# CarboEurope-IP

# An Assessment of the European Terrestrial Carbon Balance

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# Impressum

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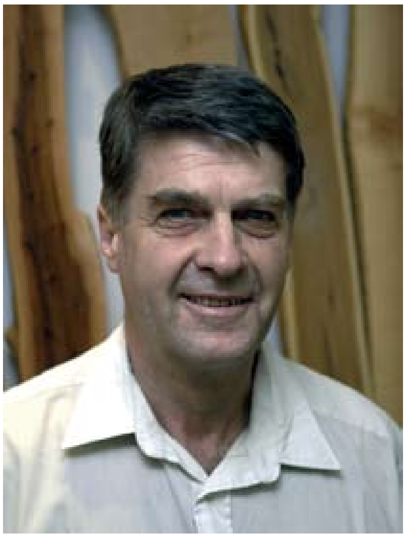
# Preface



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. The European Commission is proposing an ambitious climate and energy policy with a central aim of reducing the European Union's greenhouse gas emissions by at least 20% of their 1990 level through increased use of renewable energy and by better husbandry of the land surface, i.e. through land-use and land-use change.

Negotiating a new agreement will be a tough process as individual nations seek to minimise the economic risks, irrespective of whether they are real or perceived, of reducing their carbon emissions. In negotiations such as these, the first step to success is for all the parties to agree on the basic premises: that is on the need for change and the scientific evidence and understanding which identifies the problem and presents the solution. Only arguments based on sound scientific evidence will carry weight; CarboEurope-IP is providing that evidence.

Starting with the Karlsruhe workshop in 1983, the European Union has been continually supporting this field of research, building European expertise in carbon cycle research. By 1998 it had become clear to the science community that a large, integrated research programme was needed and at the Orvieto workshop of the ESCOBA programme a proposal was made to construct a joint Carbo-Europe programme – applying a pan-European approach to carbon cycle research. This joint-venture was achieved initially by joining all the projects in the sector in a CarboEuope-Cluster; CarboEurope-IP, an integrated project in the 6th Framework Programme, followed.

In struggling to prevent climate change by controlling the amount of carbon in the atmosphere we are effectively attempting to manage the future carbon balance of the planet. To plan such global carbon management 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 the regional level. Without this knowledge it would be like trying to manage your own bank balance without knowing how much money you are earning, or how much you will be spending. That is why CarboEurope-IP is such an important project. CarboEurope-IP will allow us to put numbers to those flows of carbon into and out of our European land surface. The critical numbers needed to answer the simple question, "What is the carbon balance of the European continent?" The main emphasis of CarboEurope in this context is on land-use and land-use change. This emphasis recognises that without good management of the land efforts to reduce or stabilise the atmospheric $CO_2$ concentration may simply fail.

The task of putting a number on the continental carbon balance is extremely demanding, and can only be achieved in a research environment through a coordinated ensemble of projects all working towards this central goal. Based on the successful model of the CarboEurope-Cluster the European Union has thus supported additional integrated projects, mainly CarboOcean-IP, NitroEurope-IP, CarboAfrica, LBA-Brazil and TCOS-Siberia to put the continent of Europe into a global perspective.

CarboEurope-IP has brought together a team of top European scientists who are working to provide the data we need and the understanding to interpret that data. This science will give us the evidence we need to guide future policy making. This booklet explains how CarboEurope-IP is working to unravel the carbon balance of Europe: the aims of the project, what has been discovered, and what we still need to learn.

Jena, November 2008

Ernst-Detlef Schulze
Coordinator of CarboEurope-IP

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# Executive Summary - CarboEurope-IP is quantifying the carbon balance of the European continent

**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-$CO_2$eq $yr^{-1}$; 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 greenhouse 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 significantly 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-$CO_2$eq $yr^{-1}$), and only 11% of the EU-25 total greenhouse gas emissions (about 1100 Tg C-$CO_2$eq $yr^{-1}$).
- The uncertainty in the magnitude of the terrestrial sink remains high. This is a consequence of the heterogeneous 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.

# Introduction

The overarching aim of CarboEurope-IP is "to understand and quantify the terrestrial carbon balance of Europe and the associated uncertainties at local, regional and continental scale".

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 induced by climate, land history, and management. This required the establishment and operation of a network of measurement stations, which previously did not exist. "To quantify uncertainties" means that all errors, biases and doubts about the measurements and modelled qualities are evaluated and enumerated "at local, regional and continental scale" requires upscaling rules across several orders of magnitude. CarboEurope-IP's aspiration is to reduce the uncertainty in our estimate of the European carbon balance to about 10%. The main tool used to assess uncertainties in CarboEurope-IP was the simple idea that each quantity would be measured twice, by approaching it from the larger top-down approach and from the smaller scales of the bottom-up approach. Although in many cases larger scales are simpler to assess than smaller scales, CarboEurope-IP aimed at increasing the resolution of the smallest scales to a length of between 10 and 50 km.

The project is not only highly demanding, but also critically important in a global context. Europe is one of the regions of this globe with very high fossil fuel emissions and very intensive land-use. Does the continent emit carbon from its terrestrial surface? The global emissions have increased exponentially since 1950 (**Fig. 1**). We also know that emissions from land use and land-use change have made a significant contribution to carbon emissions, but the exact amount is still unclear. Some of the anthropogenic carbon emissions have been compensated by uptake by the oceans and by the terrestrial biosphere, but the majority of the carbon remains in the atmosphere. The oceanic "sink" increased up to the 1980s, but since then the uptake has remained almost constant. Apparently, the oceans have become too warm and too acid to further increase uptake (WBGU, 2006). In contrast, the biospheric uptake has continued to increase, but it exhibits huge oscillations in concert with the atmosphere. Biospheric uptake has been included into the accounting scheme of the Kyoto protocol. Thus we need to understand not only the factors which cause the general increase of carbon sequestration on land despite emissions by land use and land-use change, but also the factors which cause these large oscillations.

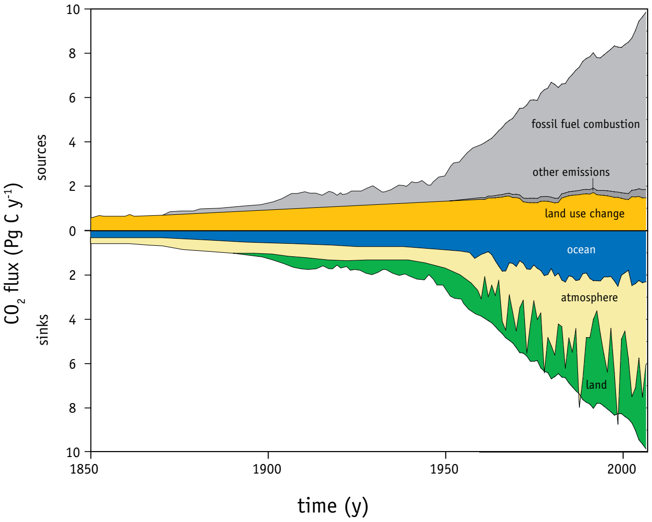


*Fig. 1: The development of carbon dioxide emissions, and the uptake by oceans, land and the atmosphere over time. (redrawn from Canadell et al., 2007)*

Clearly, the general goal of CarboEurope-IP is just as politically important as it is outstandingly ambitious. The project demands major advances in environmental research, coordinated to serve the political need for precise information on such a sensitive issue as climate change.

Meeting CarboEurope-IP's ambitious aims would be impossible without a large team of experienced specialists. Fortunately, the project did not start from scratch; it built upon the long-term experience of a series of previous projects. Starting over ten years ago with Framework 4, the European Union has consistently supported the establishment and development of a European carbon-cycle research community working on ecosystem processes, ecosystem fluxes and atmospheric carbon measurements. During a Framework 4 project meeting in Orvieto, Italy on 24 June 1998, the research community decided to continue with a coordinated consortium in Framework 5. The resultant CarboEurope-Cluster operated from January 2000 to the end of 2003. The present CarboEurope-IP succeeds the cluster in Framework 6. The history of CarboEurope-IP shows that although such large projects may have a long preparatory phase, the research capacity built up over time can deliver the necessary science and knowledge needed for policy making.

CarboEurope-IP was designed to set the stage for the commitment period of the Kyoto protocol, extending from 2008 to 2012. Detlef Schulze, the coordinator of CarboEurope-IP said, 'The next four years are going to be a critical period in the global effort to avoid dangerous climate change. By developing the tools needed to carry out carbon accounting, CarboEurope-IP is working to ensure that the forthcoming, political debate will result in scientifically-sound, evidence-based policy.'

# 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. 2**).

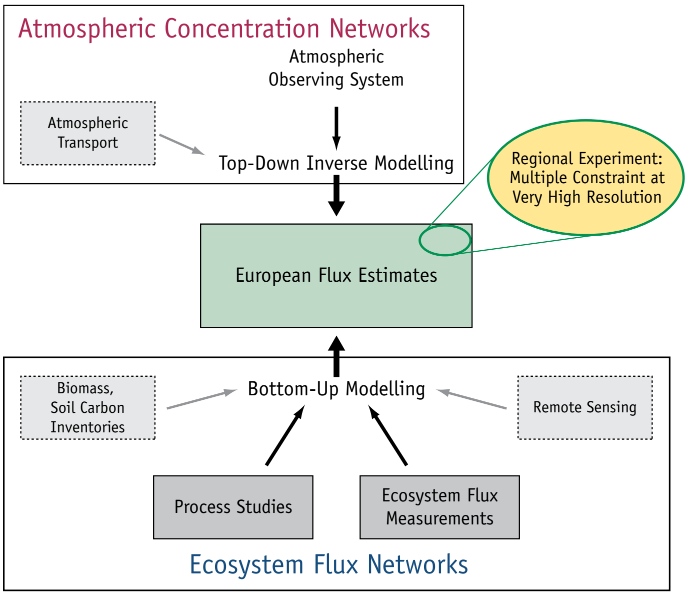


*Fig. 2: Atmospheric and ecosystem observations constrain the quantification of the carbon balance.*

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.

CarboEurope-IP "Assessment of the European Terrestrial Carbon Balance" is a European Integrated project of Framework Progamme 6 (GOCE-CT-2003-505572) running from 2003 until 2008. The European Union supports CarboEurope-IP with 16 Million €. The project has 75 contracting partners across 17 European nations, about 470 participants and 60 PhD students.
(http://www.carboeurope.org)

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. 3**). 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. 3: 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)*

# The Role of Soil

## Soils

Soil has the potential to be a major longterm sink of atmospheric carbon (**Fig. 4,5**). $CO_2$ is extracted from the air during plant photosynthesis and later enters the soil as plants die or shed their old leaves and roots. 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.

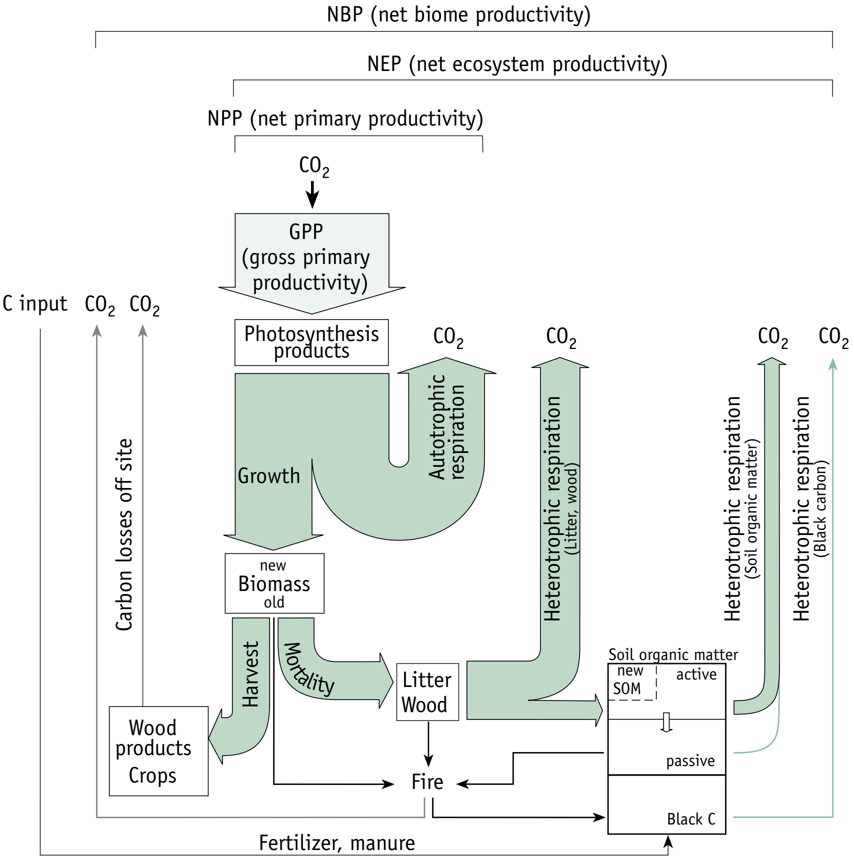


*Fig. 4: Definitions of the term "productivity" in the carbon cycle. The initial process is the gross primary production (GPP), which corresponds to photosynthesis. Growth and maintenance requires about 50% of the assimilates for the energy requirement of the plants. Biomass is formed that appears as 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)*

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. 6**).

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 12**) are starting to provide the data which will allow more realistic soil models to be developed.

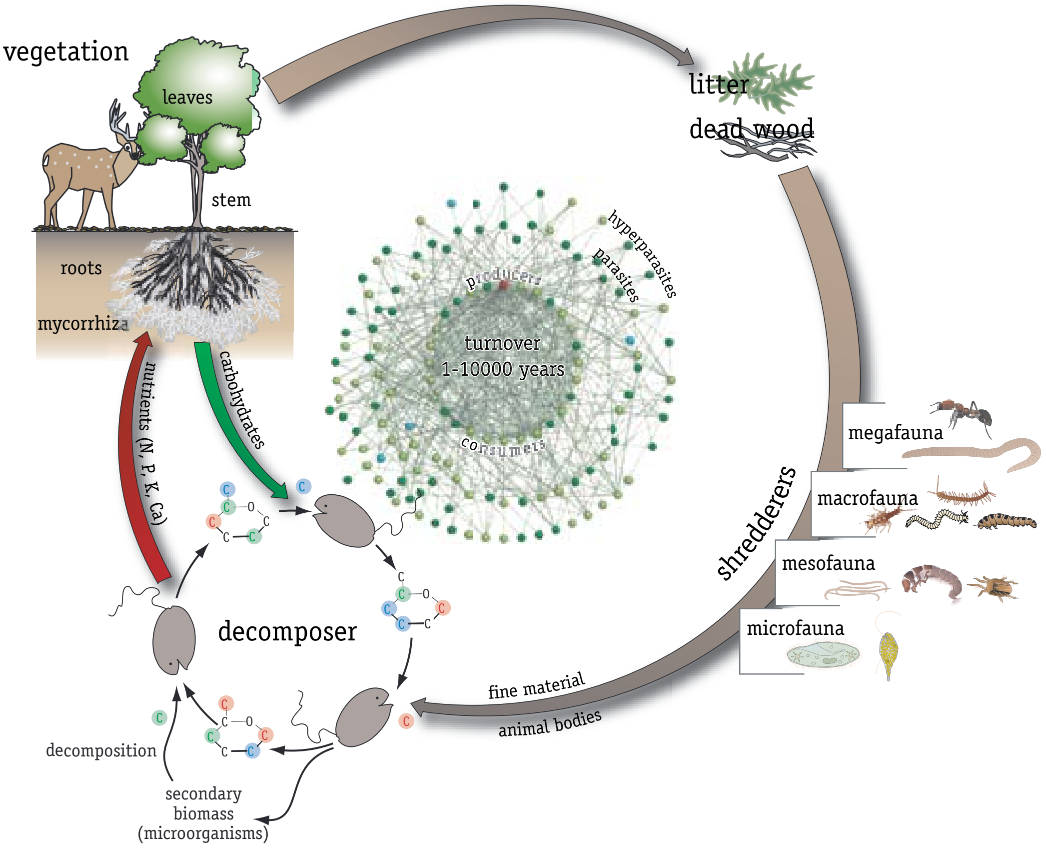


*Fig. 5: Living plants supply food to all other organisms in the ecosystem, the animals above ground and the myriad of decomposer in the soil. These organisms are all interconnected and controlled by pests and diseases. Input into the soil is via dead leaves and stems as well as via roots. The first 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)*

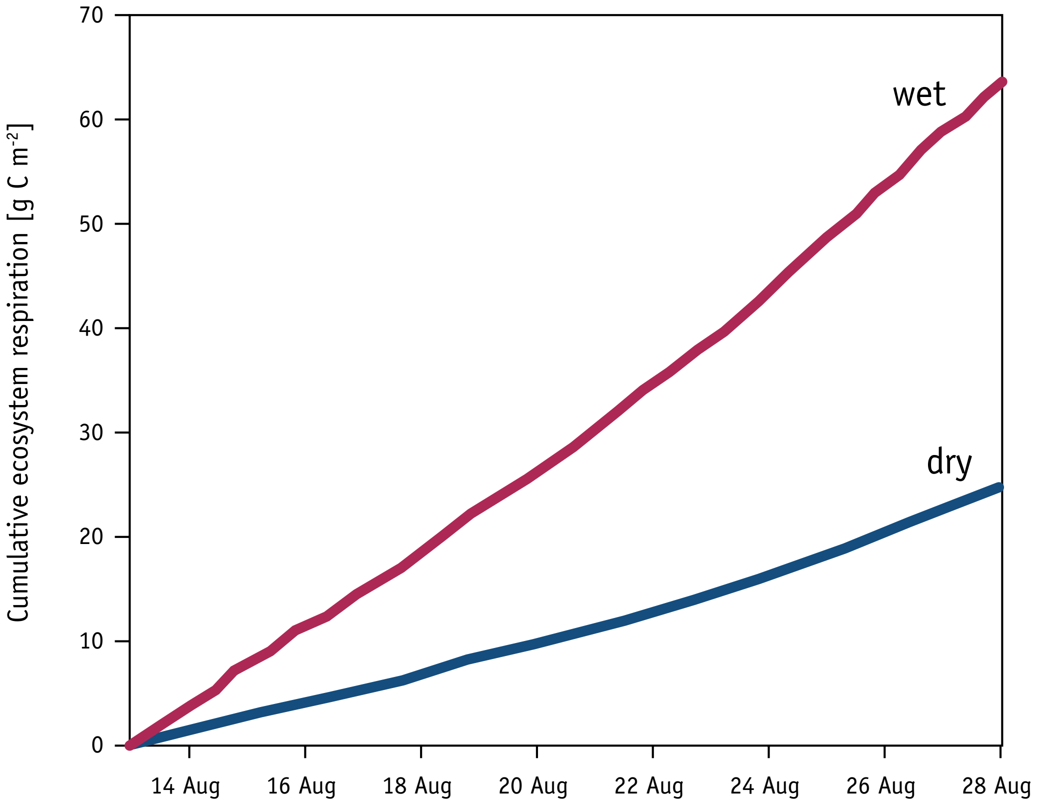


*Fig. 6: A Mediterranean scrubland ecosystem was irrigated in August, the hottest time of the year, to demonstrate the effects of soil moisture and ecosystem respiration. With irrigation, photosynthesis increased only about 10% (not shown), while respiration was reactivated immediately. The respiration rate doubled compared to the dry control. (Valentini, unpublished).*

### 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 24**). 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 13**) 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. 7**) 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. 8**). 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. 9**).

*Fig 7: 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)*

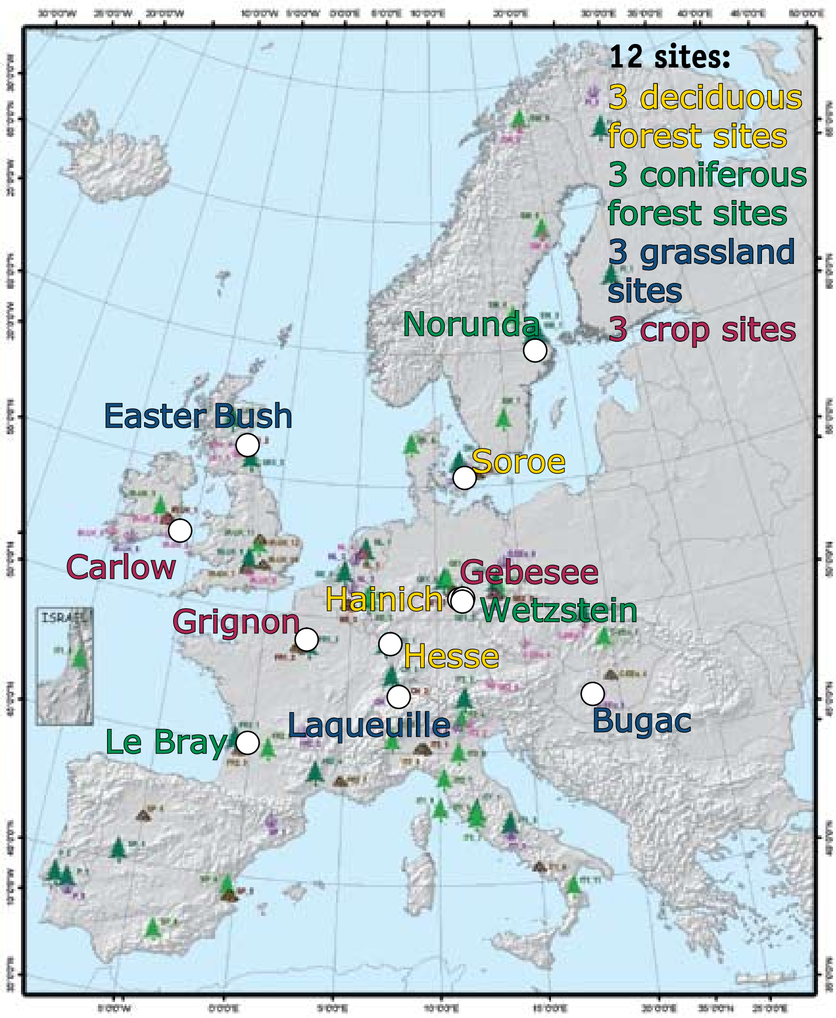


*Fig. 8: The soil sampling network across Europe. It includes intensive sites in deciduous and coniferous forests, grassland and cropland, and soil surveys of all major eddy flux stations (**see Page 24**).*

*Fig. 9: 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)*

# 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. 10a,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’.

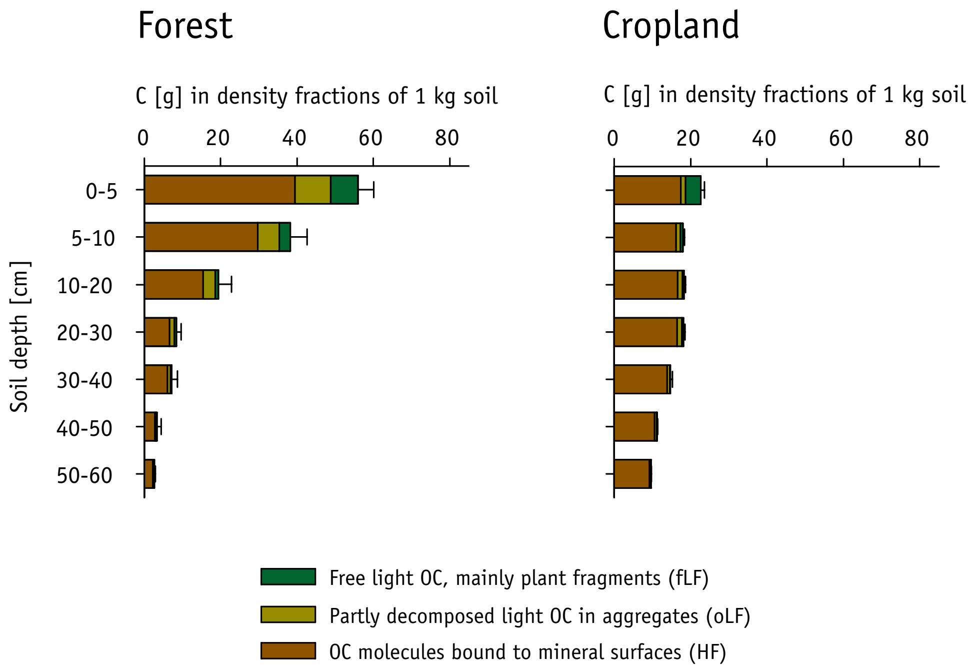


*Fig. 10a: Depth distribution of organic carbon (OC) contents of a forest and a cropland soil. Different kinds of land use result in characteristic depth profiles of soil carbon. In undisturbed forest soils, carbon contents decrease with soil depth. Ploughing leads to a homogenisation of carbon contents 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.*

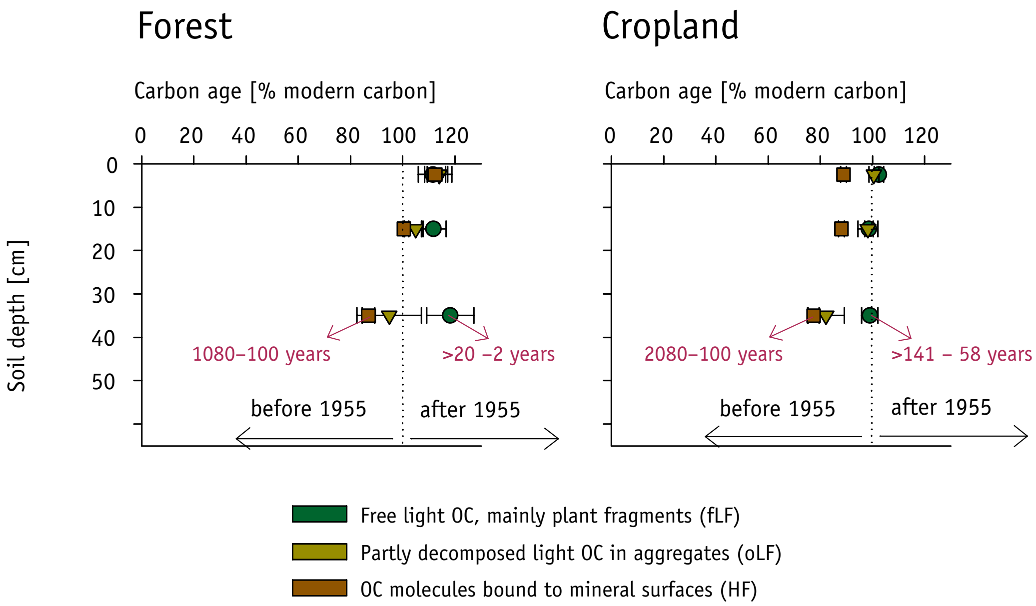


*Fig. 10b: The radioactive $^{14}C$ isotope can be used to determine the mean age of organic carbon (OC) in the fractions since the ratio between $^{12}C$ and $^{14}C$ in the atmosphere is fixed in the plants and then changes with time following the decay rate of $^{14}C$. The plant signal of wheat harvested 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?

# Forests and Farms

## 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. 11a,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 11a: The wood is harvested by heavy machinery. The harvester fells the tree and cuts it into pieces.(Photo: E.-D. Schulze)*

*Fig 11b: Forwarder carries logs out of the forest. (Photo: E.-D. Schulze)*

*Fig 11c: Logs are piled up for transport into sawmills. (Photo: E.-D. Schulze)*

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. 12**). 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. 13**).

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.

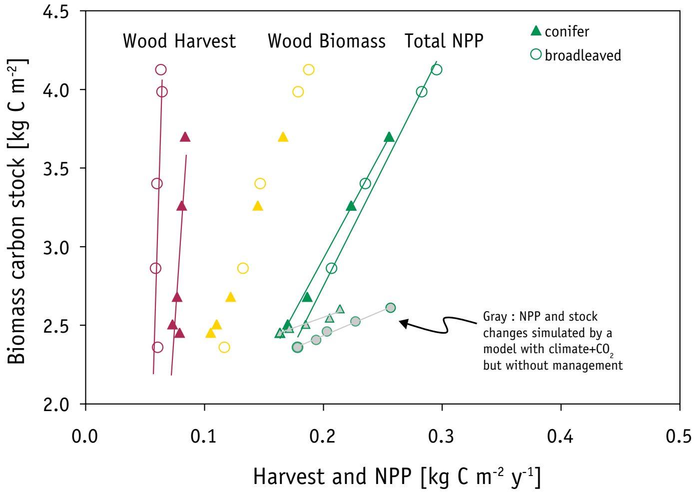


*Fig. 12: During the last 50 years, Europe has, on average, multiplied the biomass carbon stocks per hectare by 1.75 and the net primary productivity by 1.67. The forest shows that forest biomass increased with the rate of growth (total NPP). Wood harvest was only a small fraction of total NPP. Therefore 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. 13: 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)*

### 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 32**) 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 21**); 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. 14**), 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. 14: 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 24**) 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. 15a**). The yearly stem increment was even larger in Hainich than recorded by the highest yield class of yield tables (**Fig. 15b**).

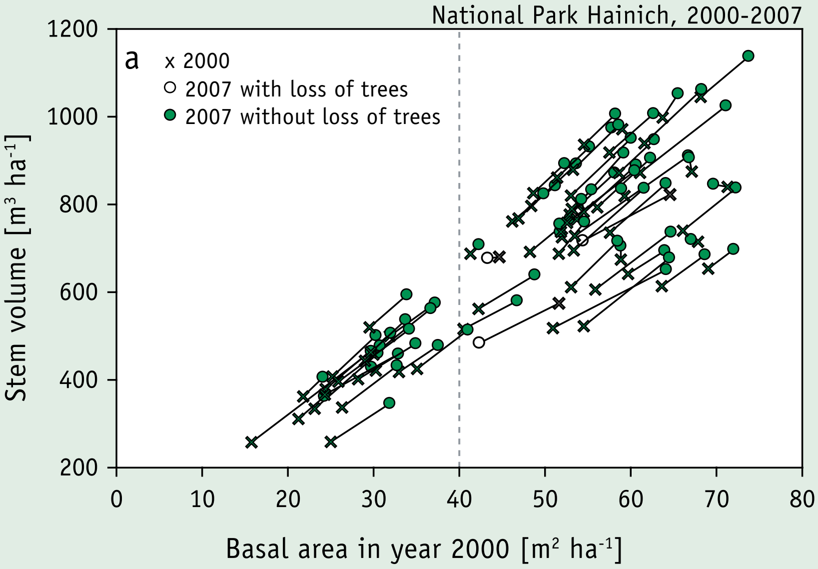


*Fig. 15a: Stem volume as related to basal area on several plots of a repeated inventory of the Hainich National Park, Germany. The inventories were made in year 2000 and 2007.*

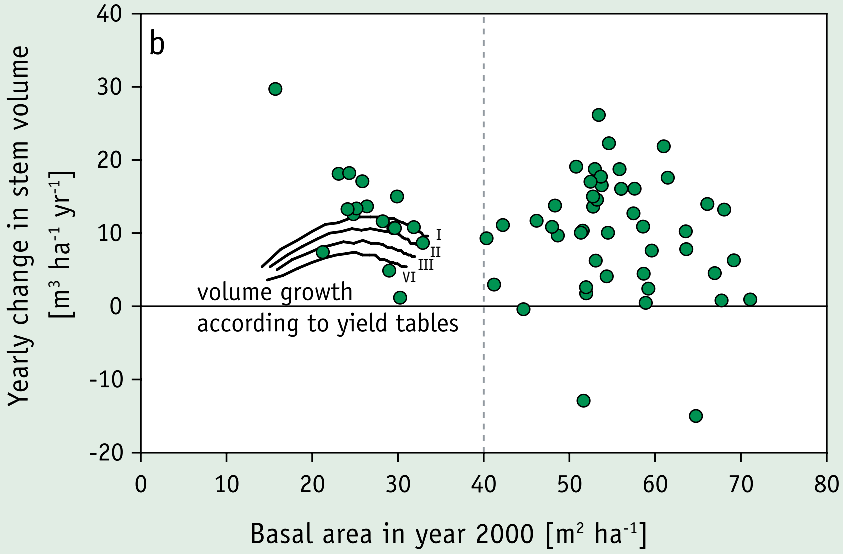


*Fig. 15b: Annual change in stem volume between the years 2000 and 2007 as related to basal area in year 2000. Negative numbers indicate the loss of a major canopy tree. The small parabolic curves show the yearly increment in stem volume of different yield classes according to yield tables. It is interesting 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)*

### 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. 16**). 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. 12**).

*Fig. 16: 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 **Fig. 17** 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 30**). 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. 18**). 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. 17: 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)*

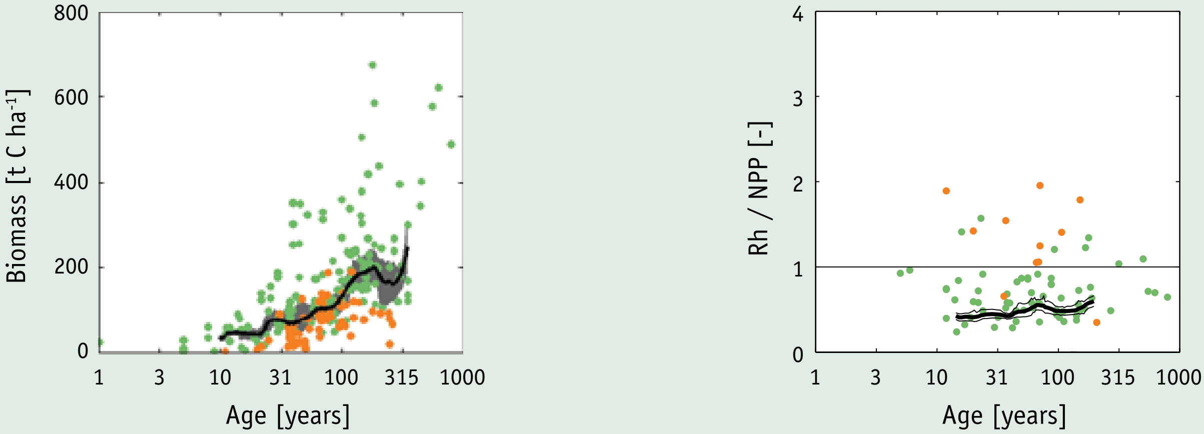


*Fig. 18: Carbon stocks in forest biomass and the observed ratio of heterotrophic respiration (Rh) and net primary productivity (NPP). The green dots show observations of temperate forests and orange dots of boreal forests. The thick black line shows the median within a moving window of 15 observations. 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)*

### 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. 19**). 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. 20**). 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. 19: Agricultural landscape near Gebesee in Thuringia, Germany (Photo: E.-D. Schulze)*

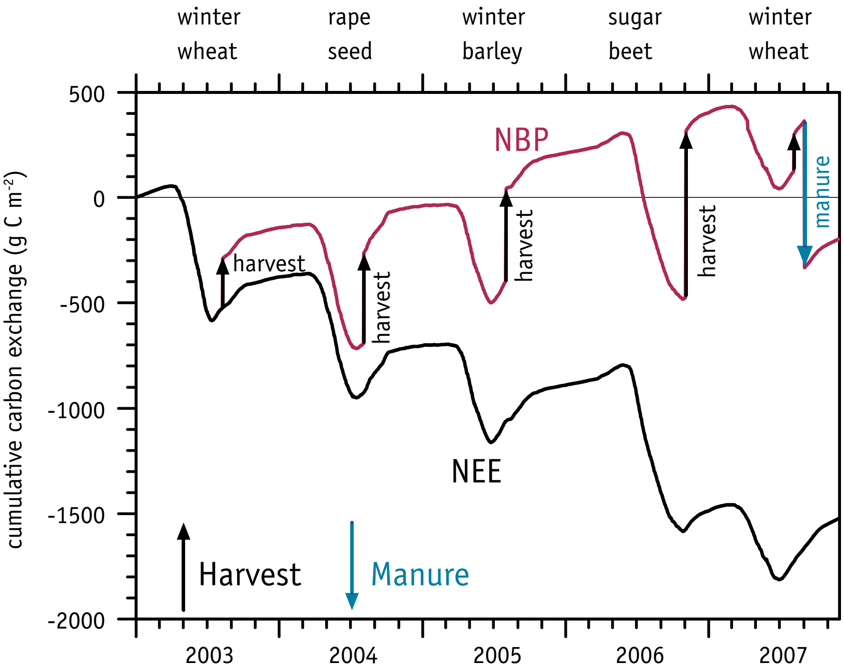


*Fig. 20: Cumulative carbon exchange by various crops, with net ecosystem exchange (NEE) integrating the carbon balance irrespective of harvest and the net biome productivity (NBP) indicating harvest losses and manure application. In early spring agricultural fields with summer crops may be sources for $CO_2$ 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)*

## 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. 21,22**). 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. 23**).

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.

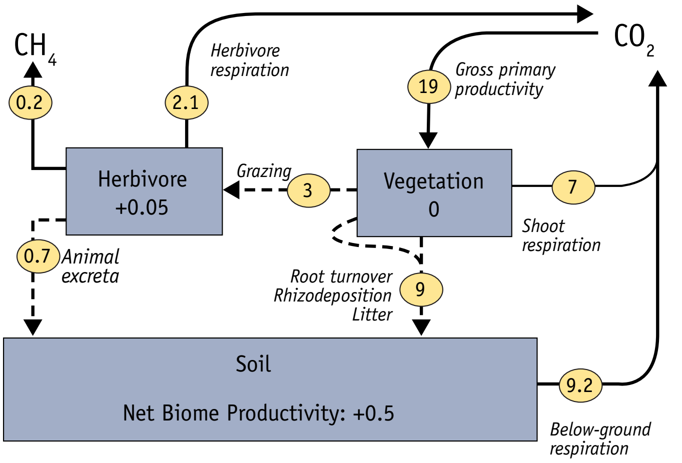


*Fig. 21: Carbon cycling in grazed grassland. The main carbon fluxes (t C $ha^{-1}$ $yr^{-1}$) are illustrated for intensive grassland grazed continuously by cattle at an annual stocking rate of 2 livestock units per hectare. (Soussana et al., 2004).*

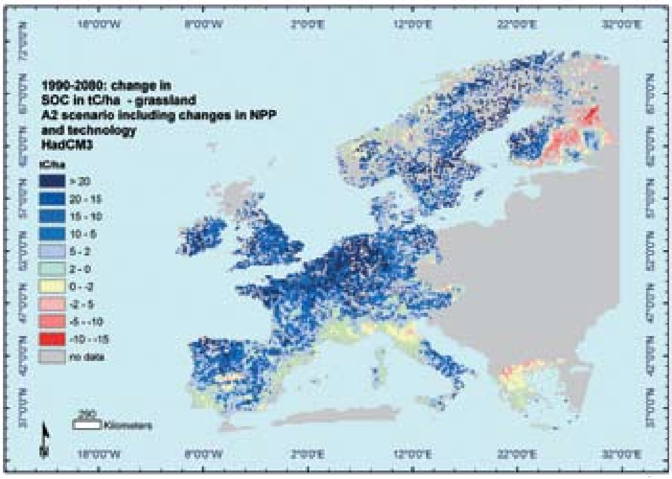


*Fig. 22: Map showing model results of difference in mean soil organic carbon (SOC) stocks in grasslands between 1990 and 2080 for a climate change scenario (A2), including changes in NPP (net primary productivity), advances in technology and regional differences in SOC stocks. (Smith et al. 2005)*

*Fig. 23: "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. 24**). 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. 25**) 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 24: 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. 26**). 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.'

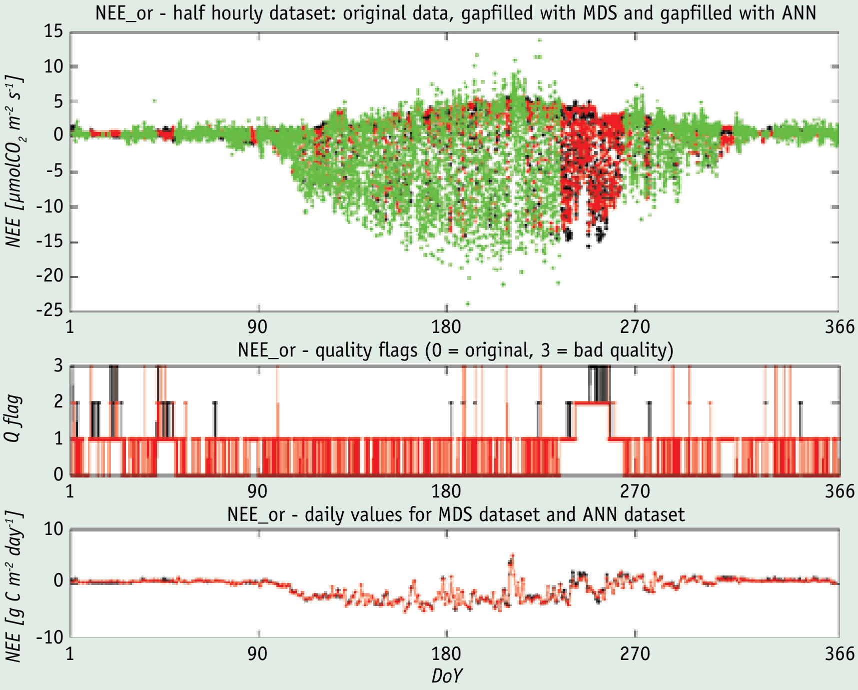


*Fig. 25: Example of eddy covariance dataset (Hyytiala forest site, Finland, 2004). Negative values indicate $CO_2$ sink, the red and black dots are two different gap-filling methods applied and their difference is an indication of the uncertainty introduced. In the central plot the quality of each half hour is indicated.*
*(D. 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 |

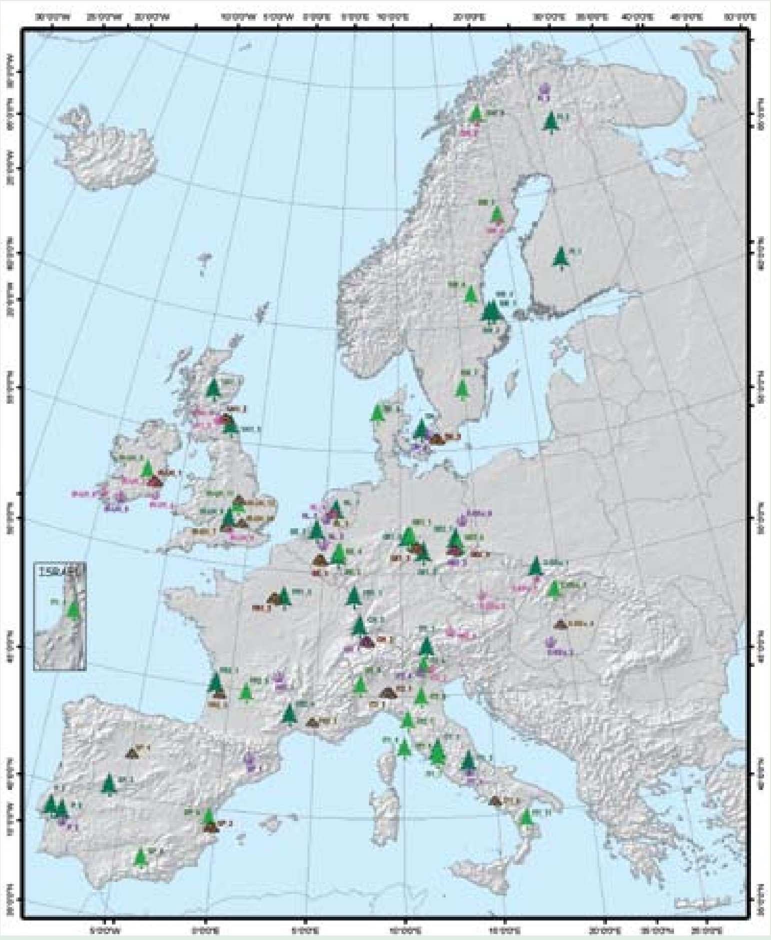


*Fig. 26: Flux network of Europe. There are 122 flux towers across Europe supporting CarboEurope-IP as main sites (50 towers) and as associated sites (72 Towers). The towers explore the net carbon fluxes of deciduous and evergreen forest, of grasslands and of croplands.*

### 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. 27**), 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. 28**) 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. 29**). 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. 27: Stubble in early September 2008, Chernozem, Thüringer Becken. (Photo: E.-D. Schulze)*

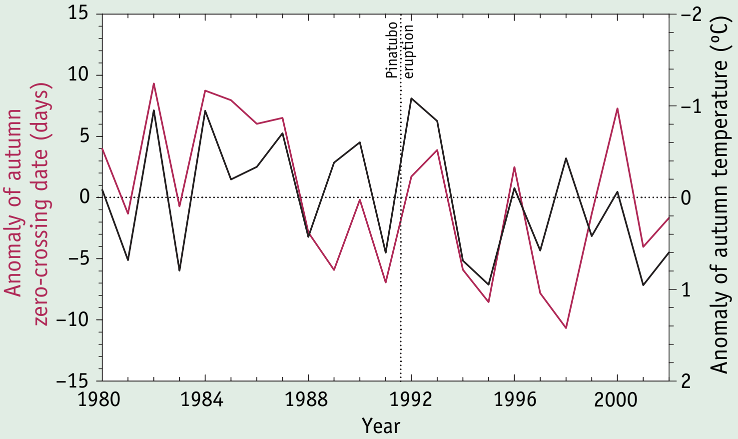


*Fig. 28: The browning of Europe is closely related to increasing temperatures in the northern hemisphere. Atmospheric $CO_2$ concentration data analysis from long-term records of the global NOAA-ERSL air-sampling network (red) is closely linked to the autumn temperature at Point Barrow, Alaska (black) - shown as differences (anomaly) from the long-term average. The station oversees the region between 51° and 90° N. (Piao et al., 2008)*

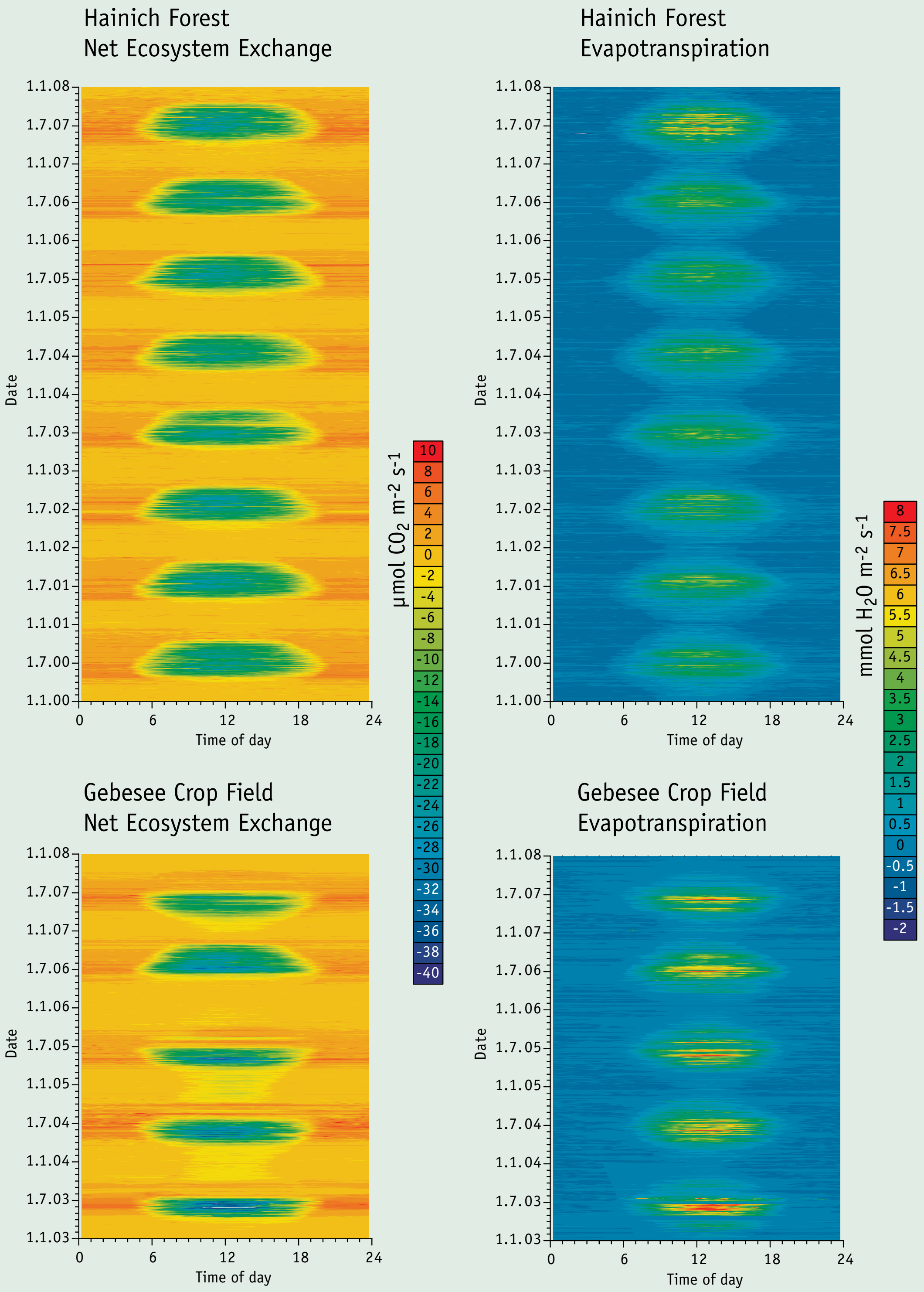


*Fig. 29: Annual and daily progress of net ecosystem $CO_2$ and $H_2O$ exchange of Hainich Forest and a cropland in Gebesee, Germany. Uptake of $CO_2$ by photosynthesis is characterised by negative numbers (yellow, green and blue colours) and $CO_2$ emissions due to respiration in winter and during night 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 ecosystems. (Kutsch, Rebmann unpublished)*

## 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 effect of 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.*

# 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?

# Peatland

## Peatlands

Natural peatlands are a typical boreal and arctic landscape (**Fig. 30**). 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. 31**). 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. 32**), 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.

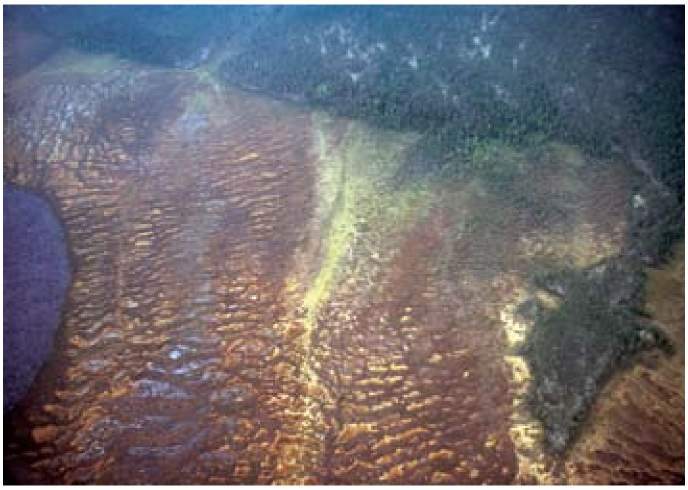


*Fig. 30: Peatland in Siberia. (Photo: E.-D. Schulze)*

*Fig. 31: The use of peat as an energy source: The drying of peat-bricks for burning, Ireland. (Photo: A. Börner)*

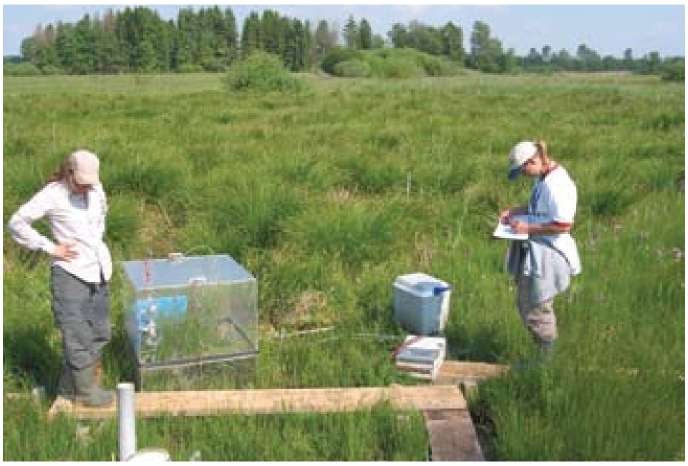


*Fig. 32: Measurements of net ecosystem exchange (NEE) by transparent chambers in a restored fen peatland in South Germany. The campaigns comprise frequent repeated measurements over a day, giving the response of NEE to changing light and temperature. (Photo: A. Freibauer)*

# Peatland

## European peatlands

CarboEurope-IP scientists are using “eddy covariance” to measure $CO_2$ and $CH_4$ (**see Page 24**) 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. 33a,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.

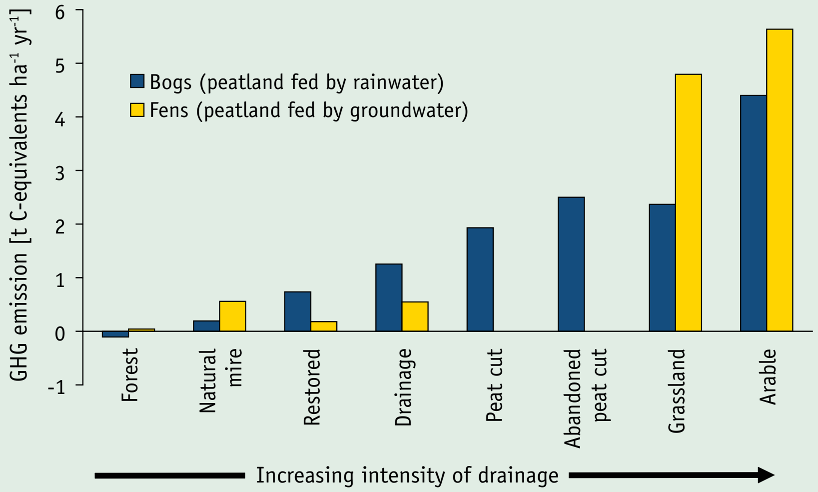


*Fig. 33a: European average greenhouse gas emissions from peatlands under different land use. Emissions are given in C-equivalents, calculated as the sum of $CO_2$, $CH_4$ and $N_2O$ according to their respective global warming potentials (GWP100): 1 kg $CH_4$ = 21 kg $CO_2$, 1 kg $N_2O$ = 310 kg $CO_2$. Emissions increase with the intensity of drainage and land use. The columns show various types of management on peatlands. (Byrne et al., 2004)*

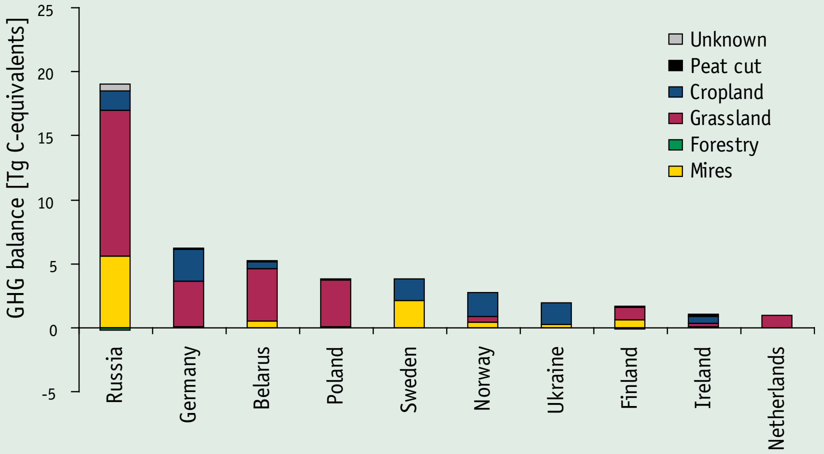


*Fig. 33b: Conservative estimate for the peatlands greenhouse gas budget of the top ten peat countries by area in Europe. The columns show various types of management on peatlands. (Drösler et al., 2008)*

**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?

## 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.

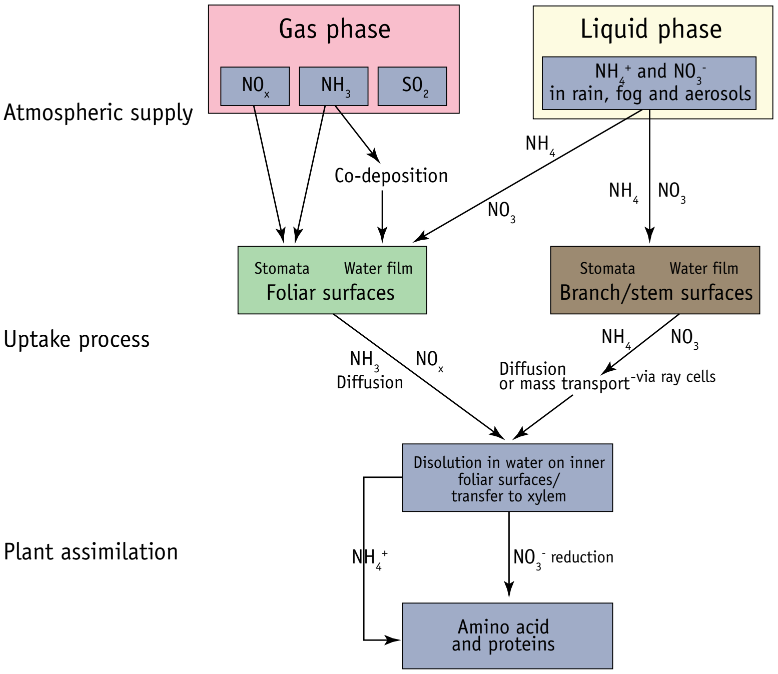


*Fig. 34: Major pathways for the uptake of gaseous and liquid nitrogenous compounds into the canopy from the atmosphere. (Harrison et al., 2000)*

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. 34**). 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.

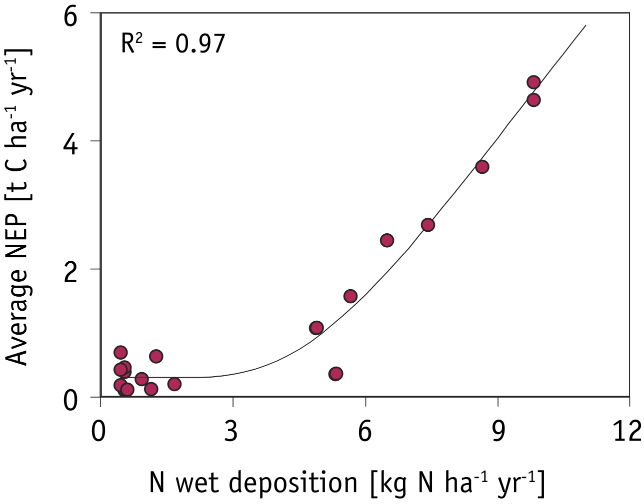


*Fig. 35: Environmental control of the average carbon exchange of forest ecosystems over an entire rotation period. Average NEP is strongly related to nitrogen deposition. (Magnani et al., 2007)*

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 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. 35**). 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 above-ground 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.

## 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. 36**). 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.

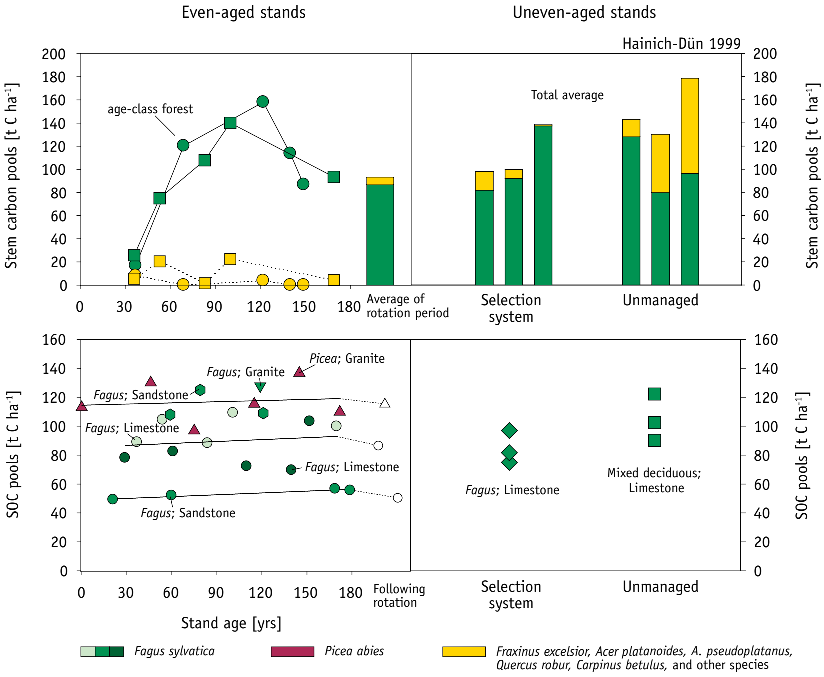


*Fig. 36: Carbon pools in stem biomass of mixed beech forests on limestone (above) and in the mineral soil (SOC: soil organic carbon) of mixed/pure beech and spruce forests on different bedrock (below) as a function of stand age and silvicultural system. Dotted lines at the end of the SOC-age-sequences 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 sequestered 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 conditions?

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

# Extreme Events

## 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. 37**).

$CO_2$ 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. 38**).

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.

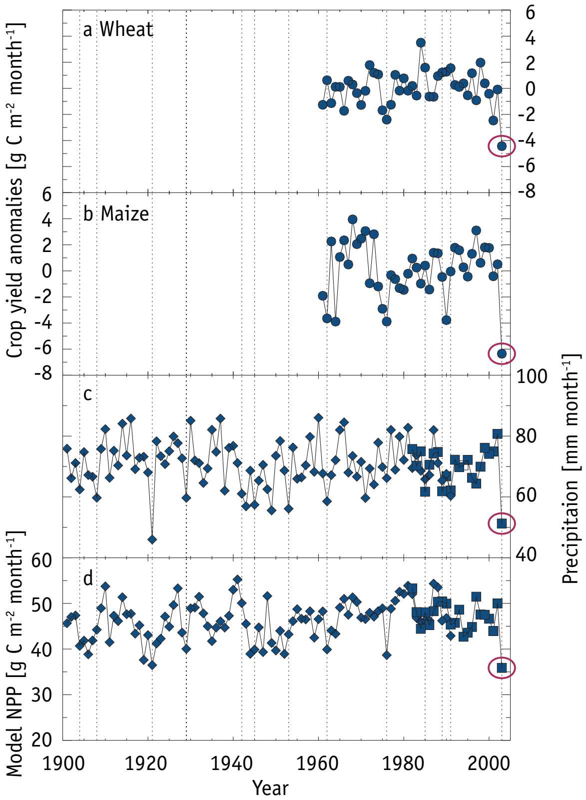


*Fig. 37: Observed crop yield and modelled crop net primary production (NPP) changes in response to climate variability over France and Italy during the past 100 years. a) Winter wheat yields. The trace shows area-weighted national yield records after a linear trend has been removed from the data to 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. 38: Desiccated trees with brown leaves in Southern France in the summer (not autumn) of 2003. (Photo: P. Ciais)*

### 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 ecosystems, or replacing one type with another. Often when wild-fire destroys a forest (**Fig. 39**) it is replaced by a different type of forest or by bush-type savannah. Increases of insect outbreaks (**Fig. 40**), as triggered by increasing temperature and drought, may be just as effective in destroying the forest as fire, and the increasing frequency of extremes of wind have devastated European forests through windthrows (**Fig. 41**). During 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 following 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 dying 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; insufficient 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 sources, 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. 39: Forest fire. This fire occurred in Siberia, where fire is a natural re-occurring event. However, recent investigations show, that more than 90% of forest in the boreal region are caused by humans and not by flashes. (Photo: E.-D. Schulze)*

*Fig. 40: Insect damage at the National Park Bayerischer Wald, Germany. All trees up to the horizon are dead. (Photo: T. Stephan)*

# Extreme Events

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. 41**) carbon was mainly lost from the upper organic layers (**Fig. 42**). 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. 41: 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)*

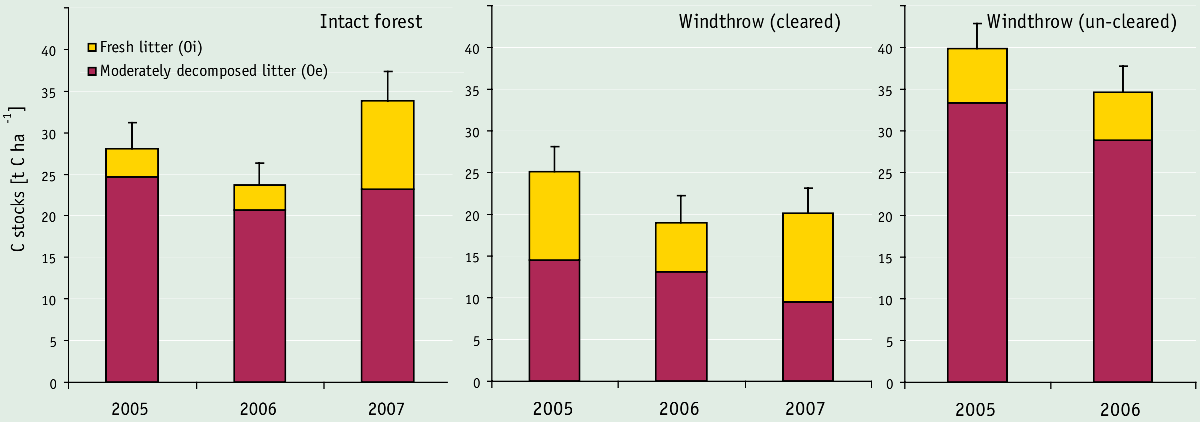


*Fig. 42: Soil carbon was lost from the organic layers (Oi and Oe) at the cleared windthrow site and at the un-cleared windthrow left for natural succession. (Don et al., unpublished)*

**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?

# Modeling the Continental Scale European Ecosystem Carbon Balance

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, weather 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. 26**).

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, **Fig. 43a** 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 continent 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. 43b**. 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. 43c**, which can be directly compared to the decadal average summer fluxmap shown in **Fig. 43a**. 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.

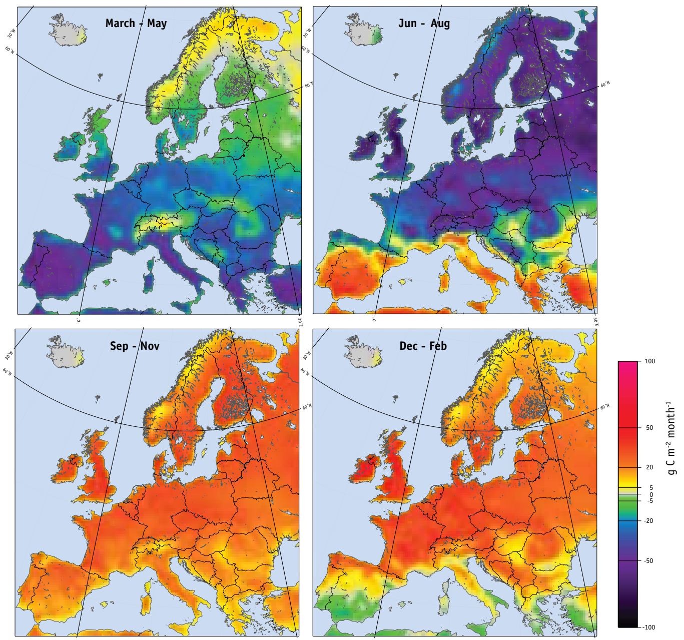


*Fig. 43a: Seasonal cycle of carbon uptake and release by European ecosystems as computed by the CarboEurope-IP biogeochemical models (multimodel average). Each panel shows the three-month seasonally averaged net flux between the atmosphere and the ecosystems. Negative values (green and blue colours} indicate uptake, positive values (yellow and red colours) a release of* $CO_2$*. (Data: Vetter et al., 2008; Figure: M. Heimann)*

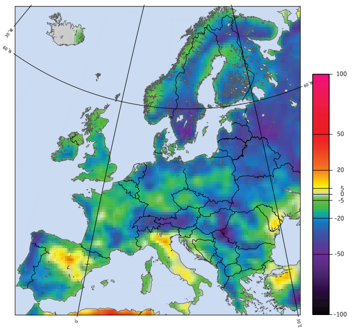


*Fig. 43b: Decadal average (1996-2005) carbon uptake by European ecosystems calculated by the CarboEurope-IP biogeochemical models (multimodel average). Negative values (green and blue colours} indicate uptake, positive values (yellow and red colours) a release of* $CO_2$*. This map can directly be compared with the mean summer carbon flux field depicted in Figure 29a (Jun-Aug panel). (Data: Vetter et al., 2008; Figure: M. Heimann)*

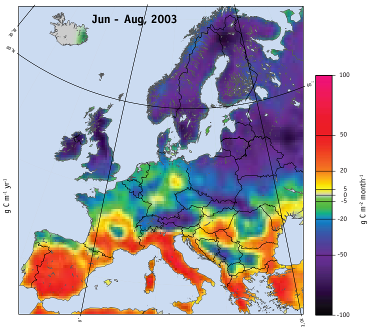


*Fig. 43c: Carbon flux in the summer (June-August) of 2003 during the large drought and heat wave in Europe as simulated by the CarboEurope-IP biogeochemical models (multimodel average). This map can directly be compared with the mean summer carbon flux field depicted in Figure 29a (Jun-Aug panel). (Data: Vetter et al., 2008; Figure: M. Heimann)*

# The CarboEurope Regional Experiment

## 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 24**) 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 43**), 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 46**).

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. 44**). 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 coordinated 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.'

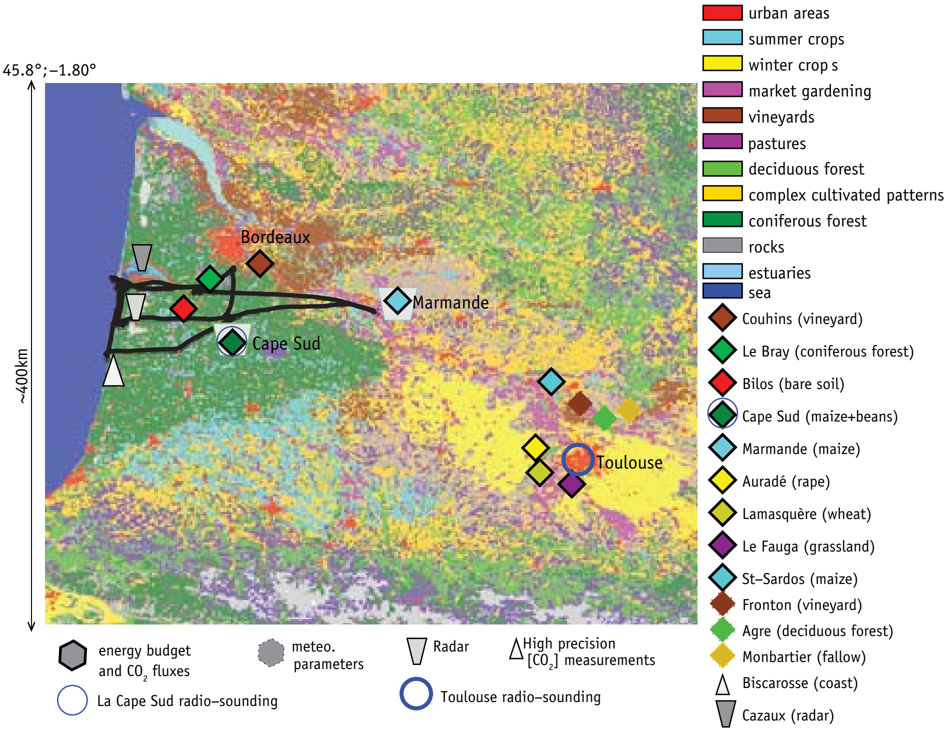


*Fig. 44: Les Landes Regional Experiment in the south-west region of France: land cover map at 250-m resolution showing the different location of summer and winter agricultural crops. Also shown are the locations of the ground-based observation sites of surface fluxes and flight paths of the aircraft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

# 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. 45**). 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.

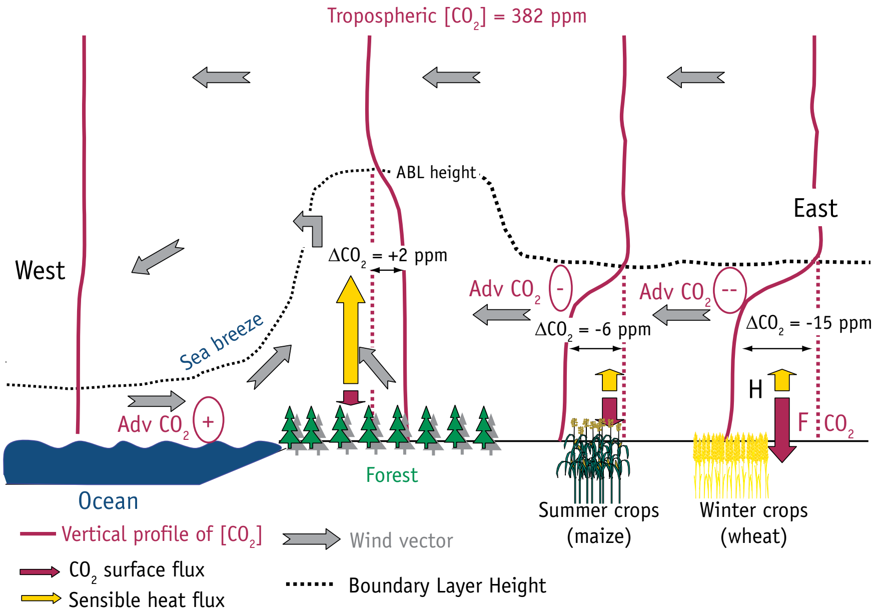


*Fig. 45: Schematic description of the main physical processes along a vertical west-east cross section on 27 May around 14:00 Universal Time (UTC): the higher Atmospheric Boundary Layer (ABL) above the pine forest is due to a greater sensible heat flux. The $CO_2$ concentration slightly increases in 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. 46**). 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. 46: 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. 47**).

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.

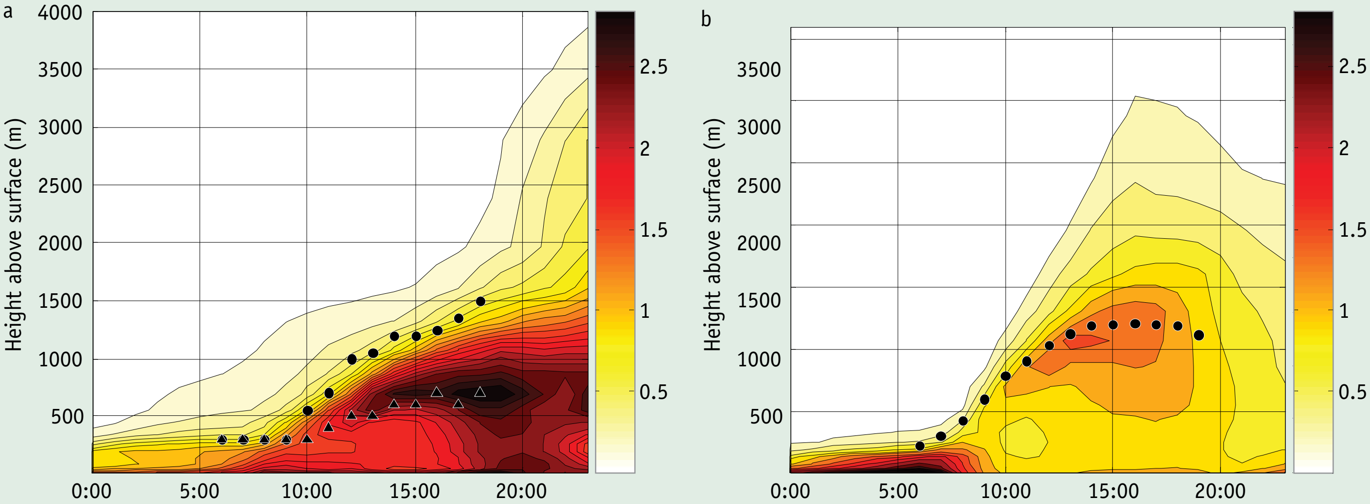


*Fig. 47: Variations of the representation errors in ppm on 27 May 2005 (a) and 6 June 2005 (b) with time and altitude. The representation errors are averaged over the area north of 44.16oN. The circles in a. indicate the height of the boundary layer in the convergence zone and the triangles the main 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)*

# 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. 45**). 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 40**), 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 42**), 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. 48**) are currently being refined to extrapolate and test the improvement of regional carbon and water models on the inclusion of fluorescence

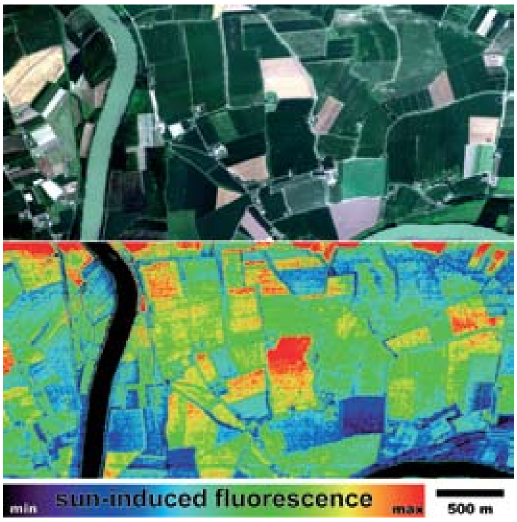


*Fig. 48: Map of sun-induced fluorescence showing the photosynthetic efficiency of different fields at an agricultural area by Marmande (Southern France). Fluorescence is currently tested to quantify gross primary production (Source: Forschungszentrum Jülich, ICG-3 and Humboldt-Universität zu Berlin, 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?

# $CO_2$ Concentration and Fluxes

## 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. 49**). Many of these measurements are made on tall towers (**Fig. 50,51**): 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 43**) can then be used to deduce the most likely field of surface fluxes to have produced this pattern.

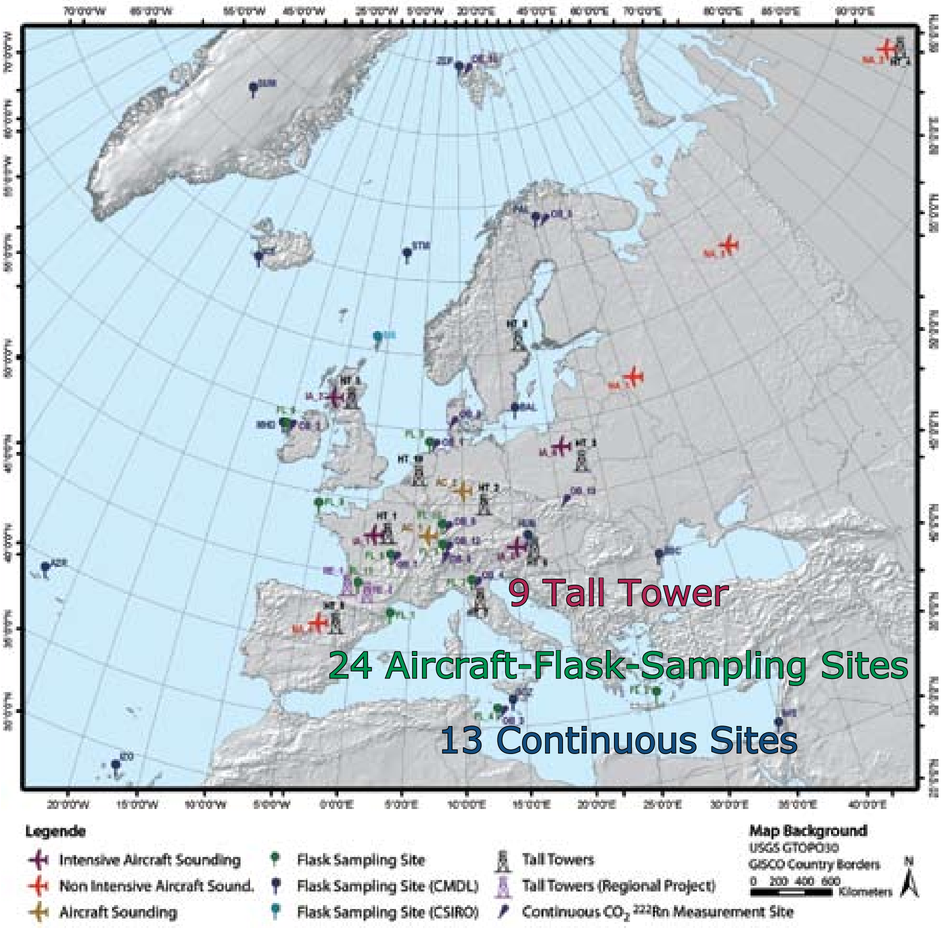


*Fig. 49: Atmospheric measurement sites in CarboEurope-IP.*

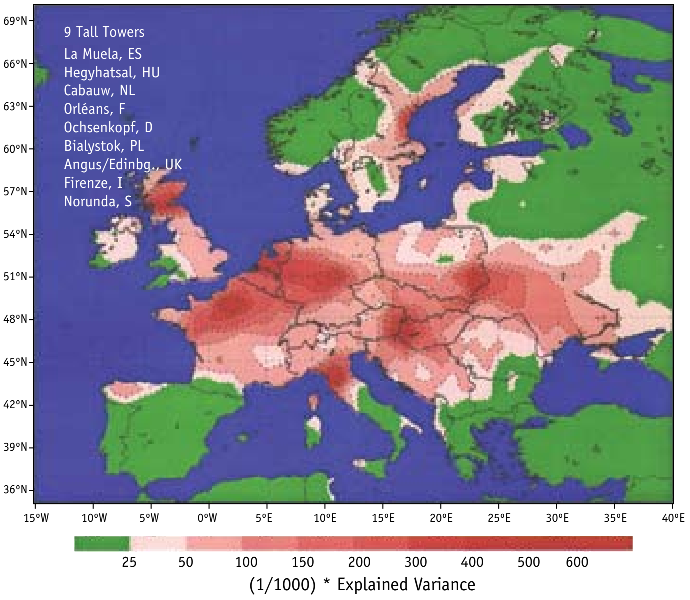


*Fig. 50: Footprint of the 9 European Tall Towers.*

*Fig. 51: 300m Tall Tower near Bialystok in Eastern Poland, equipped with instruments for continuous measurements of $CO_2$, $CH_4$, CO, $N_2O$, $SF_6$ and $O_2/N_2$ ratio from five heights. (Photo: M. Heimann)*

# $CO_2$ 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. 52**). 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 34**) 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 45**).

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.

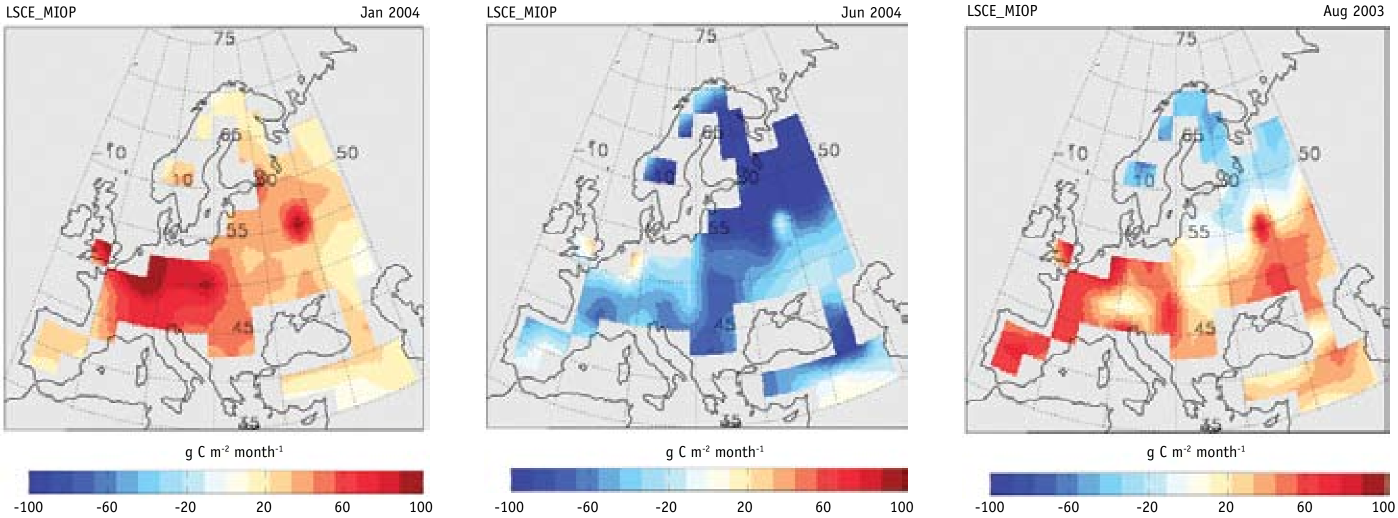


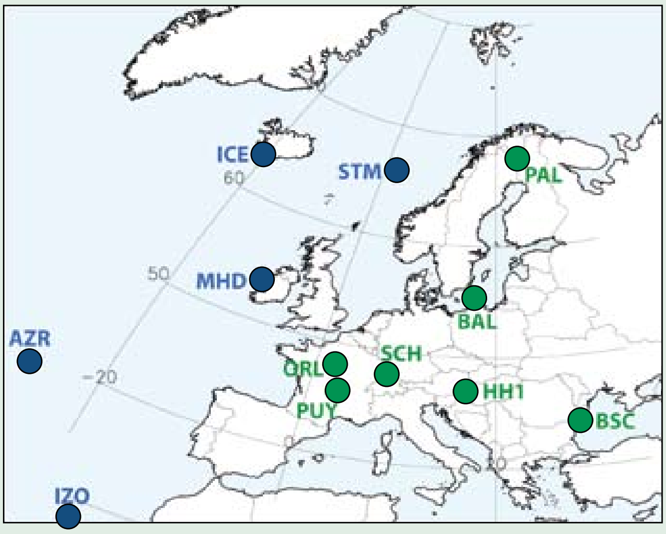
*Fig. 52: Maps of Europe showing modelled sources and sinks of $CO_2$ as on http://inversions.lsce.ipsl.fr/index.php.*
*(1) The net carbon flux for the months of January and June 2004. Negative fluxes (blue) indicate up-take of carbon by the surface; positive fluxes (red) indicate emission of carbon. The fluxes are estimated using the inverse modelling method. In January carbon emission dominates; in June the continent is taking in carbon as plants photosynthesise.*

*(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.*
*(http://inversions.lsce.ipsl.fr/index.php)*

### 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. 53,54**). 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. 55**). 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.

*Fig. 53: Remote atmospheric station at Mace Head, Ireland. (Photo: M. Ramonet)*



OCEANIC
AZR - Azores
IZO - Izana, Teneriffe
ICE - Iceland
MHD - Mace Head (Ireland)
STM - Ocean Station M (Norway)

CONTINENTAL
BAL - Baltic Sea (Poland)
BSC - Black Sea Constanta (Rumania)
HH1 - Hegyhatsal (Hungary)
ORL - Orleans (France)
PAL - Pallas (France)
PUY - Puy de Dome (France)
SCH - Schauinsland (Germany)

*Fig. 54: Location of key flask monitoring stations*

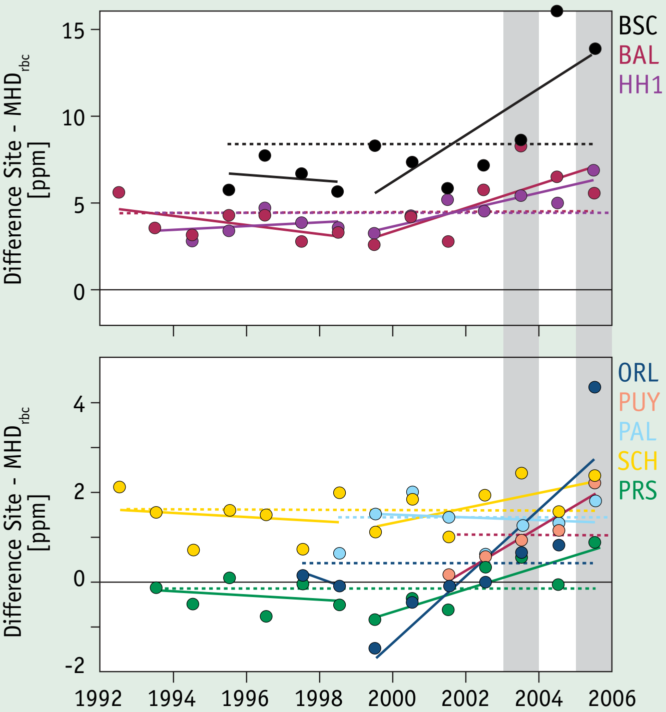


*Fig. 55: CO$_2$ concentration difference between Mace Head and various continental stations. (Ramonet, unpublished)*

## 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 ($CO_2$, $CH_4$, $N_2O$ 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. 56**). 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.

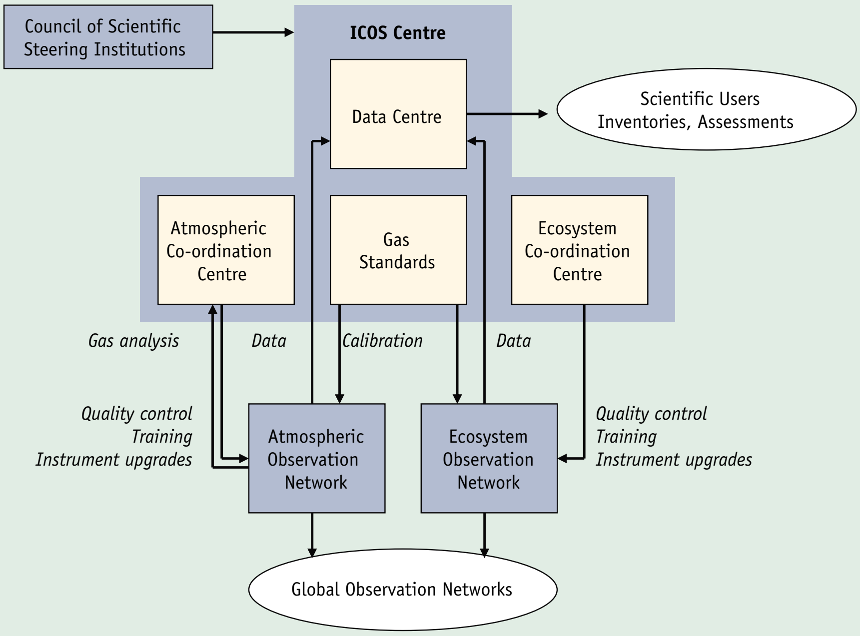


*Fig. 56: Organization of the ICOS infrastructure, a project originating from CarboEurope-IP research.*

**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?

## 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. 57,58,59**), 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. 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.

### 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 $^{14}C$.

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. 60**).

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

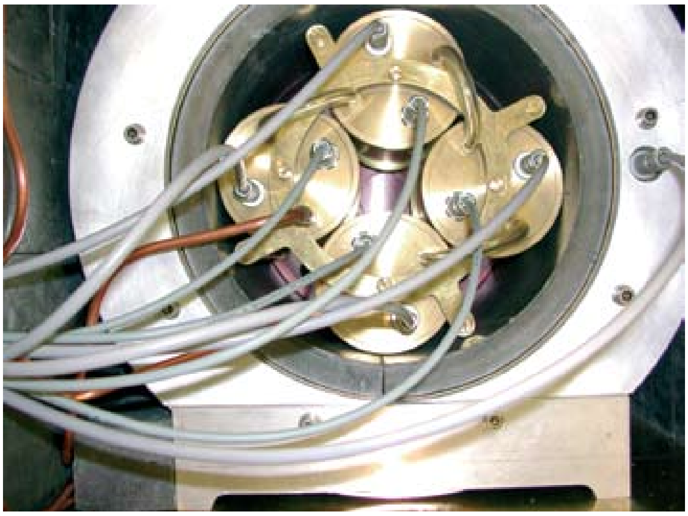


*Figure 58: $^{14}CO_2$ counting system of the Heidelberg Radiocarbon Laboratory. (Photo: B. Kromer)*

# Fossil Fuel Emissions

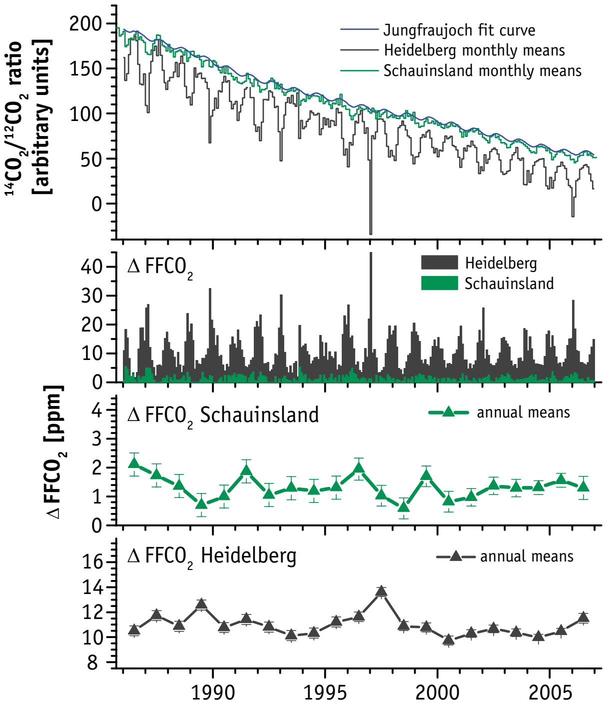


*Fig. 59: Monthly mean $^{14}CO_2/^{12}CO_2$ ratio measurements in Heidelberg and at Schauinsland station in comparison to the continental reference level over Europe as derived from observations at Jungfraujoch (upper panel). Fossil fuel $CO_2$ component at Schauinsland and Heidelberg as calculated 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)*

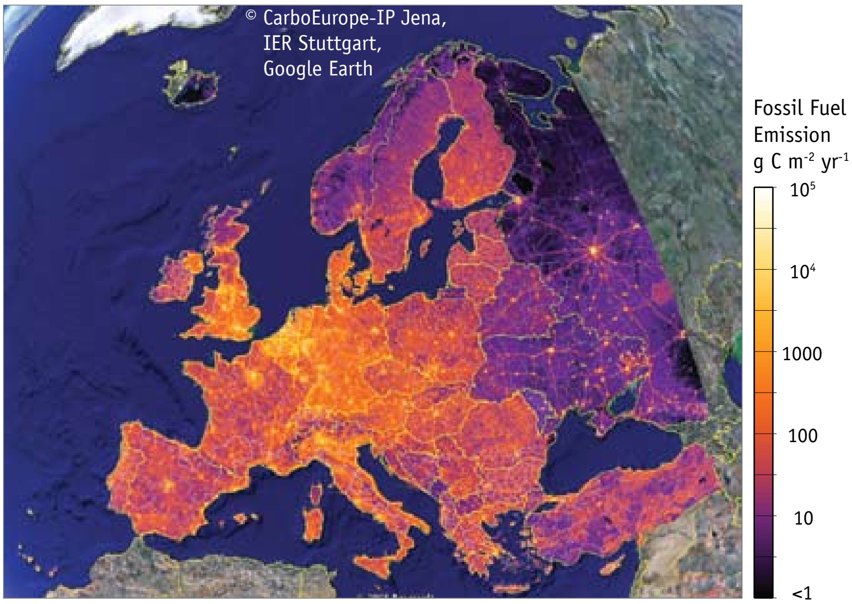


*Fig. 60: European distribution of the annual fossil fuel $CO_2$ emissions compiled on spatial grid with 5′ latitude by 5′ longitude resolution. Logarithmic colorscale with brighter colors indicating higher emission rates. The total emissions over geographical Europe (including Turkey) are 1.6 Pg C/a (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 46**) 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'.

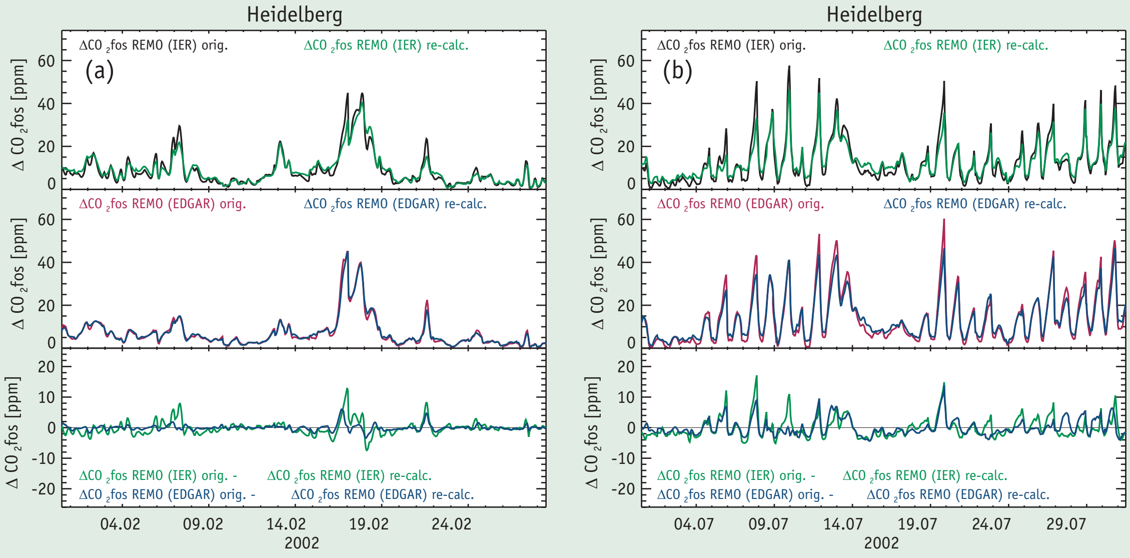


*Fig. 61: Sensitivity tests with REgional Model (REMO) of the uncertainty of CO-based fossil fuel-$CO_2$ estimates: Upper two panels: $\Delta CO_2$(foss) estimated from "atmospheric" $\Delta CO$ records and weekly mean $\Delta CO/\Delta CO_2$(foss) ratios calculated from original "atmospheric" results 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)*

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-$CO_2$eq $yr^{-1}$ and the bottom-up balance to 44 Tg C-$CO_2$eq $yr^{-1}$ (100yr horizon) averaging 92 Tg C-$CO_2$eq $yr^{-1}$. 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. 62**). 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. 62a**), grasslands (**Fig. 62b**) and croplands (**Fig. 62c**), it emerges that as a European average, the carbon input (GPP) is about 20% higher in grasslands than 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.

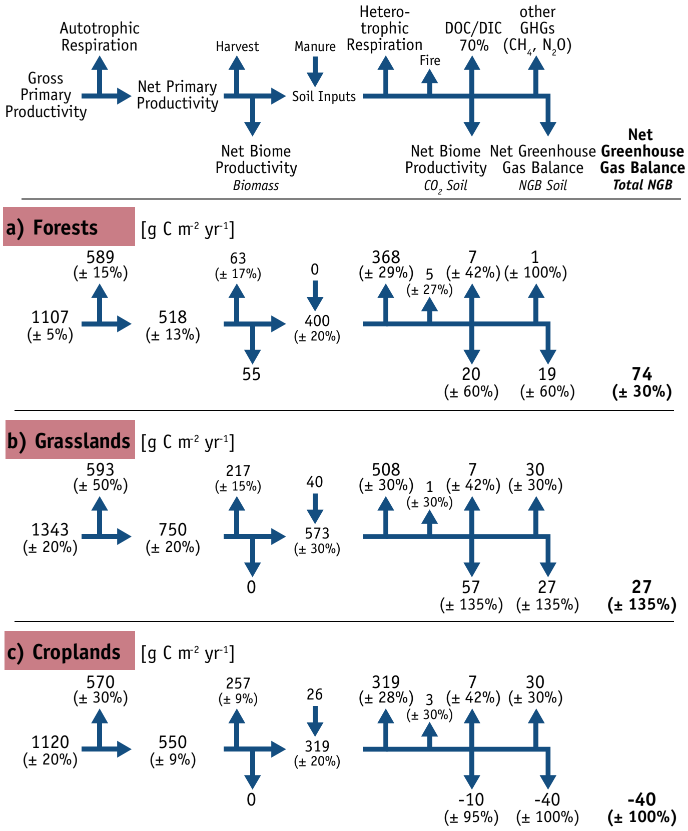


*Fig. 62: Carbon flow through major land-use types from $CO_2$ fixation (Gross Primary Productivity) to long-term sequestered carbon (Net Biome Productivity). The data show European averages ± variation coefficient. Results of the Jena annual meeting.*
*(Janssens, Ciais, Luyssaert and Schulze, unpublished)*

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$_2$O 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. 62** 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. **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 km$^2$) | NBP (Tg C yr$^{-1}$) | Relative uncertainty | NBP (Tg C yr$^{-1}$) | Relative uncertainty | Area (Million km$^2$) | 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$_2$eq + other C gases (1, 2) | | | | -76 | ** | | -32 | ** |
| Top-down N$_2$O flux (1, 2) | | | | -113 | ** | | -90 | ** |
| **Top-down ecosystem GHG sink (CO$_2$+CH$_4$+N$_2$O)** | | | | **133** | * | | **5** | * |

| | | Continental Europe | Continental Europe<br>Old estimate by Janssens et al. 2003 | | Continental Europe<br>New estimate by CarboEurope-IP | | EU-25 | EU-25<br>New estimate by CarboEurope-IP | |
|---|---|---|---|---|---|---|---|---|---|
| | | Area (Million km$^2$) | NBP (Tg C yr$^{-1}$) | Relative uncertainty | NBP (Tg C yr$^{-1}$) | Relative uncertainty | Area (Million km$^2$) | 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** | * | **279** | ** | **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.*

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-$CO_2$eq $yr^{-1}$,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 45**).

**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 279 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-$CO_2$eq $yr^{-1}$, 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-$CO_2$eq $yr^{-1}$ 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.

# 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.'

## 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.'

## 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.'

## 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.'

# 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. 63**)

wald und klima ·net

*Fig. 63: 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. 64**). 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.

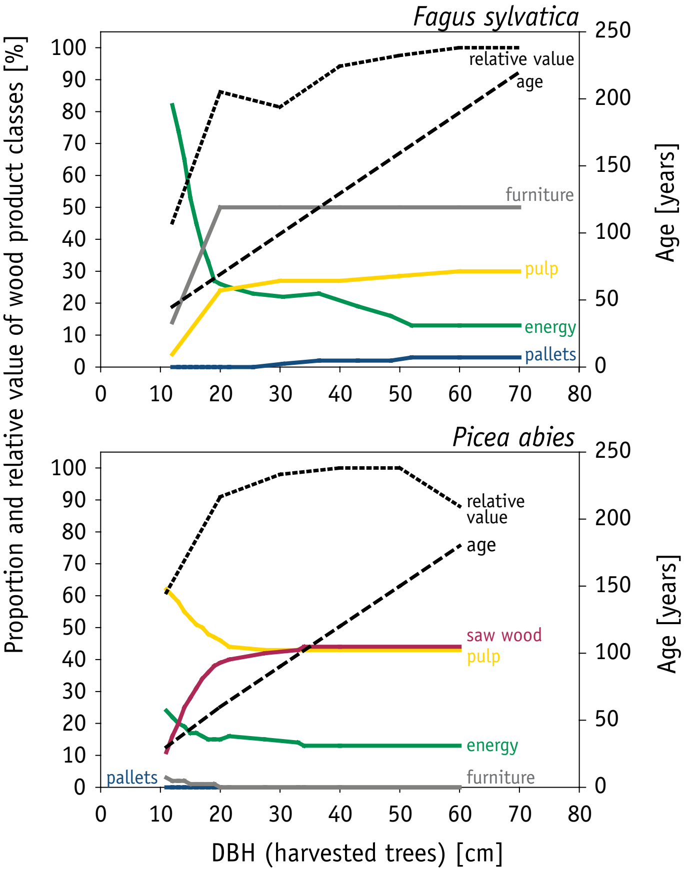
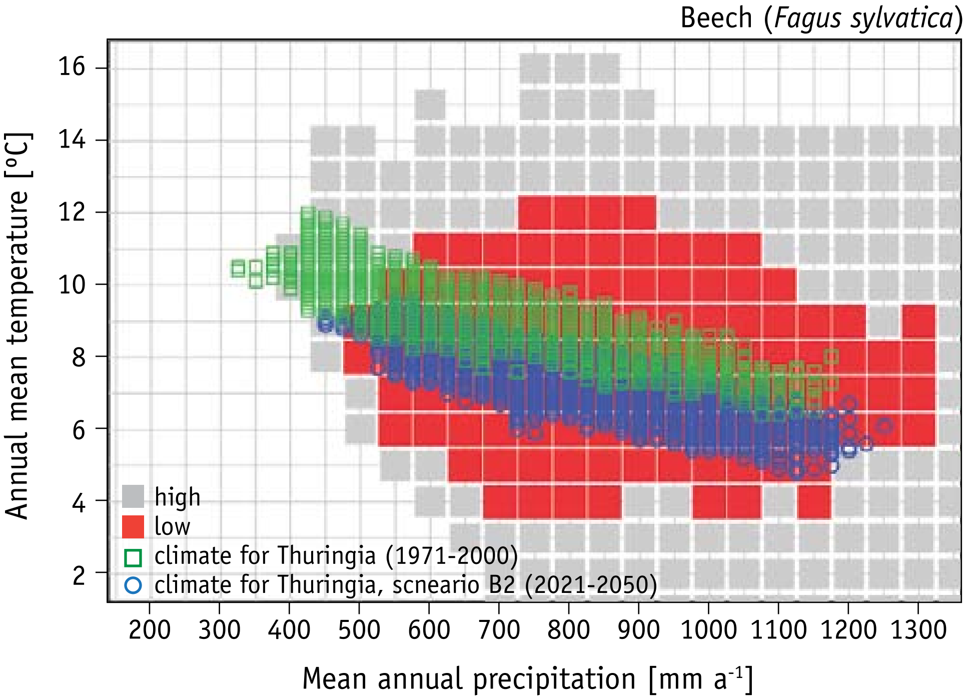


*Fig 64: Assignment of wood product classes to the diameter at breast height (DBH) of harvested timber. For spruce timber with a DBH below 25 cm the standard tables for wood products of Schoepfer and Stoehr (1991) were used, for all other cases the tables of Schoepfer and Dauber (1985). Parquet wood 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)*



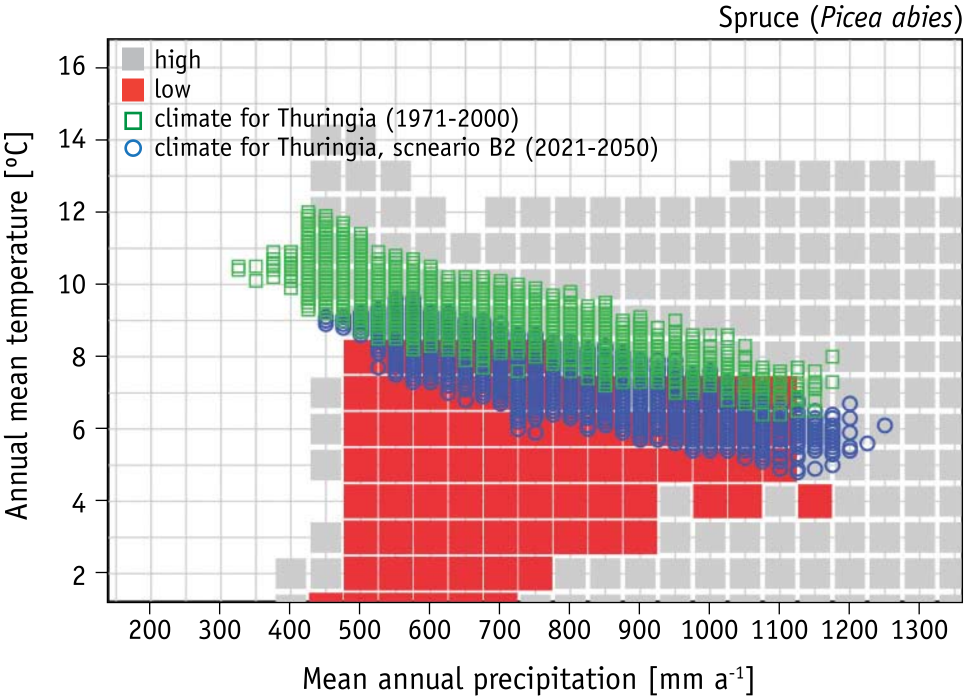


*Fig. 65: Climate envelope for beech and spruce nach Kölling (2007) modified for present climate conditions (1971-2000, blue) and future conditions according to the IPCC scenario B2 (2021-2050, green) for Thuringia. Red areas indicate temperature-percipitation-combination with high presence according 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. 65**), which might further disappear from lower elevations and suffer serious problems in the East of Thuringia (**Fig. 66**). 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. 65**). 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.

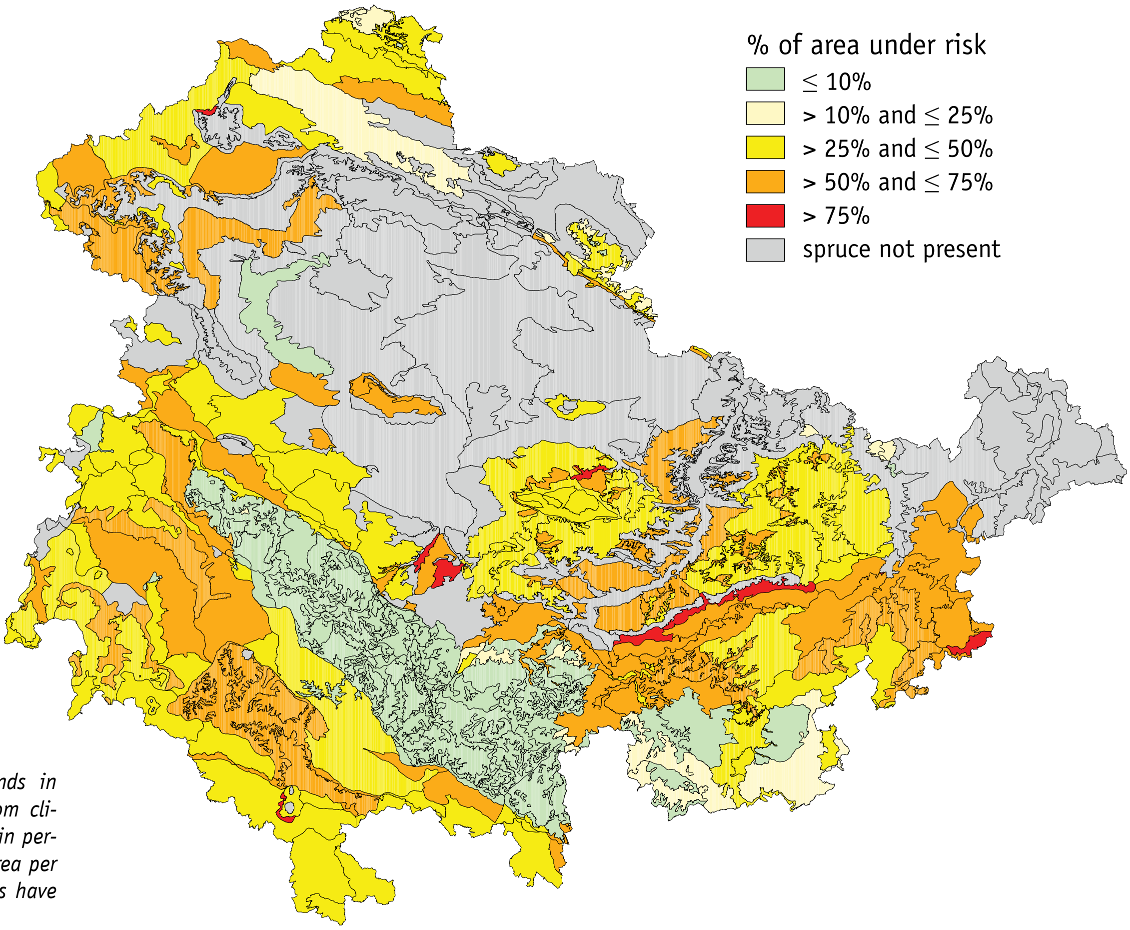


*Fig. 66: Present spruce stands in Thuringia at potential risk rom climate change. Data are given in percentage of the total spruce area per macroclimatic unit. Grey areas have nearly no spruce stands.*

**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 uneven-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?

# Training and Outreach

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. 67a-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 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.

*Fig 67a: Pupils from Lycée Max Linder (Libourne, France) discover CarboEurope-IP research with INRA scientists in the Cestas forest, near Bordeaux. (Photo: S. Hayes)*

*Fig 67b: Students at Benevento's agricultural secondary school IPSAA "Vetrone" experiment sod-seeding techniques without tillage with CNR-IBIMET researchers. (Photo: D. Marandola)*

*Fig 67c: Students test soil samples for calcium content during the Girls' Day 2008 at Max-Planck-Institute for Biogeochemistry, Jena. (Photo: B. Michel)*

*Fig 67d: With an endoscope students and staff from Max-Planck-Institute for Biogeochemistry, Jena explore soil life in earthworm tunnels. (Photo: B. Michel)*

*Fig 67e: 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.

# 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.

Successful 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

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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

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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

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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

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# 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 45**). 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).

## 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.

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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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# CarboEurope-IP History

Carbon Cycle research emerged from research into acid rain. In the 1980ies forest decline was a major concern across Europe. A large, coordinated research effort identified acid deposition and SO2 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 Bruenning, 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.

# List of terms

**Carbon stocks**

Carbon stocks describe the total amount of carbon per unit ground area.

**Continental Europe**

refers to the geographic region of Europe from the Atlantic coast to the Ural

**Eddy covariance**

A method to measure the amount of carbon dioxide, water vapour or heat moving into or out of a sample plot of vegetation.

**Flux**

The rate of import or export of a substance per unit time and unit ground area.

**Flux tower**

A mast which extends above a sample plot of vegetation, used to hold the instrumentation to measure fluxes into and out of the surface.

**GPP**

Gross primary productivity is the rate of photosynthesis per unit ground area by a sample plot of vegetation.

**Land use**

refers to the present use of land (e.g. forest, grassland, cropland)

**Land-use change**

refers to a change of present land use into another type of land use (e.g. grassland into forest, also known as afforestation)

**NEP**

Net ecosystem productivity describes the net balance of carbon assimilation by photosynthesis and carbon losses by respiration

**NPP**

Net primary productivity describes the growth rate of a sample plot of vegetation per unit ground area.

**NBP**

Net biome productivity describes the net increment of carbon in a sample plot of vegetation taking into account losses by harvest, grazing and fire.

**Photosynthesis**

The process by which plants use sunlight to build up sugars from water and carbon dioxide

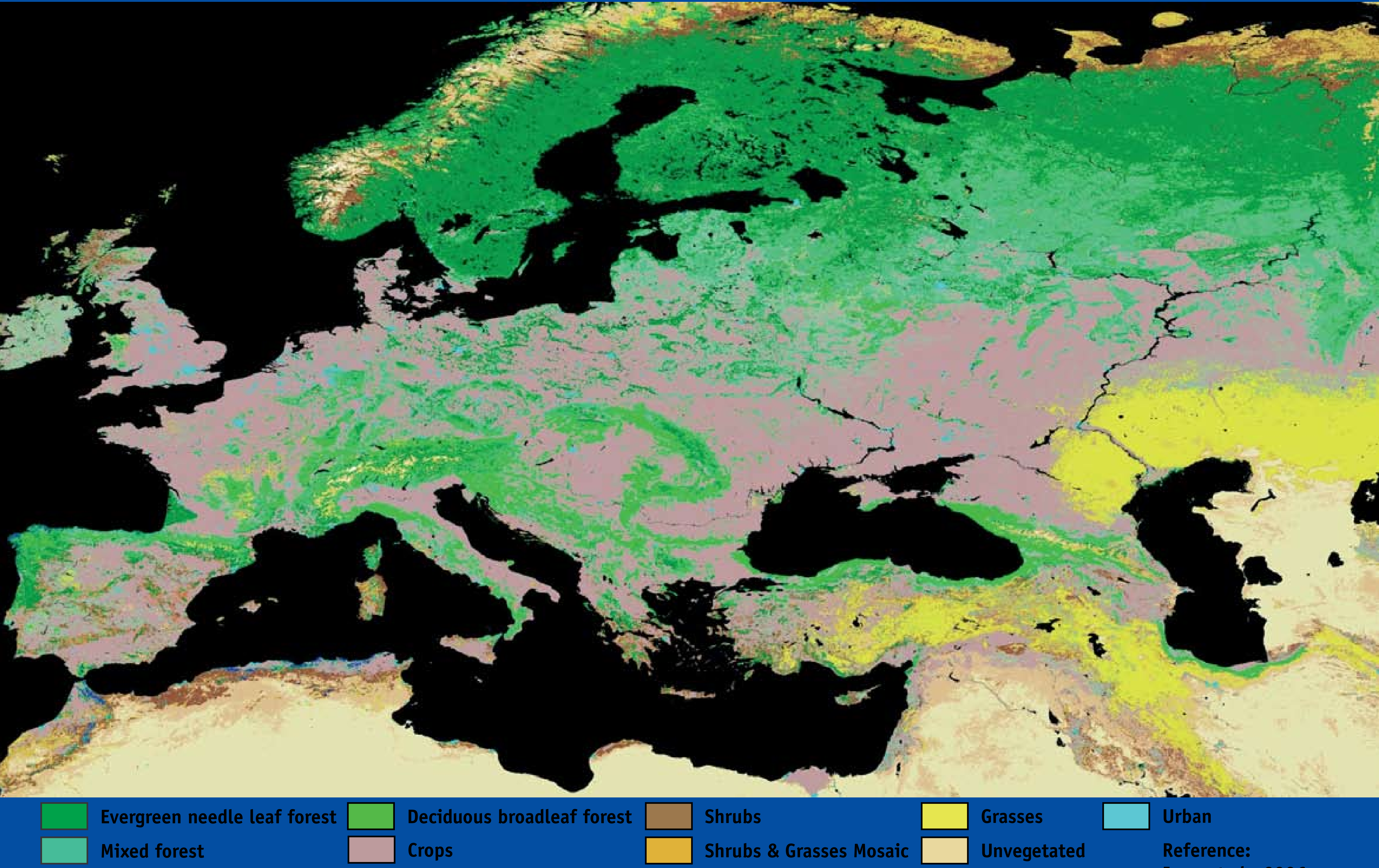
**Respiration**

**heterotrophic respiration**

The process by which soil microbes break down plant material creating carbon dioxide.

**autotrophic respiration**

The process by which plants create carbon dioxide by burning sugars; it provides the energy plants need to stay alive



Reference:
Jung et al., 2006