



What we have learned

Achievements, surprises & worries from global carbon research

Key research questions about the global carbon cycle

Greenhouse gas emissions (mostly CO₂ from fossil fuel burning and tropical deforestation) have been increasing exponentially since the industrial revolution and today constitute the widest perturbation to the Earth ever caused by human beings. Fortunately, the natural carbon cycle is currently 'soaking up' a little more than half of our CO₂ emissions by absorbing them in the vegetation (30%) and the ocean (25%). Thanks to that, there is much less CO₂ in the atmosphere than there would otherwise be and hence the onset of a severe warming (caused by this greenhouse gas) and its dangerous effects is being delayed. The CO₂ fraction that remains in the atmosphere (45%), however, is already disturbing the climate and in return is affecting the capacity of the land and the ocean to continue absorbing our emissions. If the current trends continue, the future proportion of our emissions staying in the atmosphere will increase more and more.

What is happening to the carbon absorbed in the vegetation and ocean 'sponges' or 'sinks' as we rather call them? What is determining the efficiency of these sinks and will they eventually become ineffective at some stage? What will happen as the natural carbon cycle is more and more disturbed by our ever-growing emissions? What will be the consequences on the Earth system? We critically need to be able to answer these questions much better if we want not only to set targets to stabilise our climate but to actually be able to reach these targets.

The capacity of vegetation to take-up carbon is affected by climate change. The oceans seem to absorb less and less carbon. The accumulation of CO₂ in the air is growing exponentially, although the natural carbon sinks still absorb more than half of our current emissions. In two words: no surprise - as we continue to emit more and more CO₂, planet Earth is more and more perturbed!



Measuring tree growth with automated dendrometers (Alterra)



An overview of CarboEurope results

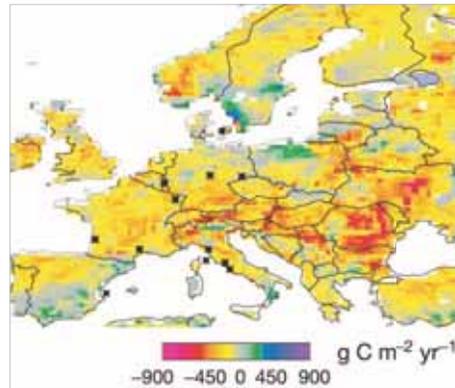
The aim of CarboEurope¹ is to investigate the carbon cycle on the European continent:

- we want to learn more about **how carbon is exchanged** between the atmosphere and terrestrial ecosystems (vegetation and soils) at all latitudes and in all vegetation types and how this interacts with other key biogeochemical cycles (nitrogen, water, nutrients...)
- we want to better understand **why carbon is exchanged this way** and which processes govern the cycle and its variability
- ultimately, we want to be more able to predict **how the carbon cycle will evolve in the longer term** under the stress of human perturbation as fossil fuel emissions continue to rise.

So... what did we find?

Surprise: the European terrestrial sink can become a source

The excitement of science reaches its peak when unexpected observations show us something that models or theory were not predicting, suddenly revealing a gap in our understanding and opening up a new path for discovery. Sometimes we prepare large and complex experiments hoping for data to confirm our theories, but



European-wide anomaly of Net Primary Production (i.e. photosynthesis) during 2003 (Ciais et al., 2005). Black dots indicate measurement sites.

nature simply instead offers us a huge anomaly. This is what happened in 2003 with the heat wave over Europe. This extreme event allowed us to detect something that had never been previously studied during the 20th and the first years of the 21st centuries: an overall reduction of 30% in photosynthesis during the summer due to a rainfall deficit (in Eastern Europe) and extreme summer heat (in Western Europe). As a consequence, **the European continent, which normally absorbs carbon**



during the vegetation growth season, became a source of CO₂ to the atmosphere in July and August 2003, counterbalancing the equivalent of five years of natural CO₂ sequestration by the European biosphere. This teaches us that the land carbon sink is vulnerable and reacts strongly to climate extremes. In a climate change scenario where more frequent extreme droughts may occur, such as the one in 2003, the European terrestrial ecosystems may reverse from net carbon sinks to sources, and in turn, further accelerate the accumulation of CO₂ in the atmosphere. The rise in atmospheric CO₂ would then no longer only result from rising human emissions but also from the biosphere, normally a sink however disturbed to such an extent that it becomes a source.

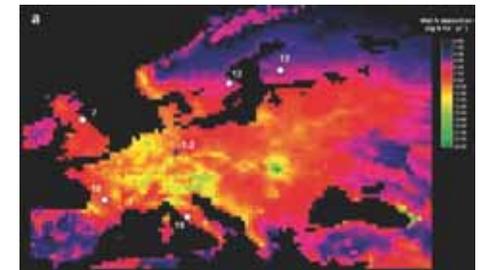
Key results

- **We have discovered that nitrogen pollution fertilizes European forests.** Our measurements of carbon fluxes over numerous forests showed important differences in the amount of CO₂ taken up by the trees. However, the typical explanations for these variations, like the age of stand, local soil or weather conditions, could not explain their amplitude. After years of patient tracking, we found the culprit; nitrogen deposited on forests by polluted air! This nitrogen pollution, mostly from the spreading of fertilizer on agricultural land and from the combustion of fuel in cities, is returned to the earth by wet deposition, that is, in rain drops and actually fertilizes the forests. We still don't accurately know the magnitude of this phenomenon but our first studies suggest that

each additional gram of nitrogen facilitates the forests to absorb between 40 and 200 grams of additional carbon. Happy times - when nitrogen pollution stimulates forests to clean our CO₂ pollution! In contrast, in the 1980's, acid rain, mainly consisting of nitric and sulfuric acid, caused a decline in forest growth, whereas now, the fertilizing effect of nitrogen obviously overrides the toxic effect of acidity.

- We have found out that **peatlands converted into agricultural fields (by drainage) emit large amounts of CO₂** due to peat decomposition. Although they only account for 3% of the land surface in the temperate western European region, **drained peatlands emit 25% of the total atmospheric CO₂ absorbed by the European forests.** It is, therefore, crucial to retain the remaining peatlands and to find out under which conditions drained peatlands can be restored (by flooding) to stop their CO₂ emissions without releasing too much methane in return, which would partly reduce the positive balance in terms of the greenhouse effect.

Wet Nitrogen deposition in Europe. Magnani, pers. comm.



¹ A more detailed presentation of the aims & methods of CarboEurope is given pp. 26-30 of the 1st CarboSchools booklet.

To learn more, you can find in www.carboschools.org:

- The first CarboSchools booklet: "What we know, what we don't know and how we try to better understand global change" – introduction to research questions, challenges and methods for CarboSchools projects (in English, French, Dutch, German & Norwegian)
- A page: "Results from CarboEurope and CarboOcean: from scientists to policy-makers and citizens" where you can download the full report *Integrated assessment of the European and North Atlantic carbon balance* & CarboEurope policy highlights for 2006, 2007 & 2008.

Sources policy: with the exception of figures, we have decided not to include any references to the scientific publications behind the results presented in this booklet. The reason is that many of the results mentioned here are sourced from several different publications, therefore, it would be cumbersome to mention them all and to mention only a few would not be representative of the diversity of sources used. You can find all the sources referenced in the EU assessment report.



- Moreover, we have found evidence that **the way we manage forests & agricultural fields has a big influence on their capacity to emit or absorb CO₂**, and we have learned a lot about **how land can be managed in order to take up CO₂ more effectively**. We established that forests are still absorbing CO₂ even when they are unmanaged. We found that European grasslands generally act as a carbon sink and that croplands, contrary to previous assumptions, are either neutral or even a small sink. We are also learning more about the factors that control whether the CO₂ fixed through photosynthesis migrates towards long-term storage in the soil, or rather, if it is quickly released back into the atmosphere. We are now preparing **recommendations for good practices in land-use (agriculture & forestry) for efficient carbon management & the protection of carbon sinks**.
- We have learned more about **how warmer autumns and springs (due to global warming) are affecting the capacity of vegetation to absorb CO₂**. Since rising temperatures in spring lead to increased carbon absorption at the start of the growing season, we were wondering if the same would be true in autumn. We have discovered that photosynthesis (taking up carbon) is also increasing during warmer autumns but that respiration (releasing carbon) is increasing even more. This is because photosynthesis in autumn

remains limited by the lower light levels and by the fact that plants cannot profit from the more favorable temperatures due to their senescence. The result is a net release of carbon in warmer autumns that cancels out the extra carbon absorbed during warmer springs. This suggests that **even when the growing season at temperate latitudes is extended by global warming, the terrestrial ecosystem does not absorb more atmospheric CO₂**.

- We are progressing towards a **new method to trace emissions from fossil fuel burning in the atmosphere**. Until now, the only way to discriminate CO₂ emissions from such human activities from the natural atmospheric CO₂ variability was to use ¹⁴C (radiocarbon) measurements, which owing to their considerable cost cannot be made at high frequency (more often than every couple of weeks) nor at high spatial density. We have found a very interesting correlation between atmospheric CO₂ and carbon monoxide, which is much easier to measure. This is still at development stage but we hope that in the near future this will lead to an operational tool for local communities to verify their efforts in emission reduction through straight-forward atmospheric measurements.
- We have validated a **new methodology for investigating the key missing component in the European carbon budget: the regional scale**. While low

populated regions like Siberia show rather similar carbon fluxes from one point to another, Europe is a complex, subtle mosaic of different land uses. Our regional experiment in Les Landes (near Bordeaux in France) combined intensive measurements at many different scales, from several meters to several hundreds of kilometres, and taught us how to represent the spatial complexity and what density of observations is needed to obtain an acceptably accurate picture of such a heterogeneous region. In the future, this methodology may be replicated in other European regions and provide the means to monitor the regional distribution of local carbon sources and sinks and how they evolve with time.

More uncertainties in the European carbon balance...

- Despite the progress made in understanding different aspects of the European carbon cycle, we still have not managed to close the gaps in our carbon budget between the different methods used; for example between estimates from scaling up local flux measurements to the European scale and estimates derived from measurements of CO₂ concentration in the atmosphere. The uncertainties in all the methods remain large – in fact the uncertainty even appears to have increased! What we have learned though, is that things are more complex than we first thought but **this higher level of uncertainty is in itself an important result**. Furthermore, we have a better understanding of the sources of this uncertainty and how to improve our estimates in the future. Policy-makers want an exact figure, however, they have to

accept that uncertainty is also a major component of decision making – do I take an umbrella tomorrow if the weather forecast is uncertain? If I want to be sure not to get wet, I take one; even if I'm unsure that I really need it.

- It is not only important for policy-makers to know the result, it is also important to know how uncertain the result is. For example, a weather forecast may not give a certainty for rain but it can still provide very useful information on which to base a decision; people may make very different choices if the chances of rain are 10% or 50%. We are progressing in quantifying the uncertainties in our estimates by constraining our models with more and more data from field observations.
- We still have plenty of “big” unsolved questions. For example, we know from the difference between the CO₂ emitted, the CO₂ absorbed by the oceans, and the CO₂ concentration measured in the air, that the northern hemisphere is overall a carbon sink. However, **we still don't really know how this sink is distributed across the various regions of the continent**. Furthermore, the atmospheric CO₂ concentration is increasing slightly more rapidly over Europe than elsewhere. This trend has been seen clearly over the past 5 years but so far we are not really able to explain it.

Future challenges

- One of our major achievements is the **carbon observation network** we have deployed and consolidated all over Europe – with air sampling stations, flux towers, tall towers, aircraft sampling sites and

Forest tree species map (Hengeveld et al., in prep., Alterra): we now have much more insight into where different types of forest are located and how they grow. This is important information for designing the optimal carbon management plan because each location will require different measures (e.g. Portugal needs fire-smart forest landscape whereas for central Europe, with large stocking of biomass, the production of biomass for bioenergy may be optimal and at the same time it reduces the storm risk. In the north, the continuous flow of harvesting for industry and the conservation of peatlands may be the optimal strategy).





campaigns, satellite observations and the associated modelling capacities. This network now forms the basis for a long-term infrastructure project called ICOS (Integrated Carbon Observing System). The overall aim of ICOS is to produce temporally resolved maps of the land-atmosphere carbon exchange across Europe² based on a harmonized observing network of atmospheric and flux measurement stations. In addition to providing broad-scale field-validated data for research and modelling, these maps will allow local communities to evaluate their own progress towards achieving carbon neutrality. A pilot phase of ICOS has now been launched to prepare the technical and financial infrastructure for equipping Europe with this leading world observatory for the carbon cycle, both on the land and in the ocean. The full implementation of ICOS is planned for 2012 and is expected to provide decades of observations.

- As industrialised societies will surely continue to emit massive amounts of CO₂ into the atmosphere, **we urgently need more accurate knowledge on how to manage land as a carbon sink** and how to monitor our progress towards this objective. The more CO₂ we manage to “clean” from the atmosphere with the help of plants, the more we will limit the harm caused by our emissions.
- Despite any success we may have in strengthening the immediate capacity of our forests and land to absorb the carbon we emit, we also know that this capacity will become more fragile as the climate changes. A critical question to further research is therefore: **to what extent and for how long can Europe rely on its terrestrial carbon sinks?**³
- Climate change is a global issue. Whatever we learn about the European carbon cycle can be applied to models across the rest of the world to help inform global research and climate mitigation policies.

A strong community across scientific frontiers

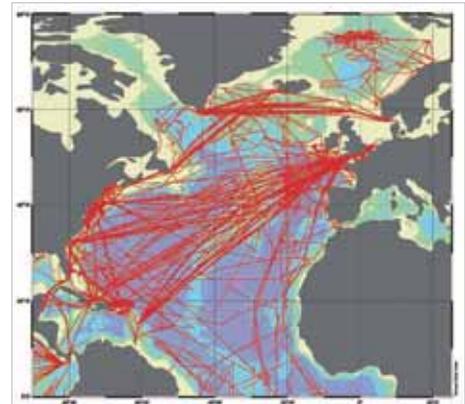
Although these scientific results represent significant steps in advancing carbon science, of no less importance is the human result, that is, **we have built a community with free circulation of ideas and data.** The Earth system is a huge complex puzzle. The biggest challenge of global change research, in a scientific tradition where we are all specialists in a small part, is to integrate all components in a way that represents the wider picture. CarboEurope has put together modellers and experimentalists, including soil, atmosphere and forest scientists, from 17 different countries for the first time in an extended way.

A direct benefit can be seen in the sharing of data within the community; for example, data from flux towers are now completely open to all. This was not the case in the past; people were afraid to see their results published by others. As a consequence of this open spirit, the number of publications has grown considerably. In the past, one single site would often lead to only one paper. Today, many more papers integrate data from the whole community, taking in numerous different sources.

An overview of CarboOcean results

CarboOcean⁴ is the counterpart of CarboEurope for the oceans:

- we want to better understand how carbon is **exchanged** between the atmosphere, the ocean (at various depths), the ocean floor and the sediments, and how it is **transported** from rivers to estuaries, coastal regions, the open ocean and finally in the ocean currents themselves.
- we want to ascertain how this natural cycle is being affected by the massive invasion of CO₂ released by humans and to be able to predict how it will evolve in the future.
- we want to know more precisely how much carbon is being absorbed by the ocean, how the uptake works and varies in time and **what effects all this extra CO₂ invading the oceans will have.** Most importantly, how will this affect the ocean's ability to continue absorbing large amounts of CO₂ in the coming decades? Furthermore, when CO₂ enters the ocean it acidifies⁵ the seawater, which may threaten various groups of marine organisms and perhaps endanger the whole ocean food chain - so what will be the consequences of this ocean acidification?



Cruise track of CarboOcean VOS lines in the northern Atlantic Ocean (Benjamin Pfeil, CarboOcean data centre, BCCR).

polated (over space and time) with the aid of ocean models and satellite observations **and allow us to deliver precise estimates of carbon uptake in different regions of the North Atlantic and its variation over time.** For example, we have calculated that the North Atlantic (from 10°N to 65°N) took up **0.25 PgC⁶ +/- 10%** in the year 2005. This important

Key results

- We have instigated the first year-round multiple-ship observation system for the North Atlantic carbon cycle through the “Voluntary Observing Ships” (VOS)



4) A more detailed presentation of the aims & methods of CarboOcean is given pp. 31-36 of the 1st CarboSchools booklet.

5) The pH of the seawater is decreasing due to physical-chemical laws but stays above 7: the water acidifies, but remains alkaline.

6) 1 PgC means 1 peto-gram of carbon, which is the equivalent of one giga-ton (one billion of tons). 0.25 PgC +/- 10% therefore means 250 million tons of carbon plus or minus 25 million tons.

2) Flux maps are already available at <http://inversions.lscce.ipsl.fr>

3) A new EU research project called CARBO-Extreme is dedicated to this question and will try to estimate the probability that the quantified emission reduction commitments of Europe should be increased by 5, 10 or 20 % to counter reductions in ecosystems C sinks by 2020 and 2050 for various emission scenarios. A major product will be maps showing the risks of not attaining targets in emission reduction as a result of a weakening of the European C sink.



In order to continuously obtain new data, commercial ships such as the MV Benguela Stream (cargo ship to the left) were equipped with a CO₂ measurement system. With the help of these continuous data, scientists can monitor the North Atlantic sink and quantify how the CO₂ uptake changes over time and varies for different latitudes. (Source: T. Steinhoff and U. Schuster).

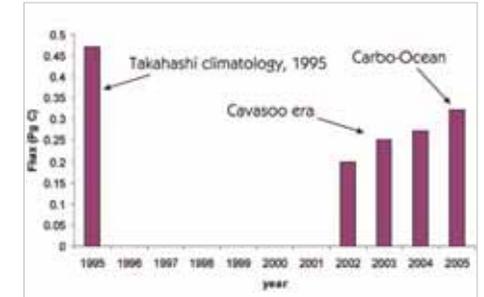
result will also help CarboEurope to deduce the continental budget: when you know accurately how much CO₂ is emitted by human activities, how much is uptaken by the ocean and by how much it has increased in the atmosphere, then the difference between them is the terrestrial sink. This more precise estimate of the North Atlantic sink will also help to distinguish the North-American from the Eurasian terrestrial sink. **Validating the methodology to reach this estimate is a key achievement** of CarboOcean.

- Thanks to this observation system, we see that the North Atlantic sink strength is highly variable: in the early years of the 21st century the North Atlantic absorbed 50% less CO₂ than in the mid-1990s. Recent data show that the CO₂ sink is slowly recovering. We need more years of observations to see whether the trend is sustained or if it is only part of a longer natural variation, and to better understand its causes. **In the Southern Ocean, we see that the ocean sink has been weakening since at least 1980**, a trend that has been probably brought about by the intensification of Southern Ocean winds due to climate change.
- The latest predictions from our computer models show that the oceans will continue to uptake CO₂ from the atmosphere, but **the continuous acceleration of climate change and CO₂ emissions will gradually reduce the sink strength, resulting in a temporary**

but huge increase of CO₂ in the atmosphere. This is very alarming, combined with the fact that our models also predict that by 2100 the land uptake (the biosphere sink) will decline, possibly to zero or even become a source of CO₂.

- **We are progressing in our capacity to see where the CO₂ emitted by humans goes once it enters the ocean.** Tracking how CO₂ from human activities permeates the ocean's interior is a very tricky job because we do not know what the carbon content in the ocean was before the onset of the human emissions and so far the results given by the various methods available still differ significantly, generally owing to the lack of measurements over space and time. Nevertheless, all approaches more or less agree that **the largest quantities accumulated in the high latitude northern Atlantic** close to the areas of deep ocean mixing.
- **We have learned a lot about how the terrestrial and marine carbon cycles interact through the coastal ocean.** In close collaboration with CarboEurope, we conducted intensive studies in the North Sea to better understand how carbon migrates between land & ocean in shelf seas: for example, how the carbon carried by rivers is mixed and diluted in the coastal ocean and how this affects the whole cycle. This integration of land and sea is critical to understanding the carbon cycle both regionally and globally and is particularly challenging due to the complexity and heterogeneity

of the exchanges. **In the North Sea, we are now able to observe and account for the carbon input, via rivers,** received from waste water, agriculture, and natural biological activity in the entire basin. This is one of the very few attempts in the world to quantify all relevant fluxes between land, sea and atmosphere comprehensively at the regional scale. We conducted similar observations in the Gibraltar Strait where we found out that **outflow waters from the Mediterranean Sea carry significant amounts of anthropogenic carbon into the Atlantic Ocean's interior.**



Big unknowns about carbon in the ocean

- Our picture of the marine carbon cycle is still very crude. For now, we are only beginning to witness the spectrum of potential changes in the ocean due to increasing CO₂ and rising temperatures. Due to their difficulty of access, their expanse (71% of the Earth's surface) and depth, the oceans are sparsely sampled compared to the continents. Furthermore, while CO₂ diffuses quickly in the atmosphere and is, therefore, "easy" to track (atmospheric CO₂ concentrations are rising all over the world in a rather homogeneous way), mixing in the ocean takes considerably longer and thus the concentrations are more heterogeneous. Hence, the quantities of carbon transported within the ocean with respect to space and time are largely unknown. We observe big changes and big perturbations on many parameters but **often without being able to explain what we observe, nor able to predict the consequences.** The more we learn - the more certain we become about the uncertainties!

Varying North Atlantic sink strength as deduced from a suite of collaborative projects (A. Watson & al. in prep.). In the early years of the 21st century the North Atlantic CO₂ sink was only 50% of that in the mid-1990s. It looks as if the CO₂ sink has been slowly recovering- but what will be the value for 2006 and in future years? Is it a long-term trend or natural variation? These findings show that the CO₂ sink is highly variable and needs to be continuously observed.

- The acidification issue illustrates this very well: we know with certainty that seawater is acidified as CO₂ enters the ocean and that marine life, biodiversity, and the whole food chain may be adversely affected but **we are not yet able to predict the scope of the consequences, which might threaten the Earth's ecological balance as severely as climate warming is doing.** We are making progress with new investigation methods, notably through "mesocosm perturbation experiments"⁷⁾ consisting of artificially adding CO₂ to closed columns of sea water to see how marine life



How does the marine ecosystem react to a doubling of today's atmospheric CO₂ concentration? In Norway, near Bergen, large plastic bags (called „mesocosms“, which literally means „medium worlds“) with artificially CO₂-enriched water enable the consequences of this enrichment on marine life to be observed „in situ“. (A. Volbers, U. Riebesell)

7) See example in Bergen p. 39 of the 1st carboschools booklet.



reacts to various concentrations and the related change in pH. This has become a high priority on the research agenda with a new "European Project on Ocean Acidification" (EPOCA), which started in 2008⁸.

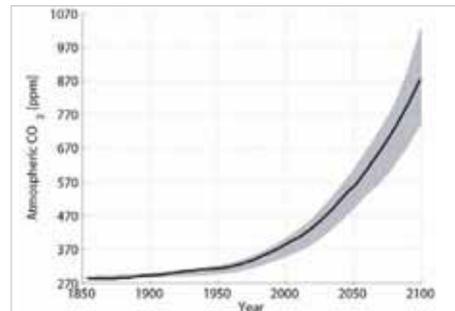
Future challenges

Ocean carbon science is faced with important questions for the future of mankind:

- what is the future of the ocean carbon sink? Is the decrease in the sink in the first few years of the 21st century in the North Atlantic a long-term trend or rather due to decadal variation? What effect will it have? A lasting decrease in this sink would accelerate the dangerous accumulation of CO₂ in the atmosphere.
- will we see a change in ocean circulation and, if so, with what consequences on climate and the ocean sink capacity?
- what levels of atmospheric CO₂ concentration and ocean acidification will be reached after the cessation of the human CO₂ invasion into the Earth system and with what consequences for marine life?

These pressing questions challenge our capacity to make reliable predictions, which directly depends on the capacity of our computer models to accurately simulate the complexity of reality. Currently far too many components of our ocean carbon cycle models are derived from purely empirical relationships or even simply "best guess estimates", due to the lack of data from field observations. **We need to vastly increase the number of observations in key regions of the world's oceans in order to validate and improve the accuracy of our models**, particularly

in the high latitudes (Arctic & Antarctic oceans), which due to their sensitivity to changes in carbon cycling and climate can serve as "magnifying glasses" for observing ongoing perturbations of the Earth system.



Here the mean atmospheric CO₂ concentration is simulated by (black line) BCM-C model as compared to the range (grey shading) from other C4MIP (Friedlingstein et al., 2006) models, based on the IPCC SRES A2 emissions scenario in which fossil fuel usage more or less continues to grow unabated (source: Tjiputra et al., in prep.)

There is a strong agreement across 11 models from the C4MIP experiment, now backed up by these new CarboOcean results, that natural carbon sinks in both oceans and on land will be weakened by the effects of climate change. This weakening, combined with the rise in emissions, explains this highly alarming curve. This does not mean that atmospheric CO₂ concentrations (governed by CO₂ emissions minus land and ocean uptake) will certainly rise in an exponential way over the 21st century, however, the prevention of such a rise, and the stabilisation of climate, will certainly require strong intervention policies from all the world's governments.



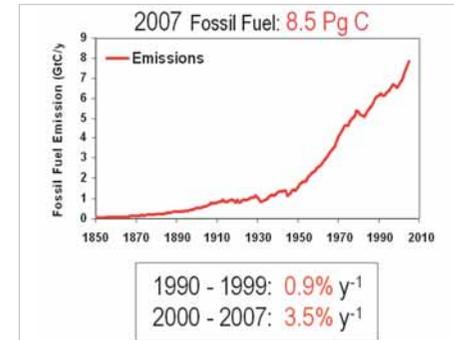
8) epoca-project.eu

The global picture

Bad news...the world's emissions are currently accelerating faster than the worst scenarios predicted and the natural capacity of the carbon cycle to absorb our emissions seems to be decreasing.

The European projects CarboEurope and CarboOcean are part of a bigger endeavour by scientists from all over the world to better understand and predict climate change. The Global Carbon Project tries to identify the big trends from all carbon-related observations all over the world. Here is a brief outlook of the most recent synthesis. You can read the summary and access the full presentation at <http://www.globalcarbonproject.org/carbontrends/index.htm>

Carbon emissions from fossil fuels



The growth rate of fossil fuel emissions is accelerating – in the period 1990-1999 it was increasing at a rate of 0.9% per year, whereas in the period 2000-2007 the rate of increase was 3.5%. This represents a multiplication by almost four in the last decade, exceeding the highest forecasted growth rate for the period 2000-2010 in the emissions scenarios of the Intergovernmental Panel on Climate Change (IPCC)⁹. The biggest increase in emissions has taken place in developing countries, largely in China and India, while in developed countries it has been growing slowly.

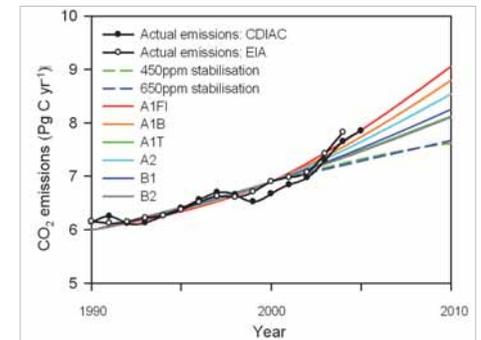
⁹ IPCC scenarios correspond to various future predictions of CO₂ emissions globally depending on various hypotheses of economic & industrial development, and population growth.

¹⁰ ppm : parts per million, unit used to measure small concentrations (1 ppm = 0,0001%)



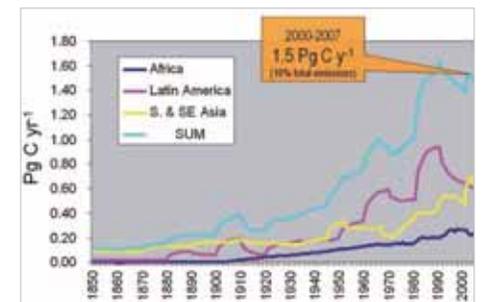
All graphs in this section are extracted from: *Global Carbon Project (2008) Carbon budget and trends 2007*, [www.globalcarbonproject.org, 26 September 2008]

Trajectory of global fossil fuel emissions



Current emissions (black) are tracking above the most intense fossil fuel scenario established by the IPCC SRES (2000), A1FI-A1 Fossil Fuel intensive, and are moving away from the stabilization scenarios of 450 ppm¹⁰ and 650 ppm.

Carbon emissions from tropical deforestation

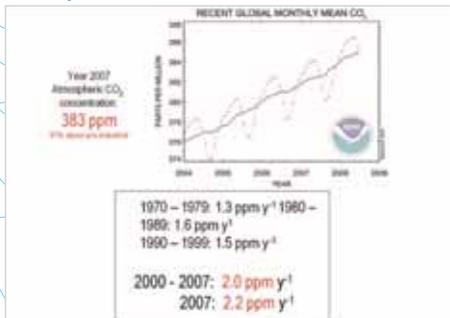




What we must do

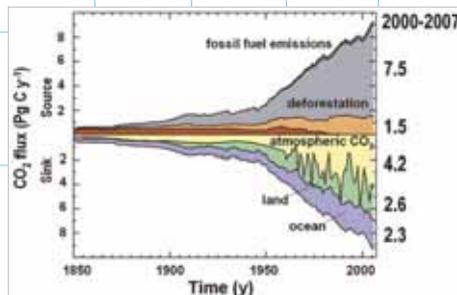
Climate change is caused by mankind? Excellent news: since we are the origin of the problem, we are also master of the solution!

Atmospheric concentration



The annual mean growth rate of atmospheric CO₂ was 2.2 ppm per year in 2007 (up from 1.8 ppm in 2006), and above the 2.0 ppm average for the period 2000-2007. The average annual mean growth rate for the previous 20 years was about 1.5 ppm per year. This increase brought the atmospheric CO₂ concentration to 383 ppm in 2007, 37% above the concentration at the start of the industrial revolution (about 280 ppm in 1750).

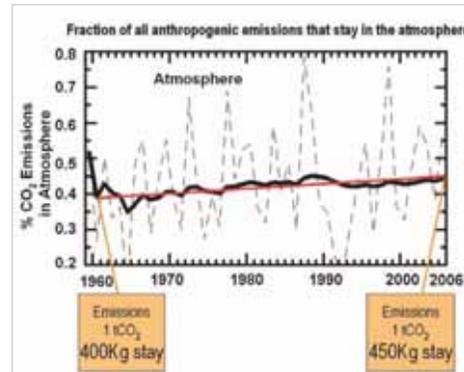
Human perturbation of the global carbon budget 1850-2006



This graph shows how the CO₂ emitted by mankind (higher part, distributed between fossil fuel burning and deforestation) progressively diffuses in the whole system (lower part, distributed between atmosphere, ocean & vegetation). Atmospheric CO₂ accumulation is directly measured, the ocean sink is modelled, and the land sink is the residual from closing the balance (it is not directly measured).

11) 1 Petagram of carbon is 1 billion tons of carbon.

The decline of the natural sinks



Natural land and ocean CO₂ sinks have removed 54% (or 4.8 PgC¹¹ per year) of all CO₂ emitted from human activities during the period 2000-2007. The size of the natural sinks has grown in proportion to increasing atmospheric CO₂. However, the effectiveness of these sinks in removing CO₂ has decreased by 5% over the last 50 years and will continue to do so in the future. That is, 50 years ago, for every ton of CO₂ emitted to the atmosphere, the natural sinks removed 600 kg while today they are removing only 550 kg, and this amount is falling. Part of the decline is attributed to up to a 30% decrease in the efficiency of the Southern Ocean sink over the last 20 years. Nevertheless it is impressive that natural CO₂ sinks were able to absorb about half of the anthropogenic emissions in 1960, when emissions were 2 PgC/yr, and similarly 50 years later when emissions are now 10 PgC/yr.

All of these changes characterise a carbon cycle that is generating a stronger climate impact and sooner than expected.

Learning about climate change can be depressing for children, especially for teenagers who are shaping their vision of their place in society, public engagement, and in the future. A worrisome sequence of events can be: asking „what can we do“, then feeling powerless, getting back to normal life, and doing nothing.

By overseeing the broad question of how we can solve the climate crisis, this chapter tries to suggest pathways for teachers to avoid this sequence of events and empower young people to take positive action and engage themselves as citizens with a sound scientific understanding.

Large-scale action is needed globally and has not yet occurred

Science has now shown that:

- human activities are perturbing the whole Earth-system at a wide-scale and with extreme speed, affecting the cycles of all major components of life: water, carbon, nitrogen etc. In particular, the massive CO₂ emissions from burning fossil-fuel and deforestation is driving global warming (and thus increases in sea level), ocean acidification, and a wealth of inter-dependent effects that we are unable to predict with reasonable certainty¹².
- the risks involved for humanity range from massive loss of biodiversity, huge costs to the economy¹³, and tragedy for billions of people unable to adapt due to

poverty, loss of land, scarcity of drinking water and other related afflictions¹⁴.

- the only way to stop taking such dangerous risks is to decrease and stop emitting greenhouse gases (GHG) into the atmosphere.
- the capacity of natural sinks to absorb our emissions is decreasing as climate gets more and more disturbed, meaning that we cannot count on the capacity of current sinks when setting our targets for emission reductions.

The dominant development model in the world, based on continued industrialisation and economic growth, is characterised by massive use of fossil fuel, intensive agriculture and deforestation - which coupled with demographic growth lead to large increases in GHG emissions.

It is therefore completely impossible to stop or drastically reduce our emissions from one day to the next¹⁵. So the key question is: how to change this unsustainable civilization into a sustainable one without jeopardizing it, and at what pace? How can we progressively stop using fossil fuels, stop deforestation, stabilize population, and at the same time, ensure that basic living conditions are satisfied for all?

Answering these questions is naturally not the responsibility of scientists, but of society, governments and politicians. **However, as scientists we need to make sure that the questions are well formulated, well documented, and well understood in the full context of their implications and that the various responses elaborated are scientifically valid.** In particular, we need to make it clear that the changes required are not just minor adjustments to mainstream pathways nor reverting to a „stone-age society“, but rather a change

12) As documented by the Fourth Assessment Report of the IPCC (2007). See also first carbo-schools brochure « What we know, what we don't know and how we try to better understand global change ».

13) As particularly well documented, in the Stern review on the economics of climate change (2006)

14) The possibility of positive effects in some places, e.g. increased agricultural productivity in Siberia or Alaska, is of no comparison with the scope of the negative effects globally.

15) In contrary to e.g. the ozone layer problem, where a single family of industrial gases (CFCs) could easily be replaced by a less harmful existing technology.