This is possible because "nearly final" versions of the data have already been distributed to the members of the various working groups. In fact, several "new" scientific discoveries were made in Paris; perhaps the most notable being the identification of a very clear pattern of decadal oxygen change in the deep Greenland-Norwegian Sea.
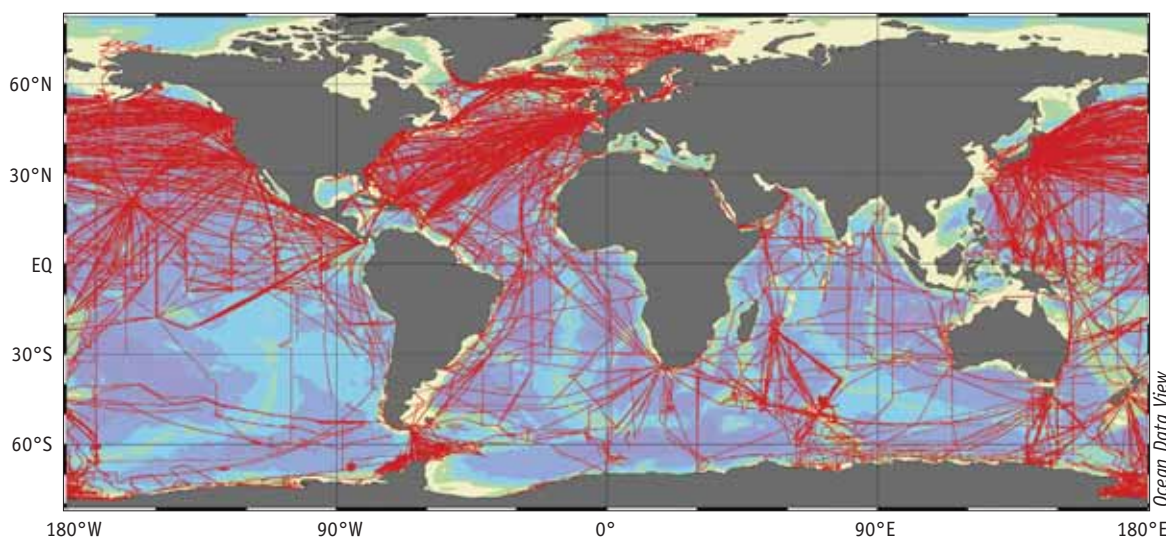

Fig. V.26: The CarboOcean-IP database includes not only all the latest data, but also makes older data available to the community. This figure shows the data coverage for surface CO_2 partial pressure data. (Source: B. Pfeil)

2.7 Ocean carbon data syntheses
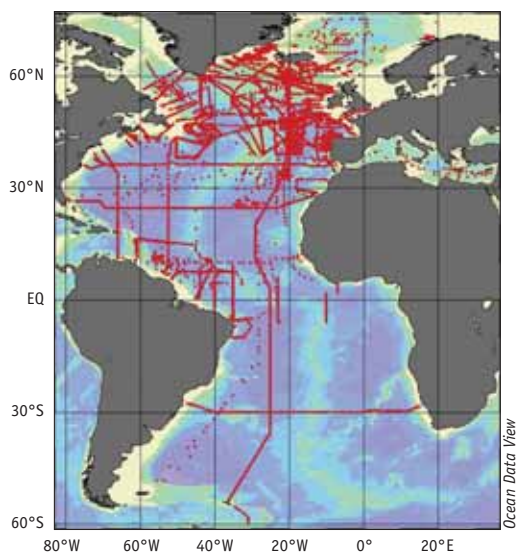
Fig. V.27: Data coverage for Atlantic Ocean deep carbon section data.
(Source: B. Key)
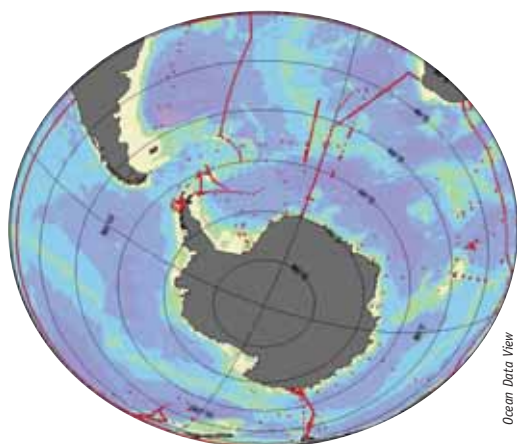
Fig. V.28: Data coverage for Southern Ocean deep carbon section data.
(Source: B. Key)
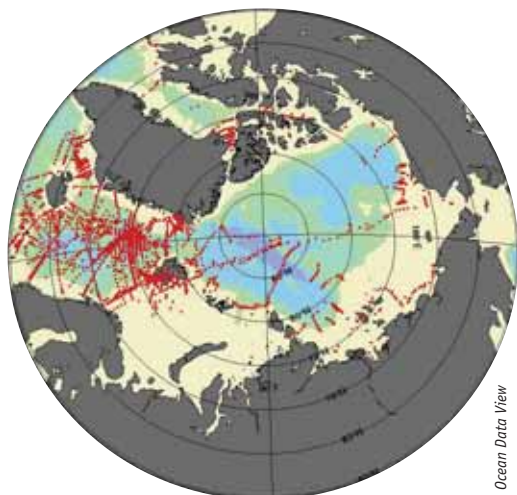
Fig. V.29: Data coverage for Arctic Ocean deep carbon section data.
(Source: B. Key)

Future tasks:

1. Each group leader will prepare a list of data corrections to be applied and submit these to the group of R. Key at Princeton University. These corrections will largely be changes to quality control flags due to newly discovered data analysis problems and metadata corrections or additions.
2. Distribution of individual cruise files and metadata from Princeton to data centres (CCHDO and CDIAC). The CarboOcean-IP data portal will echo the CDIAC holdings.
3. Each group leader will prepare a table of secondary quality control adjustments (as decided in Paris) which exceed the predetermined "minimum bias" for each parameter tested.
4. Princeton will build a merged data product for each region in which these secondary quality control adjustments are applied. The values of commonly used calculated variables (potential temperature, potential density, neutral density, apparent oxygen utilization) will be added, and the missing values for salinity, oxygen and nutrients approximated (using the GLODAP procedures). The approximate accuracy of these data products will be: Salinity - 0.003; Oxygen - 1%; Nutrients - 2%; Alkalinity 6 μmole kg-1; Total inorganic carbon 4 μmole kg-1. For some parameters on some cruises the measurement precision will not allow the accuracy to be this good. The decision to include or exclude noisy data was made individually for each parameter on each cruise. Within limits, noisy data was retained if it filled an important spatial data gap or temporal data gap (for rapidly changing regions).
5. Princeton will submit the data products to CDIAC (echoed by CarboOcean-IP data portal), where it will be available in the public domain.

Participants at the Paris meeting decided to submit a series of data papers describing the details of the CARINA collection and secondary quality control procedures. These papers will give credit to all those who actively participated in the procedure. Depending on journal constraints, there will be no fewer than three papers (one for each region) but probably no more than twelve. These publications will serve the same purpose as the Numerical Data Packages (NDP) printed by CDIAC for GLODAP. A final summary publication, similar to that produced for GLODAP, will be submitted to Global Biogeochemical Cycles. Correct reference to the data sets will be via one or more of these papers. These papers will be listed at CDIAC as the proper citations for the data. In practice, experience has shown that regardless of what we do, many outside users will simply reference the web site from which the data is downloaded.

2.8 International collaboration

CarboOcean-IP has built up worldwide links to a series of other key projects on carbon cycle research. These links are highly important because they ensure a seamless feeding of European derived data sets and model developments into the pool of internationally collected data and other model systems. Data collection, particularly in remote areas such as the Southern Ocean, and the development of advanced state-of-the-art Earth system models require large teams of people and carry heavy economical and logistical overheads. Carbon cycle research is thus expensive and the community from a single country, or even one continent, cannot hope to cover all aspects of the research when working alone. Such research will only be successful if steered by international coordination and carried out through synergistic collaboration. Recognising this, CarboOcean-IP provides the added value of European-wide integration of research activities and results, within the framework of the international research agenda.

CarboOcean-IP has been very successful in linking and embedding its work into the international community. This has been accomplished on different levels. First of all, the project consortium itself covers a broad range of expert communities from Europe, Morocco, and North America. Princeton University is a contractor to CarboOcean-IP and is participating as an extremely active collaborator, especially in the field of data synthesis. The project's international advisory board includes marine carbon experts from the US, Japan, Taiwan, South Korea, and Australia covering a broad spectrum of disciplines. Further, IOCCP (UNESCO), the International Ocean Carbon Coordination Project, is a project contractor that provides an invaluable link between CarboOcean-IP and other key projects, ensuring a smooth and open communication between the various projects worldwide. After the start of CarboOcean-IP a number of additional associate partners have entered the consortium (among others are those from Hawaii, Ireland, Switzerland, and Canada).

CarboOcean-IP cultivates the links to the US Ocean Carbon & Biogeochemistry programme and the international Global Carbon Project (ESSP). CarboOcean-IP is endorsed by the three IGBP core projects SOLAS, IMBER, and LOICZ. CarboOcean-IP results are disseminated and shared with other scientists through the participation of CarboOcean-IP scientists in key international conferences such as those organised by the AGU (American Geophysical Union), ASLO (American Society for Limnology and Oceanography), and EGU (European Geosciences Union) often with their own CarboOcean-IP-related sessions.

CarboOcean-IP is the major European provider for marine carbon data to the GMES programme and GEO, and for this purpose, a series of CarboOcean-IP partners participate in the EU FP7 coordination action COCOS. CarboOcean-IP is well interconnected with other integrated projects and networks of excellence such as EPOCA, MERSEA, SESAME, and EUR-OCEANS. CarboOcean-IP scientific expertise contributes to guardrails for global change policy: several scientists from the CarboOcean-IP consortium were involved as lead authors in the 4th IPCC assessment report of Working Group I (The Physical Basis).

2.9 Training, dissemination, and outreach

CarboOcean-IP has carried out extensive training, dissemination, and outreach on a series of levels. The training programme includes education of 25 PhD students; summer schools are organised for them, which also are open to non-CarboOcean-IP PhD students ("Measurement methods for the carbon system and related tracers in sea water", 2005, Vigo, Spain; "Modelling of the marine carbon cycle from small to global scale", 2006, Bergen, Norway; "Combining data and models - statistical analysis and data assimilation", 2007, Kiel, Germany). Special care has been given to include PhD students' talks in CarboOcean-IP plenary sessions at the annual meetings. In addition, there have been PhD student poster sessions and other events at CarboOcean-IP annual meetings where students present and discuss their own research. Each PhD student has a homepage which is part of the CarboOcean-IP training website. An additional training session is planned to help young researchers communicate their research results to the general public, in particular to schools. This will take place at the CarboOcean-IP annual meeting in 2008. CarboOcean-IP has seen the need to increase the numbers of female scientists in the field and has included mentoring sessions for female PhD students at CarboOcean-IP summer schools and has invited gender experts to plenary lectures and discussions at CarboOcean-IP annual meetings and Gender Panel meetings.

Dissemination of CarboOcean-IP results is carried out through the comprehensive website http://www.carboocean.org, (including a project summary in 17 languages), publications in peer reviewed journals, and an active programme of presentations at international conferences and meetings, both as posters and oral presentations. The conferences include the regular meetings organised by ASLO, AGU, and EGU, but also other conferences such as OCEANS 07, EurOcean 2007, Oceanology International 2008 (**Fig. V.30a**), 7th International Carbon Dioxide Conference, Open Science Conference on the GHG cycle in the Northern Hemisphere, and the US Ocean Carbon Biogeochemistry Workshops (OCB). CarboOcean-IP scientists have given several keynote talks and organised special CarboOcean-IP sessions at international conferences, such as the EGU ("Reducing uncertainties in the quantification of the oceanic sink for anthropogenic carbon", "Biogeochemistry of coastal seas and continental shelves" etc., **Fig. V.30b**).

Publications in peer-reviewed journals include those in transdisciplinary, high-impact journals such as Nature and Science, as well as more specialised journals such as the new European open-access journal Biogeosciences. The citations for these publications have been publicly listed on the CarboOcean-IP homepage, through which selected papers can also be accessed directly. Publications in newsletters, such as those of SOLAS and IMBER, DGM-Mitteilungen and QED, spread CarboOcean-IP results to a wider community within the geosciences and to global change research communities in general. Vertical dissemination to other stakeholders includes articles in The Parliament Magazine, META, and KLIMA. In early summer 2008, after the third of the five project years, the number of publications which were built on CarboOcean-IP work had already amounted 175.

Fig. V.30a: CarboOcean-IP presented its latest science at Oceanology 2007 (at the stand of the European Commission to the left) and
Fig. V.30b: at the EGU 2008 in Vienna (CarboOcean-IP press conference to the right). (Source: M. Papathanassiou and A. Volbers)

2.9 Training, Dissemination, and Outreach

Fig. V.31: CarboOcean-IP is heavily engaged in outreach and training of especially secondary schools: Several classes with 16-18 year-old pupils from the Bergen "Katedralskole" have already participated in the Norwegian CarboSchools project "CarboTokt". "CarboTokt" includes a daytrip into a Norwegian fjord on the research vessel Hans Brattstrøm. The students were accompanied by their science teachers and marine scientists from the University of Bergen – and sometimes even by curious journalists.

Fig. V.31a: The pupils get safety instructions before the cruise starts. While on board the pupils perform the experiments on their own.

CarboOcean-IP is heavily engaged in outreach to, and training of, students and teachers at secondary schools and is involved in the recently funded EC "CarboSchools+" proposal together with CarboEurope-IP and other institutions (see http://www.carboschools.org with starting portal available in five languages). The parent project, "CarboSchools", was launched in summer 2005 as a Concerted Action by CarboEurope-IP and CarboOcean-IP to increase awareness of carbon cycle research and its potential impact on climate change at a school level. Several important pilot projects on carbon cycle research issues have been successfully carried out including short cruises with research vessels (**Fig V.31a,b**), and a contribution to the three days GIFT (Geosciences Information For Teachers) workshop on the carbon cycle at the EGU General Assembly 2008. A "Regional Coordinator's Handbook", an educational booklet (**Fig. V.31c**) "What we know, what we don't know and how we try to better understand global change", a video clip about the Norwegian CarboSchools project, and a CarboSchools promotion poster can be obtained from the CarboOcean-IP project office. A second educational booklet is currently being prepared and will complete the educational package by the end of 2008.

Fig. V.31b: A girl takes water samples directly from the rosette for later lab investigation.

Fig. V.31c: The CarboOcean-IP/CarboEurope-IP educational booklet which is available in English, German, Dutch and Norwegian. A PDF-version is also available in French. (Source: A. Volbers)
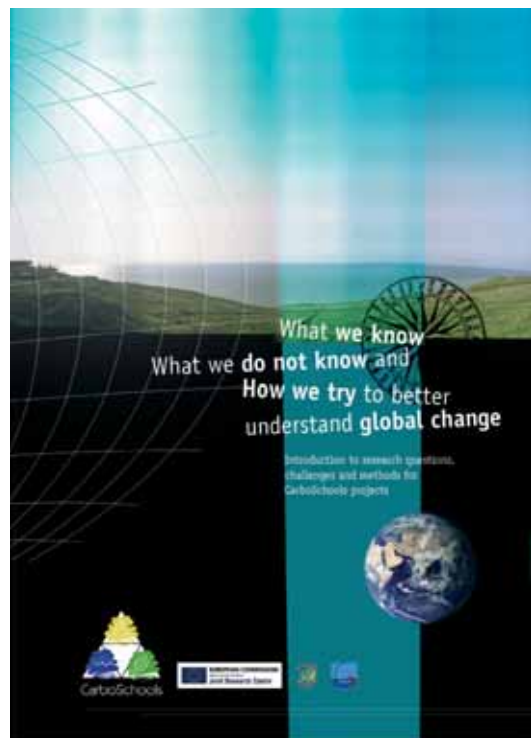
2.9 Training, Dissemination, and Outreach

Film recordings were carried out related to Theme 4 "Biogeochemical Feedbacks" on the first pelagic ecosystem CO_2 enrichment study (Espegrend Marine Biological Station, University of Bergen). The same experiment has also been filmed by a German TV station and was broadcast in the summer of 2005. Until 2007, various film clips were produced by UNIVISJON; these capture the CarboOcean-IP consortium members at work (**Fig. V.32**, film clips available are: installation of a pCO_2 instrument on a voluntary observing ship, a scientific cruise in the North Sea, the first annual CarboOcean-IP meeting in Amsterdam and an introduction to ocean acidification). The CarboOcean-IP DVD and brochure have been distributed at various international and national conferences and outreach events.

CarboOcean-IP is planning a 40 minute documentary film focusing on the latest project topics and results. The objective is to contribute to and enlighten the ongoing discussion on climate change and potential consequences for our daily life. So far, CarboOcean-IP research has been introduced to the general public over 80 times via print media (newspaper articles, newsletters, and books) and around 40 times via internet news pages. Around 20 press releases have been sent out and CarboOcean-IP scientists have described their research over 20 times on radio and TV.

Fig. V.32a: During its 2005 summer cruise in the North Sea (17 August - 07 September 2005), the R.V. Pelagia was accompanied by a film team. The film gave a good insight into how CarboOcean-IP scientists work and how their experiments are carried out. The film team had to develope creative solutions to allow them to follow the researchers' work:
Fig. V.32b/c: Here, one of the cameras followed a water sampler on its way into the water. (Source: J. Snoek and H. Thomas)

"The sea outside our door" – the Bergen CarboSchools project

By the biology teacher B. Færøvik and the scientists/technicians E. Falck, S. Kringstad, I. Skjelvan, A. Volbers

During the school year 2006-2007 17 year-old students, teachers from Bergen Katdralskole (an upper secondary school in Bergen) and scientists/technicians from the Bjerknes Centre for Climate Research (BCCR) were involved in the project, which was part of a subject called "Science". From August 2006 and onwards, there was a special focus on hands-on experiments, allowing the students to use all the scientific instruments and to perform all measurements themselves. The students took part in four science expeditions with R/V Hans Bratstrøm to explore the fjords in their local area outside Bergen.

The expeditions investigated physical, chemical, and biological aspects of seawater. R/V Hans Brattstrøm was equipped with a plankton net, seabed grabsampling equipment, a water sampler unit and a sensor for hydrographic measurements (CTD). The students determined temperature and salinity as functions of depth; they collected water samples for oxygen and inorganic carbon measurements, and determined the composition of the plankton species that could be found at that time of year.

The students did seabed grab-sampling surveys and compared the species found on the seabed at two locations. To analyse the inorganic carbon samples, five of the students visited the BCCR and used the laboratories' equipment under the guidance of an engineer. The students' collected all relevant data, analysed the data and wrote a report from the work on board. The report included pictures of all relevant equipment. The cruises resulted in substantial reports, and some of the students made a poster which was presented at several international scientific meetings. In addition a newspaper article and a video were produced from the cruise in 2006.

This cooperation also motivated the school to focus on climate change issues by arranging a "climate week" at school which consisted of scientific presentations, panel debates, etc. During the school year 2008-2009, the successful Norwegian CarboSchools project has been extended to include two more schools in Bergen (Bjørgvin videregående skole and Danielsen videregående skole).

Fig. V.33: R/V Hans Bratstrøm

Fig. V.34: Students, teachers and scientists go onboard and prepare for the cruise.

Fig. V.35: Oxygen analyses (Winkler titration)

Fig. V.36: Demonstration of a calibration tank for oxygen sensors

3 Implications for policy and future research:

3.1 Achievements and current status of policy

Marine carbon cycle research has a direct relevance for climate and global change policy as it addresses directly the question of the timing and amount of carbon dioxide in the Earth's atmosphere and hence the global warming which occurs as a consequence. The implications, however, go further than that. In a more general sense, climate is a key boundary condition for human life on Earth. All questions of economic development (including "sustainable development"), health, food, poverty elimination, and social equity are linked to this.

More specifically, marine carbon cycle research is of immediate relevance to the following issues and to answering the respective key questions of societal relevance:

(1) Informed decisions on energy production and consumption need the best available knowledge on marine CO_2 uptake kinetics. How quickly does the ocean buffer CO_2 from the atmosphere?

(2) The variability in the ocean carbon sink needs to be quantified continuously: Is the marine carbon sink working as we expect it to? Are the postulated feedback mechanisms at work?

(3) The difficult-to-establish, but critical, CO_2 flux between land and atmosphere needs to be constrained by including the effect of the oceanic carbon sink. What is the balance between net emissions from Europe versus those from North America?

(4) The longer-term timing of the oceanic carbon sink needs to be understood. How will the ability of the ocean to take up carbon change as atmospheric CO_2 levels rise and what is the optimal emission pathway? Will there be a slowing down of the oceanic marine overturning circulation and what consequences will this have for the efficiency of carbon removal from the surface layer?

(5) The long-term effects of human-made CO_2 emissions on the ocean need to be understood. What levels of atmospheric CO_2 concentrations will eventually result after the cessation of the human CO_2 invasion into the Earth system?

(6) The key impact on marine ecosystems needs to be accurately established through high quality measurements. How will the pH value change in various domains and depth levels of the marine environment and what will be the impact on marine biogeochemistry and marine life? What will be the impact in the most critical high latitude regions of the Southern Ocean and Arctic Ocean?

(7) The growing number of highly controversial mitigation technological options for greenhouse gas geo-engineering (such as artificial ocean fertilisation) need to be critically evaluated. What is the scientific foundation for banning potentially useless or harmful mitigation options?

Carbon cycle research is thus essential for resolving major issues on environmental protection and governance of the sea and for establishing its role in the sustainable management of the planet.

Altogether, this effort can only be carried out with strong international collaboration on marine carbon measurements. European research on greenhouse gas budgets must continue to play its part; a balanced world view is needed. This issue will become even more important as the global map of greenhouse gas emissions changes in response to political and macro-economic developments.

Marine carbon cycle research is essential for providing the scientific foundation for decisions linked to the following policy documents and beyond (links can be found at the end of the document under "Further Reading"):

The European Sustainable Development Strategy 2001:
http://ec.europa.eu/environment/eussd/
("Gothenburg strategy of 2001")

EU Lisbon strategy 2000, aiming specifically for economic as well as social and environmental renewal:
http://ec.europa.eu/growthandjobs/faqs/background/index_en.htm

Communication "Limiting Global Climate Change to 2° Celsius: The way ahead for 2020 and beyond":
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52007DC0002:EN:NOT

The EU Water Framework Directive:
http://ec.europa.eu/environment/water/water-framework/index_en.html

Galway Declaration on Europe's Oceans – EUROCEAN 2004:
http://ec.europa.eu/research/press/2007/maritime-briefing/pdf/24-galway-declaration_en.pdf

Aberdeen declaration – EUROCEAN 2007:
http://ec.europa.eu/maritimeaffairs/pdf/Aberdeen_Declaration_final_2007.pdf

EU Maritime Policy development, An Integrated Maritime Policy for the European Union ("blue book"):
In English: http://ec.europa.eu/maritimeaffairs/pdf/imp-vision-paper/Vision_Paper_en.pdf
Other languages to be chosen from: http://ec.europa.eu/maritimeaffairs/publications_en.html

1992 OSPAR convention as current instrument guiding international cooperation on the protection of the marine environment of the North-East Atlantic:
http://www.ospar.org/eng/html/welcome.html

1992 Helsinki convention signed by all the countries bordering on the Baltic Sea and by the European Economic Community:
http://www.helcom.fi/Convention/en_GB/convention/

London convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter
(1972 and 1996 Protocol Thereto), including amendment about sequestration of CO_2:
http://www.imo.org/Conventions/contents.asp?topic_id=258&doc_id=681

"Brundlandt report", Our Common Future, 1987, World Commission on Environment and Development, Oxford University Press.

United Nations Framework Convention on Climate Change:
http://unfccc.int/2860.php

Kyoto protocol to the United Nations Framework on Climate Change:
http://unfccc.int/resource/docs/convkp/kpeng.html

3.2 International Perspective

Patricio Bernal is the Assistant Director-General of the United Nations Educational, Scientific, and Cultural Organization (UNESCO) and Executive Secretary of the Intergovernmental Oceanographic Commission. The IOC was established in 1960 to provide Member States of the United Nations with an essential mechanism for global cooperation in the study of the ocean. In 1957, Roger Revelle and Hans Suess published a seminal paper highlighting the role of the ocean carbon cycle in climate change. In 1960, Revelle helped to establish the IOC, emphasising the need for international cooperation in the study of the ocean carbon cycle. The IOC has implemented ocean carbon coordination activities for over 30 years, including the Committee on Climate Change and the Oceans, the CO_2 Advisory Panel, the International Ocean Carbon Coordination Project and the Ocean in a High CO_2 World Symposium series. 'CarboOcean-IP provides a critical research and monitoring component for IOC's work in developing the global ocean / climate observing system in support of the UN Framework Convention on Climate Change', Bernal explained. 'Without strong national programmes and regional networks, developing a global observing system would simply not be possible. As an intergovernmental institution, we particularly appreciate CarboOcean-IP's efforts to develop information and data products that are relevant for decision-makers. This is an often overlooked but essential part of scientific research, especially when dealing with large-scale or global phenomena such as climate change. UNESCO's Climate Change Task Force has also been very impressed with the range of educational activities developed through the CarboSchools program, and we are working to adapt this approach to apply to several of UNESCO's climate education programmes.'

3.2 International Perspective

Rik Wanninkhof is an oceanographer at the Atlantic Oceanographic and Meteorological Laboratory of the National Oceanographic and Atmospheric Administration (NOAA) in Miami, USA. His research focuses on sustained observations of carbon inventories and air-sea CO_2 fluxes in the world's oceans. 'Study of the carbon cycle in the ocean has by nature of its sheer magnitude been a collaborative research endeavour,' said Wanninkof. 'One of the many successes of CarboOcean-IP has been its active outreach and collaborations with international partners. CarboOcean-IP has in many cases been the impetus of expansion, by international partners, of its research efforts beyond the geographic boundaries set up by the programme. The successful efforts to combine the extensive datasets of CarboOcean-IP partners with those of US colleagues in the North Atlantic and Southern Ocean has led to a global synthesis effort and database to estimate air-sea CO_2 fluxes and increases in surface ocean CO_2 levels.'

'The Carbon in the North Atlantic (CARINA) effort that was revived and incorporated into CarboOcean-IP has created global partnerships to assess the changing global ocean CO_2 inventories. The international collaborations have led to constraints on regional air-sea CO_2 fluxes such as those in the North Atlantic and Southern ocean, and assessment of decadal changes of carbon in the ocean interior, variability in the "natural" ocean carbon cycle in the deep ocean that was unexpected. [Regional] process studies advocated within the US Ocean Carbon and Biogeochemistry (OCB) programme are being coordinated in close association with efforts in CarboOcean-IP. Of note are the interactions in coastal studies with exchange of procedures, hypotheses, and unique opportunities to compare and contrast widely different margins. Ocean acidification and its impact on ocean ecosystems has been an emerging topic in the last years where US scientists are establishing close research ties with the EPOCA project.

'While EPOCA is a good example of how components of CarboOcean-IP have evolved into independent large efforts, a critical concern of international partners is how the substantial infrastructure and know-how garnered by CarboOcean-IP will be continued after the end of the effort. Wanninkof concluded, 'As this assessment report clearly indicates sustained observations of the anthropogenic CO_2 perturbation into the ocean, and its impacts and feedbacks have to be continued. Within the USA, NOAA in partnership with other federal agencies has initiated several sustained observational and research efforts in trends of atmospheric and oceanic CO_2. The problem is too large and too important to be done by a single nation and we strongly encourage similar sustained programmes under auspices of the European Union.'

Toshi Saino is Program Director of the Global Warming Observational Research Program of JAMSTEC, and a co-chair of the Carbon and Climate Section of the Pacific Marine Science Organization (PICES). Toshi Saino is also a member of the Joint SOLAS-IMBER Carbon Group, and of CarboOcean-IP's International Advisory Panel. He is now planning JAMSTEC's carbon cycle research for 2009-2013. 'In planning new experiments, CarboOcean-IP is an ideal example of successful coordinated research for overall assessment of the oceanic carbon cycle, comprising observations, modelling, and lab and mesocosm-experiments', Saino said. He also plans to coordinate an international carbon cycle study in the Pacific in collaboration with US OCB, and other Pacific Rim countries' programmes, taking advantage of PICES framework. He envisages that 'It would provide an excellent opportunity to draw a true global picture of the carbon cycle if the Pacific study could get started in parallel with CarboOcean-2'.

3.3 Research needs

Any future carbon cycle research strategy must address the following two main issues:

(1) Sustained observing systems for essential carbon variables are a necessary backbone for further research – these observing systems include diagnostic models to interpolate between measurements and to upscale them.
(2) Optimised prognostic models are needed for predictions under future conditions. The models' sensitivity and system dynamics must be based on process studies and calibrated against measurements. These calibrated models can then be used when no data from measurements are available, especially for future scenarios.

With respect to these issues, we can definitely specify the following **knowledge gaps and research needs**:

(1) Ocean carbon observations need to be continued and further improved/developed. Highest priority is for the continuation of the surface ocean pCO_2 observing system using VOS lines (Voluntary Observing Ships). Further needs include continuation of repeat hydrography (deep sections), time series stations, floats/buoys (carbon and oxygen), technical development of sensors and automated measurement systems, and remote sensing of *ground-truthed* key variables.
Discussions on how to include a defined subset of ocean observations in the **ICOS project (Integrated Carbon Observing System, see Page XXX)** are underway. ICOS has been submitted and negotiated from the terrestrial community as a European research infrastructure project which will sustain essential carbon cycle measurements. It is not yet clear how such a "rucksack approach" could be applied to ocean observations under ICOS, but the oceanographers may propose that some ocean-observing infrastructure be included in ICOS (potentially as a "sub-centre" under ICOS). If ICOS does become operational, the earliest start-up date will be 2012. We therefore must find an answer to the question: *How to sustain observations for the period between the end of CarboOcean-IP and when ICOS starts in 2012?*
The timeframe for the ocean community is as pressing as it is for the terrestrial CarboEurope-IP community. Most EU-funded marine carbon observing systems are supported only until the end of 2008 (one year before CarboOcean-IP will end; 2009 is dedicated to data evaluation, modelling, and synthesis). They end at the same time as CarboEurope-IP will finish.
At this critical phase of steeply increasing carbon loads in the Earth system, continuing to monitor ocean carbon, and the development of new automated measurement techniques, should be a high priority. However, it must be stressed that at present deep carbon measurements and time series stations are not included as part of ICOS. These essential measurements will also

in the foreseeable future be carried out by research institutions and not through routine measurements by national hydrographic services. Research funding must therefore be provided if these essential observations are not to stop.

(2) Predictive models of the ocean carbon cycle must be improved with better process parameterisations and the models' sensitivity must be calibrated using observed data. This means that true process representations must be fitted to true observations, so that not only the present state is represented well, but rather – and most importantly - also changes (first derivative with respect to time) and rates of change (second derivative with respect to time). Such a model calibration is absolutely necessary if we are to identify the correct model sensitivity. The challenge is to optimise coupled Earth system models appropriately against the observed data. At present, it is even difficult to calibrate the component models of the ocean alone through systematic data assimilation. Coupled models, however, produce their own weather and climate (internal "natural" variability) and hence cannot be so easily calibrated through real events (e.g., an El Niño event will in most cases not appear at the same time in an Earth system model as in the real world). The marine databases are often still insufficient to reveal proper statistics against which Earth system models can be calibrated. The research challenge is therefore, **to confront ocean carbon cycle models with observations in a systematic way**, so that the models' predictive skills are improved. This methodological problem has to be solved urgently in order to narrow down uncertainties in future projections of the carbon cycle. It will be feasible to calibrate a part of the models' sensitivities through consideration of the **seasonal cycle** and the **glacial/interglacial changes** in the carbon cycle and to introduce improved **process parameterisations**.

Further research challenges include the following issues:

(a) The biological pump in the ocean is strongly coupled to nutrient cycling (element cycles of nitrogen, phosphorus, silicon, micronutrients such as Fe, Zn, etc.) and changes in oceanic circulation. How do the **marine nutrient cycles** change as a consequence of human activities and climate change? This includes the change in methane and nitrous oxide due to changes in stratification and biological production. The associated coupled biogeochemical cycles have to be understood using a common approach. Changes in the **oxygen budget** provides crucial information about the mode of changes in the carbon cycle (biospheric versus physical/chemical cycling). High precision measurements of carbon, oxygen, and nutrients are needed as a tool to help in detecting and diagnosing large scale changes in oceanic overturning, which cannot easily be measured by physical techniques. There are already well established links to the IGBP core projects SOLAS, IMBER, and LOICZ, but links to the trace metal core project, GEOTRACES, have to be improved.

3.3 Research needs

(b) How to correctly **couple the terrestrial and marine carbon cycles** together? One option is clearly using atmospheric inverse studies to diagnose the land-atmosphere and sea-atmosphere fluxes simultaneously. However, these computations are diagnostic and are not suitable for making future predictions. Evolving advanced Earth system models offer further development options by including river transport, estuaries, and shelf sea systems.

(c) How to **link oceanic carbon cycle models to the economy**? Marine carbon cycle models rarely include an economic evaluation component. Here preliminary design work is necessary; the essential impact areas have to be defined (e.g. consequences of ocean acidification), and economically relevant variables have to be identified.

(d) How to **further reduce uncertainties** in projections? In general, our estimates of uncertainties have become more realistic, but somewhat larger as we discover new sources of error. Therefore, our original goal of reducing the size of the uncertainties may have to be modified to first identifying the uncertainties correctly and comprehensively, and then secondly to systematically reduce them.

Further integration of the European and international carbon research community:

Coordinating carbon cycle research is itself a challenge due to the interdisciplinary nature of the work. A **better interdisciplinary integration** is certainly needed if the marine and terrestrial science communities are to understand each other's work. At this stage, the terrestrial and marine communities are still quite separate and to a degree must remain so, if we are to prevent loss of focus. Nevertheless, as the carbon cycle is a global phenomenon crossing over all Earth system reservoir boundaries, a firm link needs to be established and cultivated. The link is required for the exchange of information and the establishment of closed carbon budgets. One encouraging initiative was the greenhouse gas conference in Crete 2006, which was attended by participants from the three EU *Integrated Projects*, CarboEurope-IP, CarboOcean-IP, and NitroEurope-IP. Unfortunately it revealed, that it is not always easy for everybody to develop enthusiasm for wide areas of research, outside their own area of specialisation. The COCOS project (COordination action Carbon Observation System, dedicated to linking European carbon data sets with GEO/GEOSS, kick-off meeting on 21 May 2008) will be important in fostering the link between the land and ocean communities, as was the 5 October 2007 experts' meeting in Brussels (with attendees from all major European-funded greenhouse gas projects) which showed the potential in cross-discipline work. The meeting agreed that **we need a continuous platform for common interdisciplinary carbon cycle research in Europe (which is also linked to the other networks worldwide)**. How to keep carbon cycle research projects in Europe together – how to keep the emerging network going?

Linking the larger research projects running in parallel with a common coordination action or "communication action" could be an effective answer. The major research would then be done in separate projects tailored to their specific needs. Certain areas, which are by their nature overarching (such as Earth system modelling), could be approached as separate additional projects linking ocean and land cycles closely together. Fully synchronous collaborative research projects (same start and end dates) for land and ocean would be a simple and effective way of building a seamless cooperation between land and ocean communities.

Data management aspects: It is self-evident that no one person, laboratory or country can produce sufficient data to address the questions we are currently asking (whether the questions be European or Global). Logically it follows that we need to have all high quality data in the public domain and available to all scientists; to be accessible the data must be easily locatable and in an easily usable format. Achieving this will require steady funding, but the total amount is small relative to the scientific return.

Certain sub-sets of carbon cycle related issues are being carried out in separate research initiatives (EU or nationally funded), for example the upcoming FP7 collaborative projects on "ocean acidification" and "impacts of climate variability and extreme events on terrestrial carbon storage, exchange flows and soil functioning". These **more specialized research projects cannot replace overall assessments of the terrestrial and oceanic carbon fluxes**. For example, the acidification project members would find it impossible to create the measurement network for pH value and carbonate saturation they need themselves; they must rely on cooperation with other projects (in this case CarboOcean-IP). The most practical way forward would be with a project structure in which marine and terrestrial core projects provide the backbone observing system data collection and co-ordination-communication, while smaller projects provide the specialised research.

The link of research-oriented carbon cycle measurements with more service-oriented **end-user friendly data products** should be enabled through **Kopernikus** (formerly GMES). The timeframe and exact functioning of data transfer from research networks to end user interfaces needs better definition. It is hoped that a part of the operational service of ICOS will be taken over by GMES. We are still in transition from research to operational observing systems (examples: ICOS, ARGO) and expect a certain sub-set to stay in the research realm.

3.4 CarboOcean-IP History

Ocean carbon cycle research in view of the ocean's uptake of human produced carbon dioxide has a long time history reaching back to the pioneering works on marine CO_2 buffering of Revelle, Bolin, and Eriksson in the late 1950s. The kinetics, i.e., the timing of marine uptake of anthropogenic CO_2, could be quantitatively estimated in the 1970s with a series of box models by Siegenthaler, Oeschger, Broecker, and further researchers. Oceanic carbon cycle research was boosted by detection of the glacial/interglacial CO_2 variations from Antarctic ice core analysis and the parallel findings of stable carbon isotope variations in deep sea sediment cores. First studies on oceanic uptake of human-produced CO_2 using ocean general circulation models were carried out among others by Maier-Reimer and Sarmiento in the late 1980s. The international carbon dioxide conferences at Bern, Kandersteg, and Hinterzarten revealed the importance of the oceanic carbon sink but also showed that many details on oceanic carbon cycling were not yet known with sufficient detail.

The IGBP core project JGOFS (Joint Global Ocean Flux Study, 1989-2003) was initiated in parallel to WOCE (World Ocean Circulation Experiment) in order to determine how the biological carbon pump modulates the CO_2 cycling between ocean and atmosphere and to better understand the sedimentary record of climate change. A series of EU Framework Programme 4 ("MAST") projects were created in order to better quantify the various biological and physical carbon pathways in the ocean. Among these projects were a series of specifically targeted projects, such as ASGAMAGE on the process of air-sea gas exchange, ESCOBA on linking carbon cycling with ocean circulation, and CARUSO on the coupled carbon-nutrient cycling in the Southern Ocean. CANIGO was dedicated specifically to the coupling between climate change and carbon cycling in European waters, while OMEX I and II focused on carbon cycle relevant processes at the continental margins. SINOPS closed important gaps in our knowledge about the silicon driven biological pump in the ocean from sea surface to sediments. General ocean carbon cycle circulation models were intercompared in the FP4 project OCMIP (phase 1).

Through these projects a series of new issues emerged and were addressed in collaborative research projects also in EU Framework Programme 5. The role of the trace metal iron and its role on biological carbon cycling was in detail studied through project IRONAGES. In ORFOIS, the role of changes in marine particle fluxes in the carbon cycle was addressed through a comprehensive modelling approach. The role of ocean circulation on carbon transport was investigated in projects TRACTOR, OCMIP-2, NOCES, and GOSAC. A systematic use of voluntary observing ships (VOS) for semi-automatic measurements of surface ocean CO_2 partial pressure, surface air CO_2 concentrations, and air-sea CO_2 fluxes in the North Atlantic was introduced by project CAVASSOO.

All these efforts provided extremely useful new insight into marine carbon cycle processes. In order to merge European efforts on quantifying the natural and human-induced carbon fluxes, it became obvious that the expertise and the specific knowledge of European research groups on marine carbon cycling needed to be integrated for full exploitation of relevant capacities. As marine carbon cycle research has a clear large scale and global dimension – the ocean is linked worldwide through the oceanic circulation and climate – researchers were as yet not as well integrated as terrestrial communities which operate on a geographically more confined domain. In order to provide the foundation for a European integrated marine carbon research effort covering all aspects of the problem, a group of 20 key European marine carbon scientists mainly consisting of previous project coordinators met at Amsterdam in June 2002. Subsequently an expression of interest (under the name MARCASSA) concerning an integrated project on marine carbon cycle research was submitted to the European Commission. The essence of this proposition was transferred to the FP6 work programme and finally the successful CarboOcean Integrated Project proposal was submitted including participation from the US. The start of CarboOcean was a milestone in European carbon cycle research as a fragmentation of the European carbon cycle research community could be overcome and all relevant disciplines could be united under one research project.

For the 4th assessment report of the Intergovernmental Panel on Climate Change, 5 lead authors and a series of contributing authors out of the CarboOcean consortium, shaped important sections on marine carbon cycling and respective feedback processes. CarboOcean researchers also took care that for the first time ocean acidification through human-produced CO_2 uptake was adequately addressed in this report. CarboOcean researchers were key to promoting and realising a new FP7 project on ocean acidification (EPOCA) which would have not been possible to the present degree and sophistication without the pre-existing CarboOcean Integrated project.

On an international basis, CarboOcean was strongly influential towards the creation of overseas ocean carbon cycle programmes such as OCB (Ocean Carbon & Biogeochemistry, USA) and *Pacificarbon* (Pacific research communities). The EU FP7 coordination action COCOS will now realise a merging of terrestrial and marine carbon cycle observations and their analysis for the benefit of the European GMES and global GEOSS programmes.

CarboOcean is grateful to the European Commission, in particular to Claus Brüning, Giovanni Angeletti, Anastasios Kentarchos, and Elisabeth Lipiatou for their constructive cooperation in order to advance European ocean carbon cycle research to internationally acknowledged top standard.

3.4 Further reading, links, etc.

Past and running EU projects related to the marine carbon cycle

Dedicated specifically targeted research projects – various approaches from different directions and different disciplines and for different regions:

FP4/MAST:
1. CARUSO
2. ESCOBA
3. ASGAMAGE
4. CANIGO
5. SINOPS
6. OMEX I and OMEX II
7. IMCORP
8. MERLIM
9. ESOP I and ESOP II
10. OCMIP I & II
11. BIOGEST

Progressing combinations of field data, modelling, and process studies within single projects - bridging disciplines, building observing systems, developing prognostic models, dedicated researcher training:

FP5:
1. ORFOIS
2. IRONAGES
3. TRACTOR
4. CAVASSOO
5. EUROTROPH
6. OCMIP (phase 1 and phase 2)
7. GREENCYCLES
8. GOSAC
9. NAOC
10. NOCES

Interdisciplinary synthesis of specific ocean science problems, development of prototype observing/prediction systems, pooling knowledge across the disciplines:

FP6:
1. CarboOcean (IP)
2. Eur-Oceans (NoE)
3. MERSEA (IP)
4. SESAME (IP)

Books and articles for reading:

"Brundlandt report", 1987, Our Common Future, World Commission on Environment and Development, Oxford University Press.

Broecker, W.S., 1985, How to build a habitable planet, ELDIGIO PRESS, LDGO BOX #2, Palisades, New York 10964, 291 p.

Schubert R., et al., 2006, The Future Oceans – Warming Up, Rising High, Turning Sour, WBGU, Berlin, 110 p., ISBN 3-936191-14-X. http://www.wbgu.de/wbgu_sn2006_en.html

Websites with useful information:

Science:

CarboOcean-IP website: http://www.carboocean.org

CarboSchools, projects for secondary schools: http://www.carboschools.org

Carbon Dioxide Information Analysis Centre, US: http://cdiac.ornl.gov/

The International Ocean Carbon Coordination Project : http://www.ioccp.org/

SOLAS: http://www.uea.ac.uk/env/solas/

IMBER: http://www.imber.info/

LOICZ: http://www.loicz.org/

Global Carbon Project: http://www.globalcarbonproject.org/

IPCC 4th Assessment Report of Working Group I : http://ipcc-wg1.ucar.edu/wg1/wg1-report.html

Policy:

The European Sustainable Development Strategy 2001 ("Gothenburg strategy of 2001")
http://ec.europa.eu/sustainable/sds2001/index_en.htm

EU Lisbon Strategy 2000, aiming specifically for economic as well as social and environmental renewal.
http://ec.europa.eu/growthandjobs/key/index_en.htm
Environmental issues :
http://ec.europa.eu/growthandjobs/key/environment_en.htm
Energy issues :
http://ec.europa.eu/growthandjobs/key/energytransport_en.htm

Communication "Limiting Global Climate Change to 2° Celsius: The way ahead for 2020 and beyond"
http://ec.europa.eu/environment/climat/future_action.htm

The EU Water Framework Directive
http://ec.europa.eu/environment/water/water-framework/index_en.html

Galway Declaration on Europe's Oceans – EUROCEAN 2004
http://www.eurocean2004.com/pdf/galway_declaration.pdf

Aberdeen Declaration – EUROCEAN 2007
http://ec.europa.eu/maritimeaffairs/declaration_en.html

EU Maritime Policy Development, An Integrated Maritime Policy for the European Union ("blue book")
http://ec.europa.eu/maritimeaffairs/dev_imp_en.html

1992 OSPAR convention: the current instrument guiding international cooperation on the protection of the marine environment of the North-East Atlantic
http://www.ospar.org/eng/html/welcome.htm

1992 Helsinki convention signed by all the countries bordering on the Baltic Sea and by the European Economic Community
http://www.helcom.fi/Convention/en_GB/convention/

London convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972 and 1996 Protocol Thereto), including amendment about sequestration of CO2
http://www.imo.org/home.asp?topic_id=1488

United Nations Framework Convention on Climate Change
http://unfccc.int/2860.php

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The added value of integrated research of the terrestrial and marine environments

The overall goal of the research described in this booklet is for policy decisions on climate mitigation and adaptation to be made on the basis of scientific evidence. Because climate change depends on the interactions between land, ocean and atmosphere "Integrated" research is needed which transcends the barriers of conventional scientific disciplines. Europe has declared it will take the global lead in the climate change mitigation and adaptation process, making this type of integrated research essential for the decision making process. The two "Integrated Projects", CarboEurope-IP and CarboOcean-IP, one focusing on the terrestrial surface of Europe, the other on the oceans, are an example of the joined-up thinking that is needed if we are to succeed in the battle to avoid dangerous climate change.

The real challenge of CarboEurope-IP and CarboOcean-IP was to bring marine and terrestrial science closer together, despite their different methodologies and experimental designs. In the Introduction and in the main reports we have discussed how climate models must integrate the marine and terrestrial effects of fossil fuel emissions, the magnitude and distribution of sources and sinks governed by biology, physics, as well as chemistry, and the human uses of these environments which range from fisheries to deforestation for food or energy crops. As all this knowledge is fully integrated within climate models the uncertainty in their predictions will reduce and the value of these predictions to policy and decision makers will become progressively more relevant.

What happens on land in Europe cannot be separated from what happens in the North Atlantic. Conversely, the future role of the North Atlantic in the carbon cycle and as a climate driver depends strongly on the way we manage our land, and on our future fossil fuel consumption. Soil is an enormous reservoir of carbon, which if we do not manage properly, has the potential to become a source of carbon that would dwarf the emissions from fossil fuel burning. In a very short time, globally about 1000 times as much carbon could be released from soils than is presently emitted from fossil fuels. Thus fossil fuel emissions and land-use are largely independent sources of carbon. Their combined effect could be additive, or an increase in one may be compensated by a decrease in the other. Either way, both will affect the processes, which operate in the North Atlantic. A slowing down of the North Atlantic three-dimensional circulation scheme due to enhanced warming and related freshwater delivery would in addition retard the oceanic carbon uptake and also enhance ongoing climatic change in Europe.

Both CarboEurope-IP and CarboOcean-IP, are embedded in the Global Carbon Project, an international effort to quantify the global carbon cycle. The Global Carbon Project is coordinating research to develop a complete picture of the global carbon cycle, including both the biophysical and the human dimensions, and associated feedbacks. In fact, CarboEurope-IP and CarboOcean-IP could serve as a model of how the global carbon cycle should be investigated in different regions of the world. This is essential if we are to explore the full potential of managing carbon sinks and sources across the globe for climate mitigation.

By initiating these two Integrated Projects, Europe has taken a global lead in carbon cycle research. As Kevin Noone, the Executive Director of the International Geosphere-Biosphere Programme stated: "These projects are excellent examples of how BASIC KNOWLEDGE can be developed and made useful for decision support on adaptation and mitigation issues". This statement emphasises the need for future funding of carbon cycle research. We do not yet know enough about the basic processes controlling the carbon cycle; consequently the models lack realistic representation of these processes. More FUNDAMENTAL-CARBON CYCLE RESEARCH is urgently needed before short-term applications can be made with confidence.

The main findings of CarboEurope-IP and CarboOcean-IP were:

- forests are a major sink of carbon, but grasslands may even be more effective. This could have serious implications for European agricultural policy, and questions the wisdom of erasing "useless" grassland in favour of croplands growing maize.

- the terrestrial surface of Europe still is a significant sink, compensating 17% of the fossil fuel emissions. This sink is twice the fossil fuel emission-reduction target of Europe in the Kyoto protocol. If we lose this sink, e.g. by mis-guided changes land-use, the fossil fuel reduction targets for 2020 should not be 20% but 40%.

- it is quite clear that the proposed pace of reduction in fossil fuel emissions is much too slow to mitigate climate change before major impacts appear. A major issue is now whether the feedback from temperature changes in the Northern Hemisphere, which is by and large shared between North America and Europe, will affect the Global hotspot of the marine sink, the formation of deep-waters in the northern North Atlantic.

- The North Atlantic is an important, highly variable carbon sink of about 200-450 Tg C yr^{-1}, which is equivalent to a total of 1/5 of the carbon emissions of Europe and Eurasia. If this sink diminishes, as seen by CarboOcean-IP, this would require even faster and more stringent fossil fuel reduction policies than previously thought.

Added value of integrated research

- The Southern Ocean sink for anthropogenic CO_2 weakened during the past two decades, presumably due to decadal climate variability. The trend has to be observed carefully, a challenging task which needs strong international collaboration and the further development of automated measurement systems. Due to its large volume, small changes in the anthropogenic carbon storage of the Southern Ocean can have important implications for the global atmospheric CO_2 concentration.

- Marine biogeochemical feedbacks have been identified as playing a significant role both in ecosystem processes, particle fluxes, and sediment geochemistry, as functions of temperature, CO_2 concentration, and pH value.

- Future climate projections with coupled carbon-cycle climate models show a net reinforcing of climate change by carbon cycle processes. This effect has to be taken into account when drawing up emission reduction targets for climate change mitigation.

- The North Atlantic mainly acts as a sink for emissions from North America rather than Europe. The natural sink for European emissions is located in Siberia. Thus future funding strategies should view the Eurasian region as a whole, and direct funds at developing understanding of the carbon cycle at this even larger scale.

Land and ocean carbon cycles are intimately linked with each other as active parts of the Earth's climate system (**Fig. VI.1**). The increase in radiative forcing through human-derived carbon emissions is changing the climate system. At this moment the marine and terrestrial carbon cycles are able to partially compensate for the man-made CO_2 emissions through carbon uptake. In future the land sink may turn into a carbon source to the atmosphere due to land-use, land-use change, climatic change and rising atmospheric CO_2 levels. Globally averaged, the ocean will always act as sink for CO_2 emissions to the atmosphere, but the sink strength may change considerably due to climate change, changes in ocean circulation, as well as biogeochemical feedback processes to warming and increasing CO_2 levels. Therefore, the integrated assessment of carbon sources and sinks in relation to the climatic feedback is therefore essential for policymakers. Such an assessment is only possible through an integrated scientific systems approach as successfully carried out by CarboEurope-IP and CarboOcean-IP.
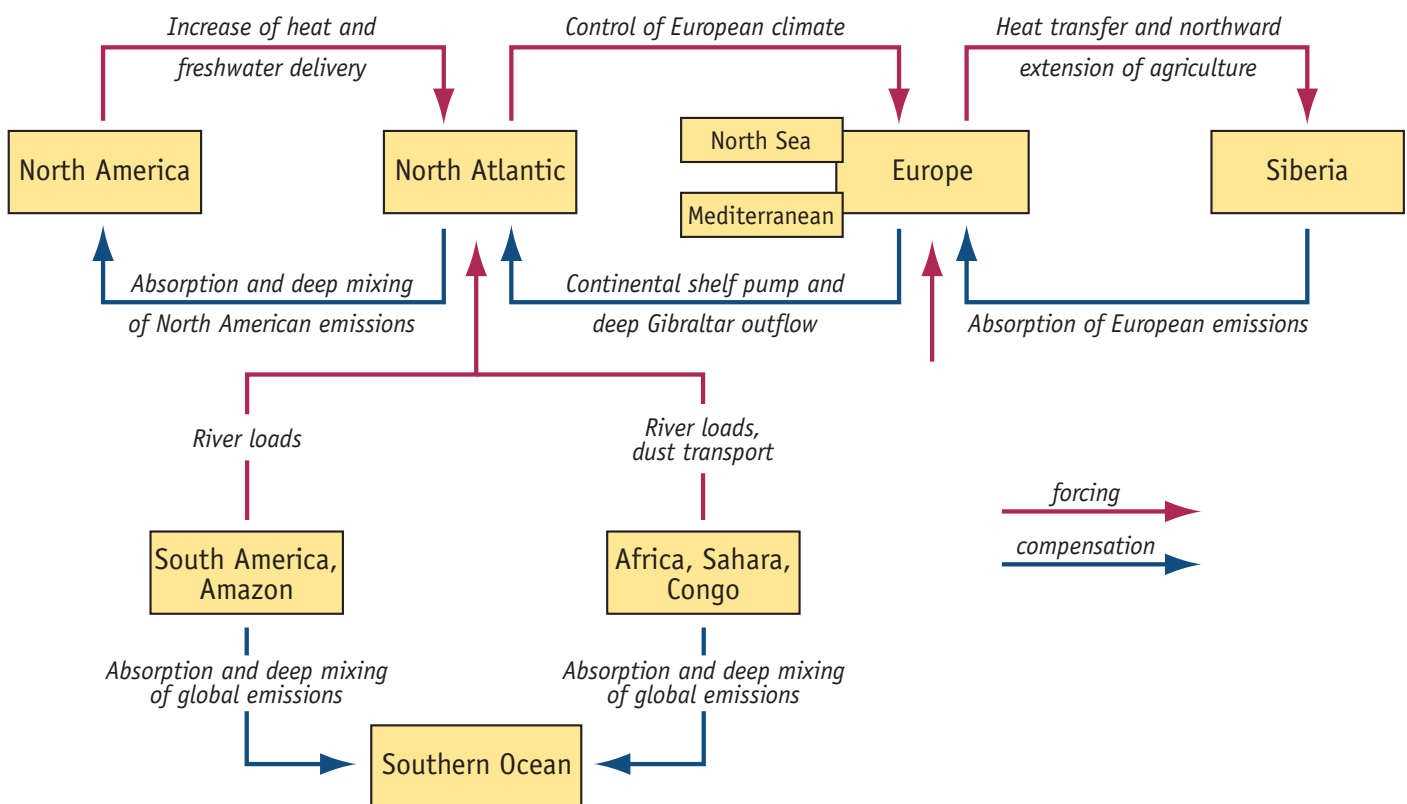
Fig. VI.1: Positive forcing and compensation processes of relevance for the European carbon balance as part of the Earth system.

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Project Structure of CarboEurope:

Component 1: Ecosystems
Component 2: Atmosphere
Component 3: Regional Experiment
Component 4: Continental Integration
Data Management
Demonstration activities
Dissemination activities
Innovation activity
Training

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Core Theme 5: Furture scenarios for marine carbon sources and sinks

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Gunson Jim, Hadley Centre for Climate Prediction and Research (MetO –partner 33)

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The carbon cycle is one of the fundamental processes in the functioning of earth system and is directly connected to climate change. Rising atmospheric concentrations of CO_2 and other greenhouse gases over the past 200 years have driven substantially global warming, which in turn could trigger the release to the atmosphere of additional carbon from the oceans and the terrestrial ecosystems, thus accelerating climate change. The interactions and feedback mechanisms between the climate-earth system and the carbon cycle constitute one of the key scientific challenges today.

The current publication provides a comprehensive assessment of the European and North Atlantic carbon balance based on integrated research actions under the 6th Framework Programme for Research. By presenting key scientific findings, their implication for policy and future research needs, the present report provides a framework for future strategies in the field of carbon cycle research and for further discussions on this highly relevant but also complex issue, involving scientists, policy makers, and research agencies.

Evergreen needle leaf forest	Deciduous broadleaf forest	Shrubs	Grasses	Urban
Mixed forest	Crops	Shrubs & Grasses Mosaic	Unvegetated	Reference: Jung et al., 2006

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