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The IGBP Global Carbon Project: Understanding the breathing of the planet

Introduction to the Special Carbon Issue of the NewsLetter

The post-Kyoto world has put the planet's biogeochemical cycling into the forefront of international political and economic concerns, and has posed a considerable challenge to the international global change research programmes.

No longer is understanding the functioning of the Earth's carbon cycle, and human perturbations to this cycle, an esoteric exercise of the scientific community. Management of aspects of the carbon cycle, at a global scale, now prompts political consideration at the highest levels of governments, triggers strident economic debates, and even threatens to impact significantly on North-South relations.

Science can be a strong player in this international political process, and IGBP, in collaboration with its partner programmes WCRP and IHDP, is rising to this challenge by launching a major international research effort on the science of the global carbon cycle. The twin objectives of the IGBP Global Carbon Project are:

- ♦ to produce a synthesis of our current understanding of the global carbon cycle, including a fast-track scientific overview in time for inclusion in the IPCC special report on land-use change and forestry;
- ♦ to develop an international framework for collaborative research on the carbon cycle; involving appropriate elements from IGBP, WCRP

and IHDP, and to coordinate an international research effort under such a framework.

The rationale for launching a coordinated **international** research effort on carbon is simple: Understanding the carbon cycle, at a global scale, is beyond the scope of any one nation's scientific community alone, or even beyond the capability of regional groupings; it can only be understood through a collaborative effort by the entire international scientific community.

There is much carbon research in IGBP, in all of the Core Projects and in GAIM – the challenge is to put these pieces of the carbon puzzle together in a more integrated way to build a consistent, coherent and robust picture of how this global cycle works, how human activities are changing it, and how it will behave in the future.

Some of these pieces of the carbon puzzle are described on the following pages. They are not meant to represent the complete array of carbon-related research being undertaken in IGBP, but rather to give the flavour of the types of work which will become components of the IGBP Global Carbon Project. Over the next 12-18 months IGBP, in collaboration with its sister global change programmes, will have in place one of the most exciting, politically significant research endeavours ever attempted by the international environmental science community.

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Will Steffen

Will the terrestrial carbon sink saturate soon?

by Bob Scholes

Introduction

It is only possible to balance the global carbon cycle for the 1990s if there is net carbon uptake by terrestrial ecosystems of around 2 PgC/yr (1). There is now independent, direct evidence for the existence of such a sink. Now that we have found the 'missing sink', can we rely on it to persist into the future?

Policymakers involved in the UN Framework Convention on Climate Change (UN-FCCC) are striving to reach consensus on a 'safe path' for future emissions. The global carbon cycle models currently used to advise the policy process implicitly assume that the terrestrial sink will either persist at its current level, or grow in the future. Several lines of evidence suggest that the terrestrial carbon sink is a transient phenomenon, currently close to its maximum value, and will decline or even change sign in the future. If this hypothesis is true, emissions of carbon dioxide (CO₂) will have to be even more drastically reduced than is currently predicted if stabilization is to be achieved.

Causes of the terrestrial sink

The three main causes for the sink are thought to be as follows (2).

1. Differences in the functional form of the response of ecosystems to carbon dioxide and temperature.

Net carbon uptake by terrestrial ecosystems reflects an imbalance between carbon assimilation (photosynthesis) and carbon loss (respiration). Photosynthesis responds essentially instantaneously to increases in the atmospheric carbon dioxide concentration. The form of the response is a saturating curve, often empirically represented with an equation of the form

$$C_{\text{assim}}(y) = C_{\text{assim}}(x) (1 + \beta \ln(y/x))$$

where $C_{\text{assim}}(y)$ is the assimilation rate at an atmospheric carbon dioxide concentration of y ppm, and $C_{\text{assim}}(x)$ is the

assimilation rate at a reference level of x ppm. β is an empirical constant, the value of which in nutrient- and water-sufficient laboratory experiments is about 0.4, but in real-world ecosystems subject to drought and nutrient deficiency is less than 0.2.

The global carbon cycle models used for the IPCC Second Assessment Report, and which form the basis for the scenarios currently used in the Third Assessment Report include this 'carbon fertilization effect', but not the respiration effect which must inevitably follow. Thus they predict that the terrestrial carbon sink will *continue to grow indefinitely* as CO₂ rises in the future.

The respiration side of the carbon balance does not respond directly to the atmospheric carbon dioxide concentration, but to the increase in air temperature caused by the rising carbon dioxide and other greenhouse gases. There is a

time-lag of several decades in this indirect response, as discussed below. The form of the response function of respiration to increasing temperature is exponentially increasing within the temperature range under consideration here (0° C - 35° C). It is conventionally expressed as a Q_{10} factor, the ratio of the rate at a given temperature to the rate at a temperature ten degrees cooler. Reported Q_{10} values for respiration in natural ecosystems range from about 4 in cool systems to about 2 in warm ecosystems (3).

It is obvious that the graphs of these two responses must cross over at some carbon dioxide concentration. Initially, photosynthesis is promoted by rising CO₂ much more than respiration is enhanced, leading to a sink. Eventually a point will be reached above which respiration exceeds photosynthesis, and the sink becomes a source.

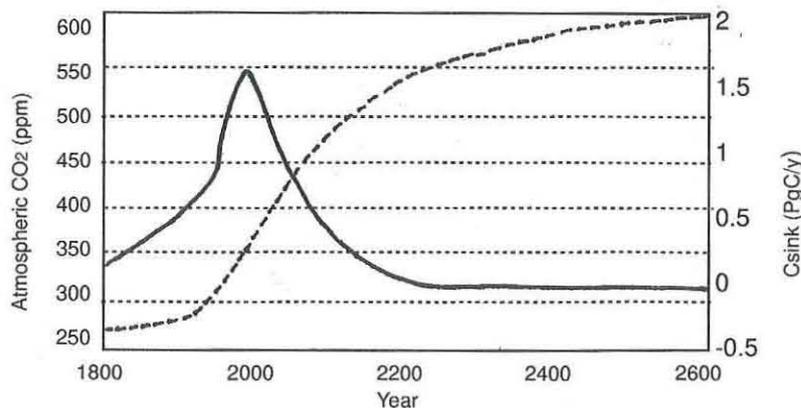


Figure 1. The time-course of atmospheric CO₂ used to drive a simple model of the terrestrial carbon cycle (broken line), and the predicted sink behaviour (solid line) which results ($\beta = 0.2$, $Q_{10} = 2$). This CO₂ time course assumes stabilization at 600 ppm in the long term. Stabilisation will, by definition, lead to a sink which declines to zero over time, but note that the decline in the sink commences much earlier. In this illustrative model the sink size does not feed back to the atmospheric concentration, so the disappearance of the sink is unrelated to stabilization.

2. Time lags in the coupled atmosphere-ocean system

The enormous thermal inertia of the oceans causes the actual increase in the global air temperature to lag significantly (in the order of fifty years) behind the increase which would be predicted from the increased radiative loading due to elevated carbon dioxide. Thus the stimulation of photosynthesis occurs almost instantly, while the full effects of the temperature rise take several decades to be felt. During this delay period there is an apparent sink. Once the atmospheric concentration of CO₂ is stabilized, which is the intention of the UN-FCCC, the temperature is predicted to continue to rise, for several centuries. The 'inertia sink' disappears, and under certain parameter combinations, can appear as a source.

3. Slow turnover in the biospheric carbon pools

Carbon is stored in terrestrial ecosystems in two main forms: about a third as carbon in biomass, principally as wood in forests; and two-thirds as carbon in the soil. Both of these forms contain sub-pools with differing turnover times, some of which are very long, and this leads to a temporary sink. For example, if elevated CO₂ causes increased growth in a forest tree, this appears as a sink. That tree would typically live for a century or two before it dies and decomposes, releasing carbon dioxide back into the atmosphere via heterotrophic respiration. Natural ecosystems, at large scales and over long periods of time, must effectively be in balance between carbon assimilation and carbon loss; thus a sink now must be balanced by a source later, unless the biospheric carbon pools increase in size. There are physical limits on how large those pools can get, and the loss of forests and grasslands to agriculture limits the area over which they can be effective. Large terrestrial carbon pools in the form of trees or forest-floor litter are highly susceptible to rapid return to the atmosphere through fire or other disturbances.

The soil carbon pool has some very long-lived sub-pools (up to centuries or millennia for the stable carbon in humified materials). An injection of fresh carbon into the soil carbon pool can take many decades to work its way through to respiration. Clay content is the main factor setting an upper limit on the quantity of carbon that can be sequestered in soils in a non-ephemeral form (4).

		Q10		
		1.5	2.0	3.0
β	0.2	128 (2441)	73 (2072)	41 (2029)
	0.4	407 (>2600)	277 (2285)	117 (2105)

Table 1. The integrated size of the terrestrial sink (Pg C) and the calendar year in which the sink becomes a source for a range of assumptions about the shapes of the photosynthetic response to carbon dioxide (β) and the respiration response to temperature (Q_{10}). Best guess values are 0.2 and 2 respectively. The present terrestrial carbon pool is about 3000 Pg C - thus under the central assumptions, the transient integrated sink is about 2.4% of the existing pool. Whether the sink eventually becomes a source, or simply declines gracefully to zero, depends on the combination of parameter values selected.

A simple model and its sensitivity

A simple whole-earth terrestrial carbon cycle model, which includes the above considerations but has no spatial dimensions, predicts a terrestrial carbon sink of approximately 2 PgC/y at the present time. However, this model suggests that we are presently near the peak of the terrestrial carbon sink strength, and it will begin to decline within the next few decades. The rate of decline and the total integrated capacity of the terrestrial sink depend on the exact values chosen for β and Q_{10} , the two key parameters outlined above (Table 1).

This over-simple model, which is purely intended to illustrate the argument, and **not** to quantitatively predict the time-course of the evolution of the sink, does not take into consideration other factors which contribute to the terrestrial carbon sink or source. For instance, about 0.5 PgC of the current sink could be due to nitrogen deposition (1). In this analysis, the nitrogen effect has been subsumed into the carbon di-

oxide fertilization effect, since they are both ultimately linked to fossil fuel consumption. Nitrogen fertilization is also a saturating curve, which could at very high levels of nitrogen lead to ecosystem failure and a net CO₂ source. Thus the conclusions of the analysis would be modified in detail but not generality by the inclusion of nitrogen.

Land use change contributes to both the sink behaviour and the source behaviour of the terrestrial biosphere. Forest regrowth in Europe and North America constitutes a sink in the current time. This sink will saturate once physical limits come into play. The terrestrial biosphere in the tropical parts of the world is largely a carbon source at present, due to the conversion of tropical forests to croplands. As this proceeds, so the extent of land available to act as a sink declines, reducing the integrated sink capacity and shortening the period to its exhaustion.

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World soils and the greenhouse effect

by Rattan Lal

World soils constitute one of the five principal global carbon (C) pools. These pools include: (i) oceanic pool, containing 38,000 Pg of C, (ii) geologic pool, with 5000 Pg consisting of 4000 Pg coal, 500 Pg oil and 500 Pg of natural gas, (iii) soil, with 2500 Pg, (iv) atmosphere with 760 Pg, and (v) terrestrial biomass pool with 620 Pg. The soil C pool comprises two components, a soil organic carbon (SOC) pool with 1550 Pg of C in the top 1m depth and a soil inorganic carbon (SIC) pool containing 950 Pg C. Therefore, the soil C pool is about 3.3 times larger than the atmospheric pool and 4.0 times the terrestrial biomass pool. These five pools are interconnected (Figure 1).

The atmospheric pool is increasing at the rate of about 3.2 PgC/yr. There are three principal anthropogenic activities that contribute to the observed increase in the atmospheric carbon: (i) fossil fuel combustion; (ii) cement manufacture; and (iii) deforestation, land use, and soil cultivation and the attendant depletion of the soil carbon pool. Until the 1950s,

as much as 75 to 80% of the atmospheric increase in C came from deforestation and land use change. By 1970, this fraction had decreased to about 50% of the annual increase in atmospheric concentration in C. By the 1990s, only about 20% of the annual increase in atmospheric C pool is attributed to deforestation, land use change and soil cultivation.

Accurate estimates of the historic loss of C from soil and terrestrial biomass pools are difficult to make because of the lack of the required baseline data on soil and vegetation. Nevertheless, rough estimates have been made: 50 to 100 Pg from the soil pool and 100 to 150 Pg from the terrestrial biomass pool. The magnitude and rate of depletion of the soil C pool is exacerbated by soil degradation and decline in soil quality.

Principal soil degradative processes include: (i) physical degradation, (ii) chemical degradation, and (iii) biological degradation (Figure 2). Soil physical degradation leads to, and is caused by,

a decline in aggregation, crusting, compaction, anaerobiosis, runoff and soil erosion. Soil erosion and sedimentation cause burial (sequestration) of C at depositional sites and in aquatic ecosystems. However, eroded soil and the C contained in the sediments redistributed over the landscape may be a net source of C to the atmosphere. Soil chemical and biological degradation processes accentuate the process of increase in atmospheric concentration of CO₂ and other greenhouse gases (e.g., CH₄, N₂O, NO_x) through reduction in biomass productivity, decrease in the biosolids returned to the soil, and an increase in anaerobiosis.

There is a potential for reversing some of these processes and sequestering C in soil and terrestrial ecosystems. The magnitude of the potential is estimated to be up to 50 to 75% of the historic C loss. In some soil-specific situations, the potential of C sequestration in soil may even exceed the C level in the natural or undisturbed ecosystem. For example, soils of the acid tropical savanna ecosystems are constrained by Al toxicity and P deficiency in the natural state. Alleviation of these constraints may cause accumulation of SOC at levels higher than that in the natural ecosystem.

Restoration of degraded soils also has a high potential for C sequestration. Theoretically, the annual increase in atmospheric CO₂ can be nullified by restoration of 2 billion ha of degraded lands, which would increase their average C content by 1.5 Mg/ha in soil and vegetation. Global desertification control has a potential to sequester 1 to 1.25 PgC/yr, a substantial fraction of anthropogenic emissions.

Judicious management of agricultural soils through agricultural intensification is another important strategy. Agricultural intensification implies adoption of best management (recommended) practices on prime agricultural land so that marginal land can be converted to

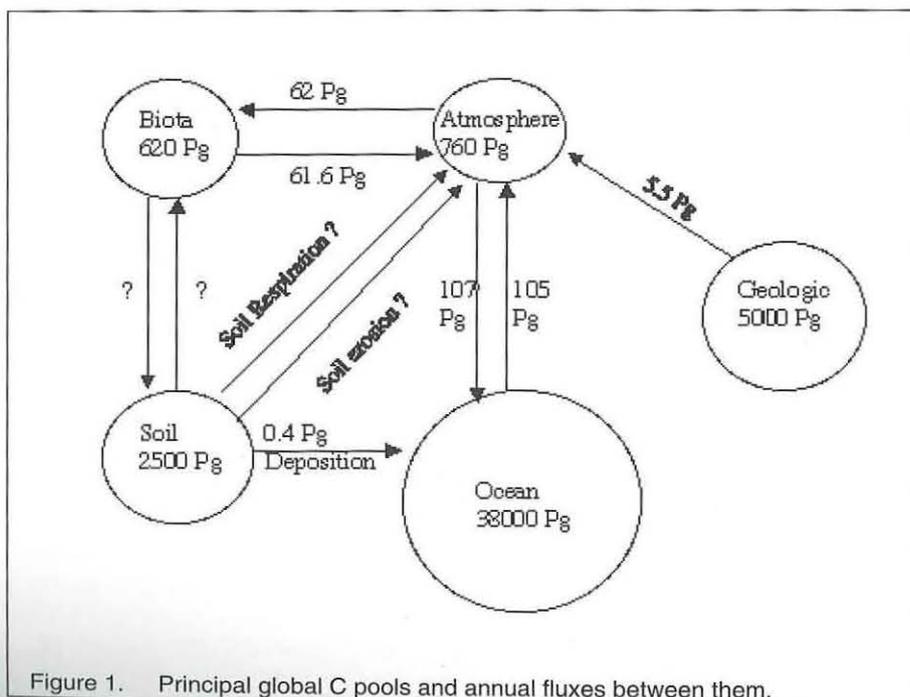


Table 1. Improved management practices for C-sequestration in agricultural soils.

C-depleting practice	C enhancing practice
Plowing	No till, conservation tillage
Residue removal/burning	Residue return
Bare fallow	Growing cover crop
Low input	Judicious use of off-farm input
Indiscriminate use of fertilizer	Integrated nutrient management and use of biosolids
Traditional cropping systems	Improved cropping systems and varieties
No water control	Water conservation and management
Native pastures	Improved pastures
Uncontrolled grazing	Rotational grazing, low stocking

restorative land use and lead to C sequestration. Through judicious input and restorative measures, the spared marginal land can be used to produce biofuel that can substitute directly for fossil fuels. The strategy is to: (i) increase density of C in soil; (ii) decrease rate of decomposition; and (iii) incorporate C deep in the soil profile. Agricultural practices that lead to an increase in the density of C in the soil are shown in Table 1. In addition to biotechnology, other plant breeding measures can be used to develop plant types with high lignin content that thus have low decomposition rate.

The new plant type thus developed may have high economic yield (e.g., grain, tuber, sugar content etc.) but also higher residue and root biomass. Plants' ability to produce high biomass depends on the availability of essential inputs e.g. nutrients, water. Therefore carbon sequestration in soil may necessitate additional use of off-farm resources for biomass production, and improving farmers' ability to return crop residue and other biosolids to the soil.

The overall strategy is to enhance soil quality or its capacity to perform specific functions (e.g. crop production, pasture growth and animal production, plantation crops etc.). In comparison with soil degradation, soil quality also comprises three components: soil physical quality, soil chemical quality and soil biological quality. Important determinants of quality are soil structure (aggregation, mean weight diameter, and stability), plant available water capacity, infiltrability, internal drainage and air capacity, and porosity and pore size distribution for soil physical quality, ion

exchange capacity and exchangeable bases, pH, nutrient pool and nutrient balance, and electrical conductance for soil chemical quality, quantity and quality of soil organic matter content, soil biodiversity and microbial biomass C for soil biological quality. Soil organic matter (carbon) content, in terms of quality and quantity, is an important factor governing all three components of soil quality. In fact, soil quality and soil organic matter content go hand-in-hand. Therefore, improving soil quality implies enhancing organic matter content through C sequestration in soil.

Soil C sequestration has economic, environmental and aesthetic/cultural

benefits. Economic benefits are due to improvements in agronomic productivity and attendant increase in farmers' profit margin. Increase in farm income and buying capacity has a positive feedback on soil quality through investment in soil restorative measures. Environmental benefits of soil carbon enhancement are due to improvement in water quality, bio-remediation, and mitigation of greenhouse effect. Aesthetic and cultural effects are due to improvement in land's appearance and human values. Therefore, evaluating economics of C sequestration need to be based on the benefits to farmers, the society at large, and other ancillary aspects.

Carbon sequestration in soil and terrestrial ecosystems has a large but finite capacity, the potential of which can be realized over a 25- to 50-year period. Nevertheless, realizing this finite potential is important because of its positive impact on soil quality, agronomic productivity, and in reducing the increase in atmospheric concentration of CO₂. This strategy thus buys us time (25 to 50 years) during which alternatives to fossil fuel and other mitigation measures can take effect. Carbon sequestration in soils is truly a win-win strategy.

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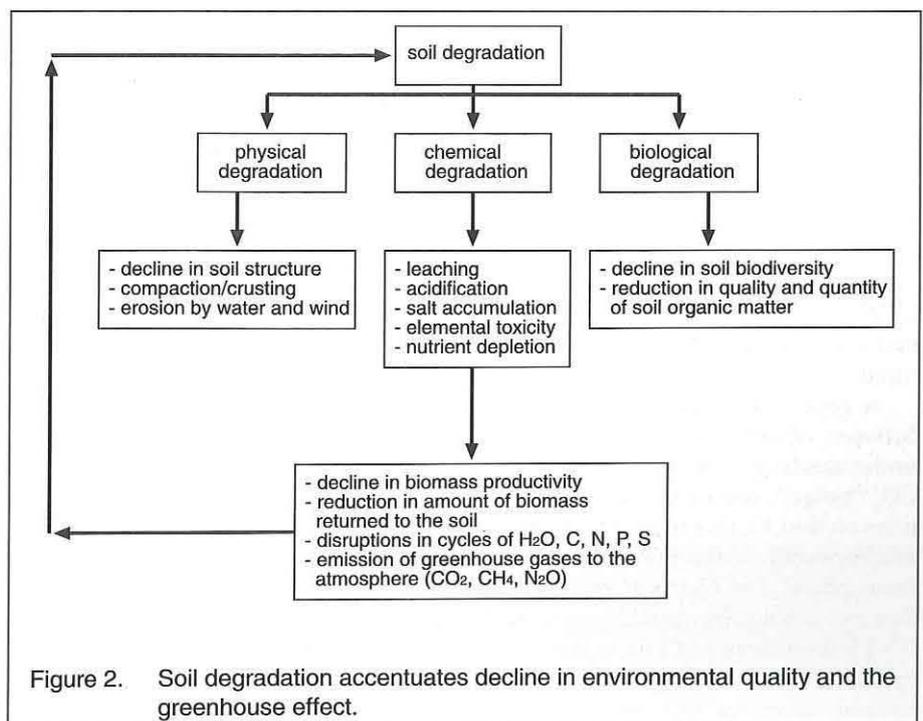


Figure 2. Soil degradation accentuates decline in environmental quality and the greenhouse effect.

The global survey of pCO₂

by Andrew Watson

We know, and have known since the 1970s, that the oceans are a "sink" for some of the carbon dioxide which human activity is adding to the atmosphere. But how large is this sink, what processes drive it, and how may it change in the future? One of the most important achievements during JGOFS has been to synthesize a detailed picture of the air-sea flux of CO₂ from tens of thousands of individual measurements made in every corner of the world ocean in every season of the year. The labour required collecting this data, and the ship-time and distance travelled aboard research vessels in its pursuit, have been prodigious. The reward, however, is that we now have a picture of how the ocean "breathes" – a detailed map of the exchange of CO₂ across the sea surface for all oceans and all seasons of the year. With this picture we can address these outstanding questions with more confidence, and in more detail, than has been the case until now.

Figure 1 shows one synthesis of this data; the average annual air-sea flux over the oceans as derived by Takahashi and colleagues (1). Blue and purple colours show regions which take up unusually large amounts of carbon dioxide from the air, while yellows and reds are areas which strongly out-gas carbon dioxide – in these zones therefore the flux is going in the opposite direction to the global mean. At the same time as this picture has been assembled, our knowledge about the processes which drive that exchange has deepened and matured.

A good example of the interaction between observations and theoretical understanding is the equatorial Pacific CO₂ "bulge", one of the strongest features on the CO₂ flux map, which shows as a huge source of carbon dioxide to the atmosphere. The observations suggest that this source, in normal years, adds 0.5-1 billion tonnes of CO₂ to the atmosphere; it is the strongest continuous natural source of CO₂ on Earth. The

immediate cause is the vigorous upwelling along the equator, driven by the divergence of surface currents there. The upwelling water comes from quite shallow depths of a few hundred meters at the most, but the water is strongly heated, warming by several degrees during its journey to the surface. This warming decreases the solubility of carbon dioxide in the water and makes the trapped gas want to escape to the air – the same process which causes a bottle of carbonated drink to produce more bubbles when it is warm than when it is cold.

Another important cause of this feature in the equatorial Pacific is biological activity, or rather lack of it. The upwelling water brings abundant nutrients to the surface, but the plankton are not able to make full use of them because of the lack of sufficient iron; there is not enough of this essential ingredient either in the water, or transported there by the atmosphere in the form of dust. Starved of iron, and possibly silica as well, the plant plankton are unable to form dense "blooms". Like their equivalent on land, these blooms would take up carbon by photosynthesis. When the detritus and dead cells sink, the effect would be to remove the carbon from the surface layer. Thus the equatorial Pacific source can be understood as the combination of physical factors producing the upwelling there, and the lack of sufficient biological production to utilize all the carbon and nutrients in the upwelling water.

The figure shows us the situation in "normal" years. During El Niño events, the pattern of upwelling in the equatorial Pacific is severely disrupted; the JGOFS EqPac expeditions to the region in 1992 encountered the El Niño condition and the measurements made at the time showed the almost complete disappearance of the equatorial "bulge" in CO₂. One of the most direct effects of El Niño on the carbon cycle is thus to abruptly shut off the equatorial Pacific "exhalation" of CO₂ for a period of many

months. El Niño affects weather patterns world-wide, and the increase in storms in the Americas and drought frequency in Asia and Australasia has a substantial effect on the land-based carbon cycle as well. The overall effect on atmospheric CO₂ is complex and variable, but the initial oceanic effect at least is reasonably well understood.

The figure illustrates that the most intense sink region in the world ocean is the North Atlantic. Here too, physical and biological driving forces team up to drive the CO₂ flux, but this time in the opposite direction to that in the equatorial Pacific. The Gulf stream and North Atlantic drift transport warm water rapidly northwards, in the process cooling it and releasing heat to the overlying atmosphere. These currents act like a huge heating system for Western Europe, transporting warmth from the subtropics and releasing it to the atmosphere with a power equivalent of about a trillion kilowatts. The cooling of the surface water which this entails has the opposite effect to the heating in the equatorial Pacific, making the water more able to absorb CO₂ and enhancing its uptake substantially. In addition, the North Atlantic is biologically the most productive ocean region in the world, because of an abundant supply of nutrients. Each winter, nutrients are mixed up from the underlying water, and there is also no dearth of iron here, for nearby the Sahara desert is a huge source of dust to the atmosphere. Biological and physical factors therefore combine to enhance the ocean sink to the maximum in this region. Similarly, the other important blue-coloured sink areas in the world are all associated with zones where the ocean is giving out heat and where biological activity is moderate or high.

The gross features of the CO₂ flux map can therefore be understood as being due to natural heat transport and biological activity, processes which have been going on since before the industrial

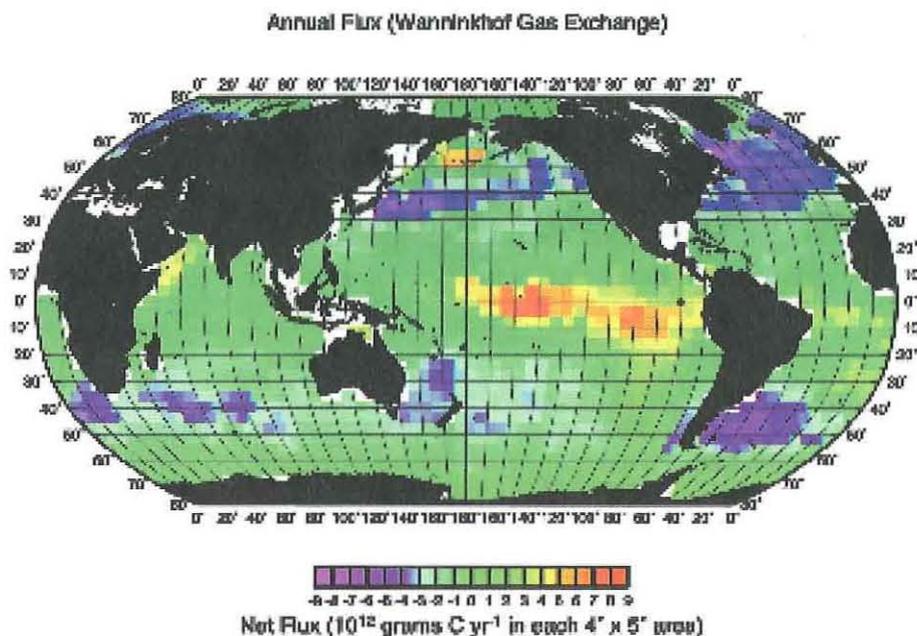


Figure 1. Mean annual net CO₂ flux over the global oceans (in 10¹² grams of C per year for each 4° x 5° area) computed for 1990 using the gas transfer coefficient formulated by Wanninkhof (1992, *J. Geophys. Res.* **97**: 7373-7382). The effect of full atmospheric CO₂ increase is assumed for normalizing observed delta pCO₂ values in high latitude areas to the reference year of 1990. Areas covered with ice are assumed to have zero sea-air CO₂ flux. [Copyright (1997) National Academy of Sciences, USA]

revolution. Where therefore is the "sink" for human-produced carbon dioxide? What has happened is that, in response to rising atmospheric concentrations, the natural source regions have become slightly weaker while the natural sink regions have become slightly stronger, leading to an overall uptake which can be assessed by accurately averaging over the entire map. In fact, in this picture most of the ocean is green – in these regions the net flux is comparatively weak and difficult to diagnose from a few measurements. In practice, local variations in temperature, biology and circulation have meant that a huge database has had to be collected to produce accurate estimates.

Assembly of the data set has added to our confidence that we have a good knowledge of the overall amount of carbon dioxide going in to the oceans, and also how this breaks down into regions and seasons. Knowledge of this is extremely valuable, and not only for studying the ocean but also the rest of the carbon cycle. For example, the annual amount being taken up or given out by vegetation on land is very poorly known, but now that we know the oceanic sink reasonably well, and because we also

know accurately how much CO₂ is produced by industrial activity, we can construct a balance sheet to work out what the land vegetation must be contributing to the overall budget. Detailed modelling of the variations seen in the atmosphere then enables us to "diagnose" the land regions where vegetation is acting as a source and where it is behaving as a sink. By this means we have discovered that the northern hemisphere forests are presently acting as a strong sink for carbon, even though there is no equivalent directly-measured map for the land sources and sinks.

As a society, we need to know how carbon dioxide concentrations will

change in the future, and to predict this it is clear we have to understand the processes driving oceanic uptake of CO₂ today. Though these are far from completely understood, the carbon dioxide data set assembled during the JGOFS programme is an absolutely essential resource with which to test our understanding of the overall "carbon system", the process which is now underway as part of the "synthesis" phase of JGOFS.

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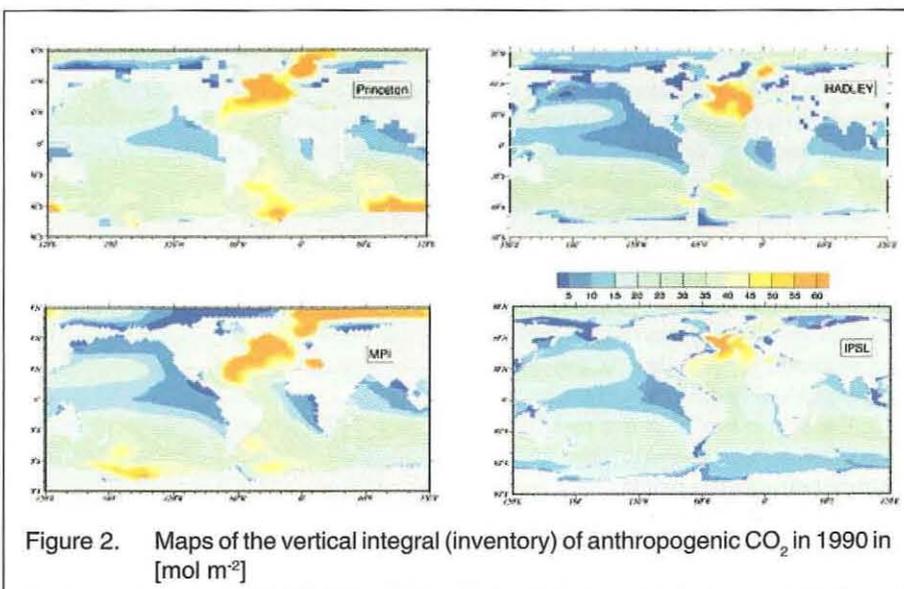
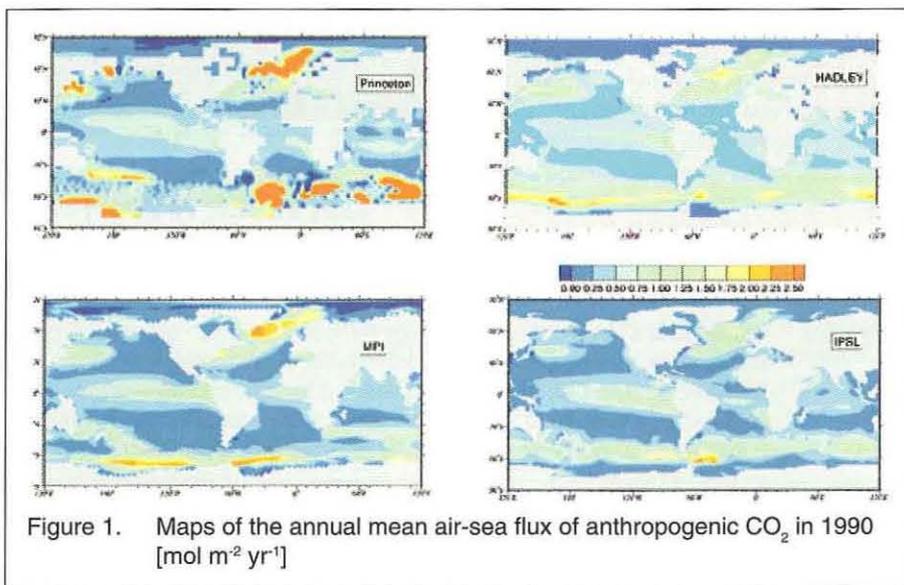
Ocean Carbon-Cycle Model Intercomparison Project (OCMIP)

by Dork Sahagian

Ocean carbon-cycle models can help synthesize our understanding of the sources and sinks of carbon in the ocean and the resulting effect on the global carbon cycle. The need to improve these models and to ultimately incorporate them into a composite description of the earth's complex biogeochemical and physical climate system motivated GAIM to launch the Ocean Carbon-Cycle Model Intercomparison Project (OCMIP). Model intercomparisons such as OCMIP are important for two reasons: (1) the basic need to compare results between models, and (2) the awareness that models improve more rapidly when resources are pooled and understanding is shared among modelling groups.

OCMIP's main interest is the carbon cycle. Hence the primary concern has been to focus on the abilities of models to predict ocean carbon distributions and air-sea fluxes of CO_2 (see also article by Watson on pages 6 to 7). The first phase of OCMIP was recently concluded (see GAIM Report No. 6, 1998), and OCMIP-2 is now underway. The OCMIP-1 strategy was to study (1) "natural CO_2 ", with simulations which were allowed to reach equilibrium with pre-industrial atmospheric CO_2 (at 278 ppm), and (2) "anthropogenic CO_2 ", with simulations forced by observed atmospheric CO_2 from pre-industrial time to present.

For the natural carbon cycle in OCMIP-1, separate simulations were run to distinguish effects due to two fundamental processes, which along with ocean circulation control the distribution of natural CO_2 . The first process relates to the temperature-dependent solubility of CO_2 . The cold waters, which fill the deep ocean from the high latitudes, are rich in CO_2 . Secondly, ocean biota act to reduce surface ocean CO_2 through the combined action of planktonic uptake, rapid transport to depth of resulting particulate organic carbon, and subsequent bacterial degradation.



These two processes are denoted as the solubility and biological pumps, respectively.

The main patterns of sources and sinks of natural CO₂ are driven by thermodynamics (heat fluxes) and to a lesser extent, changes in salinity. Thus, all solubility simulations exhibit ocean outgassing in the tropics and uptake in the high latitudes. Since the beginning of the Industrial Revolution, the rise in atmospheric CO₂ has caused the air-to-sea CO₂ flux to increase everywhere. This drift from the natural system, termed the anthropogenic CO₂ perturbation, is difficult to measure directly in the ocean. On the other hand, the four OCMIP-1 models all provided estimates of oceanic uptake of anthropogenic CO₂. Modelled ocean uptake is highest in the high latitudes and at the equator, i.e., in zones where deep waters uncontaminated with anthropogenic CO₂ communicate readily with the surface via upwelling and convection. Low fluxes are evident in the subtropics, where surface waters have had longer to equilibrate with the atmosphere. Yet, models disagree substantially about local patterns of anthropogenic CO₂ uptake. The largest differences between models are found in the vast Southern Ocean (south of 30°S), which occupies about one third of the surface area of the entire ocean. Differences are even more striking in maps of the air-sea flux of anthropogenic CO₂ (Figure 1). Three of the models show rather homogenous distributions of the air-sea flux in the Southern Ocean, but the models exhibit very different uptake patterns, both in the Southern Ocean and elsewhere. Due to ocean circulation and mixing, the inventory (vertical integral of concentration) of anthropogenic CO₂ exhibits a much smoother distribution than does the flux field of CO₂ (Figure 2). The models agree that most of the anthropogenic CO₂ is stored in the subtropical gyres, particularly in the southern hemisphere. How-

ever, predicted inventories of anthropogenic CO₂ still differ a great deal, both concerning the magnitude and location of anthropogenic CO₂ storage.

Model testing is an important part of any model intercomparison, and for evaluating ocean carbon-cycle models radioactive isotopes of carbon offer a powerful test of a model's ability to simulate deep ocean circulation. Radioactive ¹⁴C is found naturally in a small fraction of CO₂ molecules and, entering the ocean through air-sea gas exchange, can act as a tracer for deep ocean circulation. A global network of samples was established during the 1970s and subsequently extended by the World Ocean Circulation Experiment (WOCE); these data form a powerful validation tool for models.

The natural ¹⁴CO₂ concentration in the atmosphere increased sharply in the 1950s due to nuclear weapons testing, peaked in 1993, and has declined since then to about 10% greater than its natural levels. By carefully separating out the more recent "bomb" from the "natural" component of ¹⁴CO₂, researchers have been able to constrain modelled circulation of surface and intermediate ocean waters. In addition to information on ocean circulation, exploitation of the ¹⁴CO₂-¹²CO₂ relationship might provide one way of directly estimating the small anthropogenic change in dissolved inorganic carbon relative to the large pool which is naturally present.

In OCMIP-1, we demonstrated that predictions from ocean carbon-cycle models differ regionally by a substantial amount, particularly in the Southern Ocean, where modelled air-sea fluxes of anthropogenic CO₂ are also largest. The recently launched OCMIP-2 involves 13 models and additional simulations. The focus remains on CO₂, but OCMIP-2 also includes emphasis on new circulation tracers, such as CFC-11 and CFC-12, and new biogeochemical tracers such as O₂. OCMIP-2 will also in-

clude simulations with a common biogeochemical model so that participants can better study effects due to differences in modelled ocean circulation. Furthermore, OCMIP-2 includes data specialists who are leading the JGOFS and WOCE synthesis for CO₂, ¹⁴C, and CFCs, which will strengthen model validation efforts.

Studies during the first two phases of OCMIP have relied on ocean models run under present climatological conditions, where circulation patterns do not evolve with time. Beyond OCMIP-2, future work will probably focus on the impact of changing climate on marine biogeochemistry as well as the feedback of changes in marine biogeochemistry on climate. To validate such simulations, it will be crucial to focus on how well models are able to reproduce observed interannual variability. More information concerning this project can be found on the GAIM website (<http://gaim.unh.edu>) and OCMIP Web page (<http://www.ipsl.jussieu.fr/OCMIP/>).

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The LOICZ biogeochemical budget project and implications for the carbon cycle

S.V. Smith, R.W. Buddemeier and C.J. Crossland

Fundamental to answering how changes in land use, sea level and climate alter coastal ecosystems is the need to recognize that the coastal zone – the area of the Earth’s surface where land, sea and atmosphere meet and interact – is not a line boundary of interaction. It is a global compartment (Figure 1) of special significance, not only for biogeochemical cycling and processes but increasingly for human habitation.

The heterogeneity of the coastal zone severely limits our ability to realistically describe and model processes and interactions in a detailed and strictly quantitative manner and to meet all expectations of scale. By necessity, our approach must have elements which are approximate, semi-empirical, iterative and evolutionary in meeting the project goals and time frames. LOICZ is implementing an approach for evaluating biogeochemical processes for C, N and P in the coastal zone (1).

The issue of carbon and its biogeochemical cycling is central to the LOICZ approach, which seeks to provide an answer to the question – Is the coastal zone an autotrophic or heterotrophic global compartment? (2,3) [i.e., is the coastal zone a sink (or trap) for CO₂ or is it a source (or generator) of CO₂?]. Net carbon flux estimates from an array of global sites are needed to resolve if the coastal zone behaves as a sink or source of CO₂.

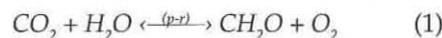
Earlier work on global budgets of carbon cycling (for example, 4) noted that organic carbon delivery from land to the ocean substantially exceeds burial of organic carbon in the ocean. Smith and Mackenzie (5) put these observations into the context of “oceanic heterotrophy, and Sarmiento and Sundquist (6) observed that this net oceanic CO₂ source should be considered in the “search for the missing CO₂” in global carbon budgets. Smith and Hollibaugh

(7) further refined the estimates of oceanic heterotrophy and argued that much of this heterotrophy probably occurs in the coastal zone. This finding remains controversial.

Although the heterotrophy argument has been supported by some researchers, other workers have argued vigorously that coastal systems are presently autotrophic. There clearly is evidence that some coastal ecosystems are autotrophic; this is to be expected in systems receiving heavy discharges of inorganic nutrients relative to organic loads.

Consequently, the subset questions of interest to LOICZ and IGBP are as follows: Globally, is the organic metabolism of the coastal zone a CO₂ source or sink? How is this net trophic status changing through both local human intervention and global environmental change? Given the extreme spatial heterogeneity of the coastal zone, what is the spatial distribution of net metabolism in the coastal zone?

The LOICZ approach to addressing the general question of coastal zone net metabolism has been directed at existing data. It was felt that insufficient time existed in the approximately decade-long expected lifespan of LOICZ to collect an adequate amount of primary data to address this question at a global scale. Moreover, it was recognized that there are very few sites around the globe with direct estimates of net carbon metabolism for the entire system. Rather, net metabolism is inferred indirectly, via relatively widely available data on nutrients in coastal ecosystems. The principle of this analysis is as follows. Net carbon metabolism can be simplistically represented by the following equation:



where (p-r) represents the difference between primary production (the forward reaction) and respiration (the reverse reaction). This difference represents Net Ecosystem Metabolism (NEM) of the system and describes the role of organic metabolism in that system as a

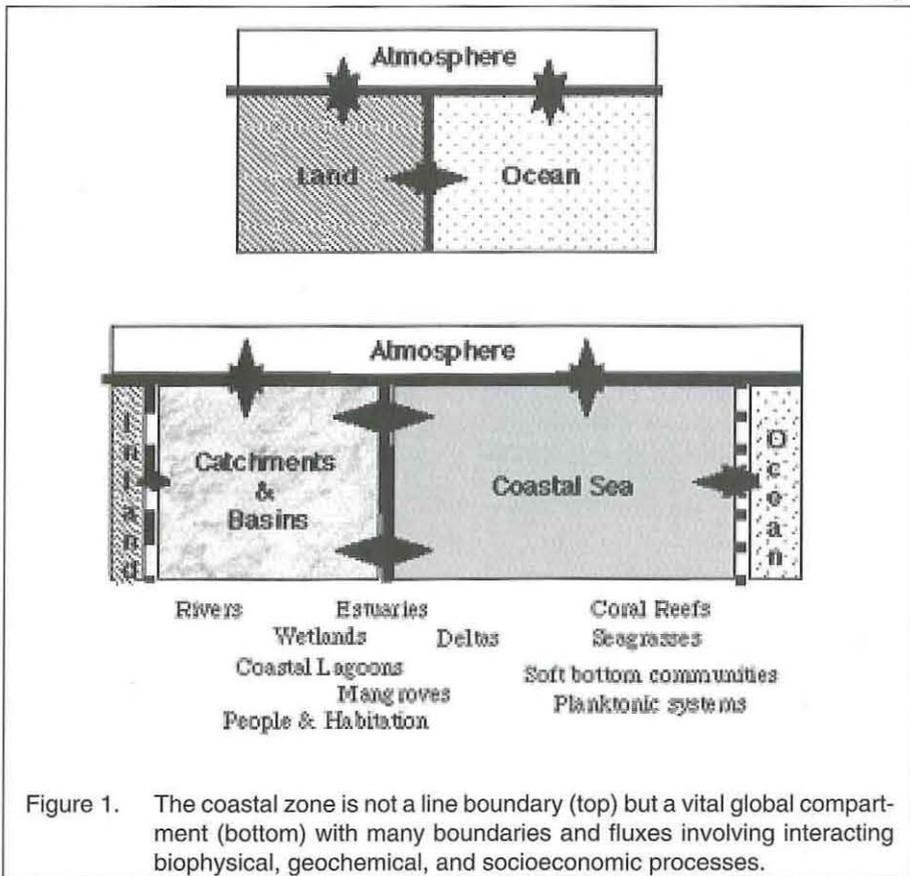
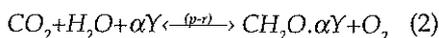


Figure 1. The coastal zone is not a line boundary (top) but a vital global compartment (bottom) with many boundaries and fluxes involving interacting biophysical, geochemical, and socioeconomic processes.

source or sink of CO₂. But the formation of organic matter via primary production also sequesters nutrients, most notably nitrogen and phosphorus, along with carbon; oxidation of that organic matter (respiration) releases nutrients. For any nutrient, Y, taken up in the ratio α with respect to carbon, equation (1) can be modified as follows:



The familiar Redfield C:N:P ratio of 106:16:1 would give a values of 6.6 and 106 for N and P respectively in planktonic systems.

Of course, equation (1) greatly simplifies reality, for three major reasons. First, use of the equation to estimate NEM requires the assumption that the forward and back reactions (that is, p and r) each are based on the same value of α. Second, it is assumed that α is known. Third, it is assumed that reactions of Y not involving this simple stoichiometry are minor.

Lacking data to the contrary, the first two assumptions (constant and known value for α) usually are addressed by the use of the Redfield ratio as discussed above. With more detail in any particular system, these assumptions can be fine-tuned. The third assumption (minor reaction rates in the system not conforming to the simple Y:C stoichiometry) is perhaps the most critical. In the case of P, inorganic sorption and precipitation reactions clearly occur. When NEM is near 0, these "non-stoichiometric reactions" probably do cause error; we do not believe this to be a serious problem when NEM is well-removed from 0. In the case of N, inorganic reactions are probably minor. However, the processes of nitrogen fixation (i.e., conversion of N₂ gas to organic N) and especially denitrification (conversion of NO₃⁻ to N₂ and N₂O gases) are likely to be of great importance in many benthic systems. Therefore, this simple stoichiometric approach clearly will not work for N in such systems.

This contrast between P and N stoichiometry leads more or less directly to the LOICZ approach. Budgets of the delivery of dissolved P and N to coastal aquatic ecosystems, minus the export of dissolved P and N from these systems, allow estimates of net dissolved N and P uptake or release by these systems. For the most part, these dissolved nutrient budgets are based on water and salt budgets to establish the advection and mixing of water in these systems. Thus,

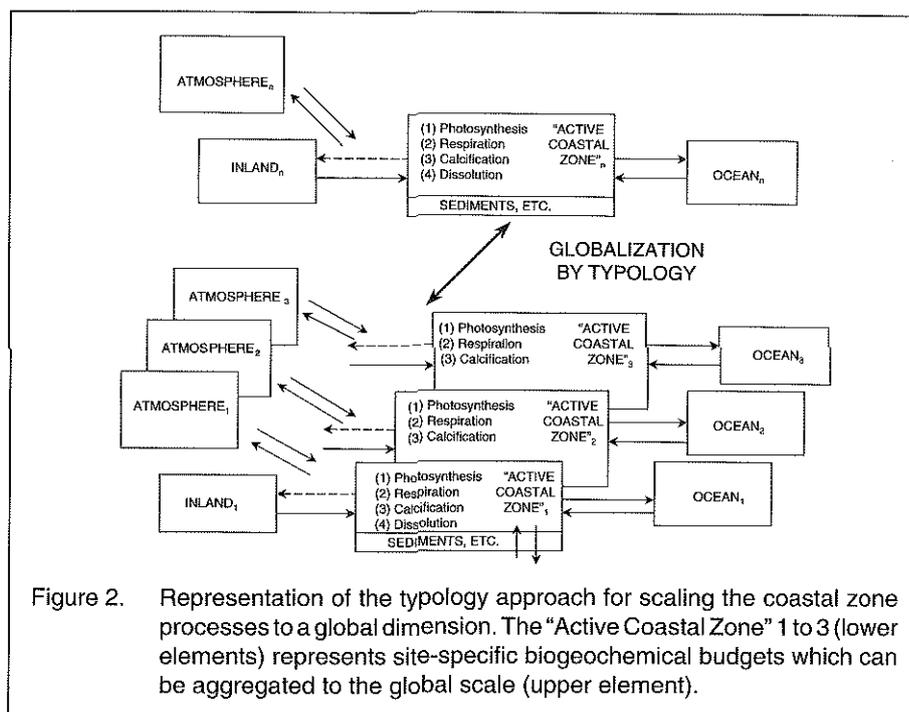


Figure 2. Representation of the typology approach for scaling the coastal zone processes to a global dimension. The "Active Coastal Zone" 1 to 3 (lower elements) represents site-specific biogeochemical budgets which can be aggregated to the global scale (upper element).

the dissolved N and P are said to "behave non-conservatively" with respect to water and salt flux. The non-conservative behaviour of dissolved P (scaled by the proportionality constant α) is used as a simple estimate of NEM. The difference between the expected non-conservative behaviour of dissolved N, according to this simple model, and the observed non-conservative behaviour is an estimate of the difference between nitrogen fixation and denitrification (nfix-denit).

Where possible, each of these rates (water exchange, [p-r], [nfix-denit]) is compared with independently obtained data; sometimes the rates are close to one another; sometimes they are not. Moreover, the estimate of NEM is compared, where possible, with primary production (p). NEM may be either positive or negative; in either case, this value is typically less than 10% of primary production. The important aspect of this last remark is that the role of the coastal zone as a source or sink of CO₂ is represented by only a relatively small fraction of the gross production of the system. This conclusion is, of course, not greatly different than the role of the open ocean. Usually less than 25% of primary production of the surface ocean is exported to the aphotic zone; this represents "export production." Of this export production, little survives the transport to the sediments; still less is permanently buried.

These biogeochemical budgets and inferred rates of net metabolism repre-

sent site-specific estimates of metabolism in the coastal zone. It is planned that, over the next two years, a total of 100-200 site-specific budgets will be derived. Results to date are posted on the LOICZ modelling home page (<http://www.nioz.nl/loicz/projects/core/biogeochem.htm>). The further challenge is to extrapolate from these sites to the global coastal zone (Figure 2). This latter problem is being approached via the development of a "typology," or classification, of the global coastal zone. Although that development is in its very early stages, initial results can be found on the LOICZ typology home page (<http://www.nioz.nl/loicz/projects/core/typo.htm>). Both the biogeochemistry work and the development of coastal typology continue to be priority areas for LOICZ activities.

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Long-term variations of the concentration of atmospheric CO₂

by Andreas Indermühle

The concentration of atmospheric CO₂ (the most important greenhouse gas after water vapour) is increasing since the beginning of industrialization from its pre-industrial value of about 280 ppmv to its present value of 365 ppmv (1, 2). In order to understand the impact of this strong perturbation on the carbon cycle and on climate it is important to investigate the global carbon cycle on all time scales. Direct measurements of atmospheric CO₂ exist since 1958. A reliable reconstruction of the concentration of atmospheric CO₂ in the past, a prerequisite for the understanding of the long-term variations, is only possible by measurements on air which is enclosed in bubbles of polar ice.

Such measurements have been done for 20 years in different laboratories with different methods. In all laboratories a sample of ice (mainly from Antarctic drill sites) of 6 to 1500 g is crushed or ground under vacuum without melt-

ing. The extracted air is then measured by infrared laser absorption spectroscopy, gas chromatography or volumetry. The analytical uncertainty is 1.2 to 5 ppmv, depending on sample size, extraction method and analytical procedure.

Mechanisms of the global carbon cycle

The main preindustrial sources and sinks of atmospheric CO₂ on a millennial time scale are the land biosphere and the ocean. In addition, ocean-sediment interactions are important processes on longer time scales.

Growth or decay of terrestrial biomass can cause a decrease or an increase, respectively, of the concentration of atmospheric CO₂. At present, the net terrestrial carbon uptake due to CO₂ and nitrogen fertilization is an important sink of anthropogenic CO₂.

The CO₂ partial pressure in sea water is mainly a function of the temperature (solubility of CO₂), salinity, concentration of dissolved inorganic carbon (DIC) and alkalinity (ALK). Changes of these properties in the ocean's surface, which is in contact with the atmosphere, translate into changes of the concentration of atmospheric CO₂ via the air-sea gas exchange. The sea surface temperature (SST) is influenced by changes of the ocean circulation or by large-scale climate transitions such as glacial-to-interglacial transitions. Sea surface salinity, DIC and ALK can be altered by dilution of the ocean surface water (by meltwater input or increased precipitation) and by changes of the ocean circulation. Furthermore, DIC and ALK can be depleted in the surface water by increased biological activity of the marine biosphere (cycling of calcite and organic matter). The biological activity depends, among other things, on the available amount of

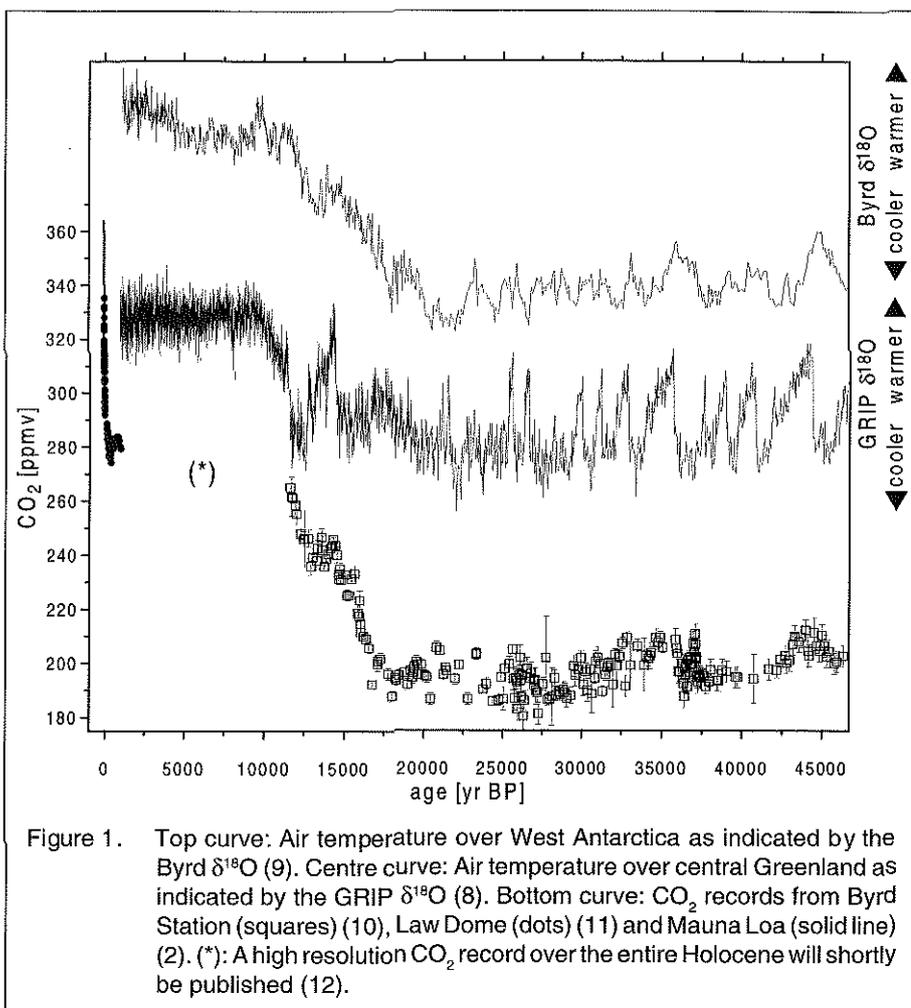


Figure 1. Top curve: Air temperature over West Antarctica as indicated by the Byrd $\delta^{18}\text{O}$ (9). Centre curve: Air temperature over central Greenland as indicated by the GRIP $\delta^{18}\text{O}$ (8). Bottom curve: CO_2 records from Byrd Station (squares) (10), Law Dome (dots) (11) and Mauna Loa (solid line) (2). (*): A high resolution CO_2 record over the entire Holocene will shortly be published (12).

nutrients, which can be varied by changes of the upwelling of nutrient-rich deep water (3).

High-resolution CO_2 records from ice cores

Figure 1 (bottom) shows high-resolution CO_2 measurements from different Antarctic ice cores, which represent with good accuracy the atmospheric CO_2 concentration. The direct atmospheric measurements from Mauna Loa are also shown. The discussion of the ice core records is divided in three parts. i) During the last glacial (until 18 kyr BP), only small fluctuations of the atmospheric CO_2 concentration of the order of 20 ppmv occur on a millennial time scale; ii) Over the transition from the last glacial maximum to the Holocene (18 - 11 kyr BP) the CO_2 concentration increases from 195 to 267 ppmv; iii) During the Younger Dryas (12.7 - 11.6 kyr BP), a cold period during the last deglaciation, CO_2 rises steadily.

Last glacial

During the last glacial, rapid changes of the air temperature in central Greenland occurred as indicated by the $\delta^{18}\text{O}$ record of the GRIP ice core (Figure 1, center). During the so-called Dansgaard-Oeschger (D-O) events, temperature increased by up to 15°C in less than 50 years and then gradually decreased and returned to full glacial conditions. The air temperature over Greenland is strongly influenced by the SST of the North Atlantic. A probable explanation of these oscillations is that the strength of the thermohaline circulation (the "conveyor belt"), which transports heat from the tropics to the North Atlantic, changed. The thermohaline circulation can be disturbed by a freshwater input resulting from iceberg discharge or melting of ice sheets. According to this hypothesis, strong perturbations of the surface water properties could develop, at least in the North Atlantic, during the D-O events, and these could influence the concentration of atmospheric CO_2 .

The comparison between CO_2 and $\delta^{18}\text{O}$ (GRIP) records suggests a link between atmospheric CO_2 and the most prominent D-O events (45 and 35 kyr BP): Slightly before or during these events the CO_2 concentration increases by about 20 ppmv followed by a gradual decrease over the next 10 kyr. The exact mechanism between the hypothesized fast changes of the thermohaline circulation and the observed CO_2 variations is still not clear. Although sparse, the $\delta^{13}\text{C}$ record of CO_2 carries some information about the origin of the CO_2 variations. This record suggests that changes in the activity of the biological pump in the ocean rather than variations in SST are the main reasons for the observed CO_2 trends.

Transition

The ~70 ppmv increase of the atmospheric CO_2 concentration between the last glacial and the Holocene has been the focus of many studies since it was first measured in Antarctic ice cores (for a summary see (4)). But each of the formulated hypotheses is in contradiction to or lacks corroboration by palaeodata. Our present knowledge is as follows:

- It is certain that the beginning of the CO_2 increase (~18 kyr BP) is before the rapid increase of the air temperature over central Greenland and elsewhere (Bølling/Allerød transition, 14.8 kyr BP).
- As indicated by the $\delta^{18}\text{O}$ data from Byrd (Figure 1, top) and the CO_2 record, it is most likely that the increase of CO_2 parallels the warming of the Southern Ocean with a lag of less than 1 kyr.

Younger Dryas

The Younger Dryas is a prominent cold period in the North Atlantic region during the last deglaciation. Similar to the D-O events, changes in the thermohaline circulation are a probable explanation for the fast cooling and warming. The atmospheric CO_2 concentration and the temperature in the high northern and southern latitudes during a YD-like event can be simulated in a circulation-biogeochemistry model and compared with climate proxies (5). In this model, ocean-sediment interactions which could have contributed to the long-term glacial-interglacial increase are not simulated. Therefore, this long-term increase is subtracted from the ice core data and then the resulting residual CO_2 is compared with the model (Figure 2,

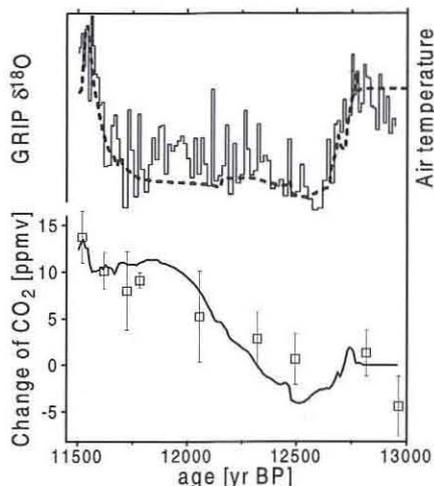


Figure 2. Younger Dryas. Top curve: GRIP $\delta^{18}\text{O}$ (8) (solid line) and modelled air temperature (dashed line). Bottom curve: Comparison of modelled changes in the concentration of atmospheric CO_2 (solid line) and residual CO_2 values from Byrd Station (squares) (5).

bottom). The residual CO_2 exhibits an increase of about 20 ppmv during the YD - in good agreement with the model. The main conclusion is that a cooling in the North Atlantic region has only a small effect on the concentration of atmospheric CO_2 because it is spatially limited and compensated by a warming in the Southern Ocean, operating much like a bipolar seesaw (6, 7).

Determination of the relation between the long-term variations of climate and concentration of atmospheric CO_2 remains a challenge. In order to quantify the contribution of the individual mechanisms to observed changes in the concentration of atmospheric CO_2 , palaeoclimatic observations with sufficient temporal and spatial resolution and with an accurate chronology are necessary.

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FLUXNET: A challenge that is becoming reality

by Riccardo Valentini, Dennis Baldocchi, and Richard Olson

The International Geosphere-Biosphere Program (IGBP) launched, in 1996, an international initiative aiming to coordinate a worldwide network of long term carbon, water and energy flux measurements over terrestrial ecosystems (1, 2). Since then FLUXNET has been growing with the addition of new sites and regional networks and a more comprehensive scientific agenda. The newest developments of FLUXNET have been paralleled by the joint cooperation of the two IGBP core projects: Biospheric Aspects of the Hydrological Cycle (BAHC), who initiated the effort, and Global Change and Terrestrial Ecosystems (GCTE), which is supporting ecological processes studies.

Over 70 scientific teams from across the world (United States, Canada, Japan, Australia, Italy, United Kingdom, France, Netherlands, Germany, Belgium, Sweden, Finland, and Denmark) are now measuring continuous and long-term fluxes of carbon, water and energy over a variety of biomes, across the globe.

Most of the research sites are associated with regional networks and are funded by local governments. The major objectives of the individual studies are to assess the annual net uptake of carbon dioxide from particular biomes, to quantify year to year differences in canopy carbon exchange and to understand the environmental and biological factors controlling trace gas fluxes. The geographical distribution of sites is presented in Figure 1.

FLUXNET is a "partnership of partnerships", formed by linking existing sites and networks. Currently AmeriFlux (North and South Americas), EUROFLUX (Europe), and MEDEFLEX (Mediterranean region) plus independent sites, participate in FLUXNET. Regional networks in Asia and Australia are under development (see Figure 2 on page 16). Measurements and terminology from existing but disparate sites and networks are brought together into a common framework and harmonized, thereby increasing substantially the usage and value of the flux data and information for the global change research community.

FLUXNET provides researchers access to consistent and integrated measurements of carbon dioxide, water vapour, and energy fluxes and associated site vegetation, edaphic, hydrologic, and meteorological characteristics. Fluxes and ancillary information are unified into consistent, quality assured, documented, readily accessible datasets via the World Wide Web (<http://www-eosdis.ornl.gov/FLUXNET/>). The collection of data from a variety of worldwide terrestrial ecosystems (including managed systems) will contribute to research on understanding how carbon, water, and nutrient cycles of terrestrial ecosystems respond to environmental and climatic perturbations, especially through the development and validation of ecosystem models and the validation of remotely-sensed products.

FLUXNET scientific agenda encompasses a range of relevant processes dealing with biosphere-atmosphere exchanges of terrestrial ecosystems and their relations with carbon and water biogeochemical cycles. These activities can be grouped into the following.

1. Cross biome comparisons of functional responses

Many key questions can be asked with data from across major biomes. Major issues are whether or not leaf-level gas exchange relations hold at the ecosystem level, which independent variables define NEE (Net Ecosystem Exchanges) and how it varies across biomes in relation to length of growing season, meteorological variables (such as sunlight, cloudiness, temperature, precipitation, humidity), leaf area index, leaf nitrogen, stand density and stand age.

Finally there is the desire to identify sensitivity relationships and controls on carbon losses and gains and water and energy exchanges. Specific questions include: How is net ecosystem carbon exchange (NEE) partitioned into gross carbon exchange (GEE), and autotrophic and heterotrophic respiration (R_a and R_h) across biomes? Do we obtain the same NEE over different ecosystems for the same reason or is the partitioning among GEE, R_a and R_h different? Do the relationships describing NEE differ depending on the time scale for which they are examined? Are relationships on daily, seasonal and yearly time scales the same?

This issue will have impact on future network design and expansion for we need information at the extremes of the scale to draw statistically robust relations, e.g. very productive (e.g. wetlands, humid temperate forests) and very unproductive (e.g. desert) ecosystems. A preliminary product on this issue can be found in Valentini et al. (3).

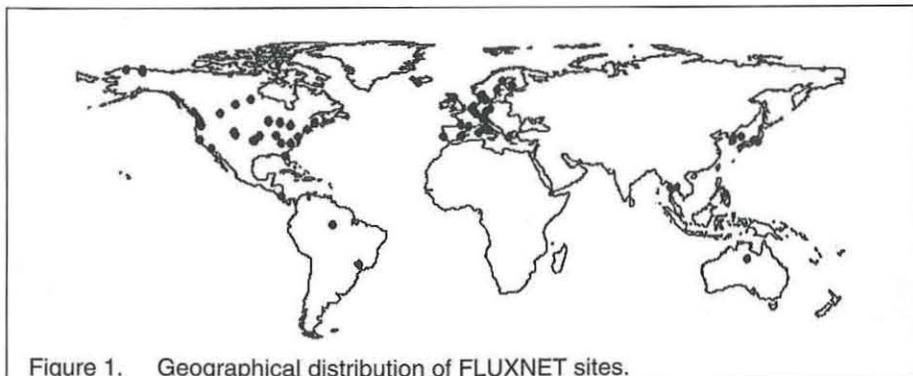


Figure 1. Geographical distribution of FLUXNET sites.

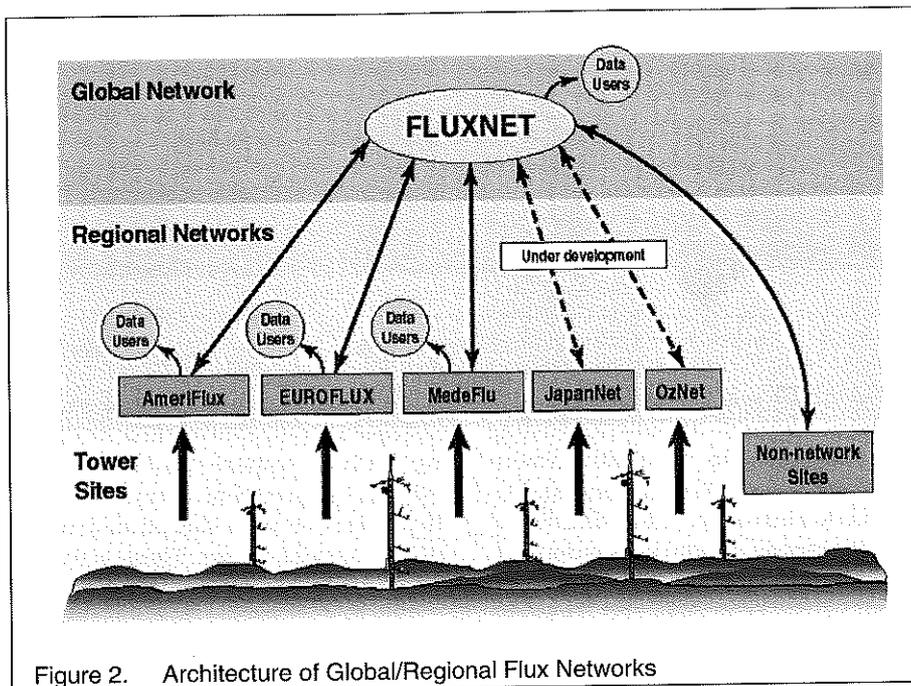


Figure 2. Architecture of Global/Regional Flux Networks

2. Inter-intra annual variation

Carbon metabolism of the biosphere shows a large year by year variation. Significant questions are: What are important driving variables of year to year differences in NEE?

To understand year to year differences in carbon fluxes there is a need to understand the constituent components of canopy carbon dioxide fluxes, photosynthesis and soil/root respiration. For example, if there is warming and NEE decreases is it because soil respiration increased or photosynthesis decreased? What is the effect of length of growing season and leaf development on carbon fluxes? What is the effect of site history on current net ecosystem exchanges, particularly in Boreal regions? These types of questions are currently discussed within the FLUXNET community (4, 5, 6).

3. Regional scaling, modelling development and testing

The eddy flux tower studies and eco-physiological measurements provide process level understanding of ecosystem function that is incorporated into ecosystem models. However, there will never be sufficient eddy flux towers or field measures to adequately characterize all terrestrial ecosystems under all conditions. Models must then be used to interpolate and extrapolate flux measurements in time and space. Hence, they are and will be a key tool for making regional and global assessments (7). A preliminary study of extrapolation of carbon flux data to the European continent was carried out by Martin et al. (8). Mechanistic ecosystem models also have the potential for predicting how ecosystems will respond to changes in atmospheric CO_2 , temperature, land use change, nitrogen loading and precipitation. FLUXNET in this respect is a unique tool for validation of models across a range of climates, biomes and time scales.

Future needs of FLUXNET are to reinforce the current strategy, maintain the long term monitoring programme, facilitate exchanges of information across components, and develop synthesis products. In particular FLUXNET can help to promote flux research stations in poorly represented regions, like Africa and to expand to include desert ecosystems, savannas, peatland and wetlands.

EUROFLUX – Studies of long term carbon dioxide and water vapour fluxes of European Forests (ENV4-CT95-0078) are funded by the European Commission Directorate General XII under the programme Environment and Climate. The project is currently in its third year of operation and it is based on 18 forest sites encompassing a range of climates going from the Mediterranean to the Boreal regions of Europe. The project is coordinated by Dr. Riccardo Valentini, University of Tuscia, Viterbo, Italy. Web page: <http://gaia.agraria.unitus.it>

The **AmeriFlux** project is running under the aegis of a number of U.S. federal agencies and offices: the Department of Energy (DOE - NIGEC/TCP/TECO), the Department of Commerce (DOC - NOAA), the Department of Agriculture (USDA - Forest Service), the National Aeronautics and Space Administration (NASA), the U.S. Geological Survey, the National Science Foundation (NSF), and the Smithsonian Institution. In addition, researchers from Canada, Costa Rica and Brazil are involved in the AmeriFlux network. AmeriFlux includes sites from tropical, broad-leaf and conifer forests, grasslands, crops, woody shrubland and tundra. The AmeriFlux program is led by Dr. David Hollinger at US Forest Service, Durham, NH. Web page: <http://cdiac.esd.ornl.gov/programs/ameriflux>.

MEDEFU is funded by the European Commission Directorate General XII under the programme Environment and Climate. The objectives of MEDEFU are to investigate the biospheric exchanges of Mediterranean ecosystems, their role in the carbon cycle and their vulnerability to climate changes. The project includes seven sites in the Mediterranean region (Portugal, Spain, France, Italy and Greece). The programme is led by Dr. Franco Miglietta, CNR - IATA, Firenze, Italy. Web page: <http://www.iata.fi.cnr.it/medeflu/minute>

JAPANET is a growing initiative in Japan which will include five sites. Relevant biospheric exchanges of carbon dioxide and water vapour, as well as other trace gases are planned in several forests, grassland and wetlands. Information can be obtained from Prof. Susumu Yamamoto: yamas@nire.go.jp

OZNET is a programme carried out in Australia where two sites are planned in contrasting land-use/cover types. OZNET is also linked with mesoscale campaigns of trace gas fluxes. Information can be obtained from Dr. Mike Raupach and Dr. Helen Cleugh: helen.cleugh@cbr.clw.csiro.au

FLUXNET receives funding from the DOE Terrestrial Carbon Program and the NASA EOS Validation Project to organize, distribute, and archive flux data from contributing networks. International workshops are sponsored to address science and data issues. Information can be obtained from Dr. Dennis Baldocchi or Richard Olson. Web page: <http://www-eosdis.ornl.gov/FLUXNET/>.

More disturbed ecosystems such as post fire regeneration, grazed lands, and logged areas need to be investigated. Further developments include the measurements of other trace gases, building on the existing flux towers.

FLUXNET's future depends strongly on its ability to attract different scientific communities and multi-disciplinary expertise. Continued IGBP support to FLUXNET is critical to maintain a high level of scientific integration between its components.

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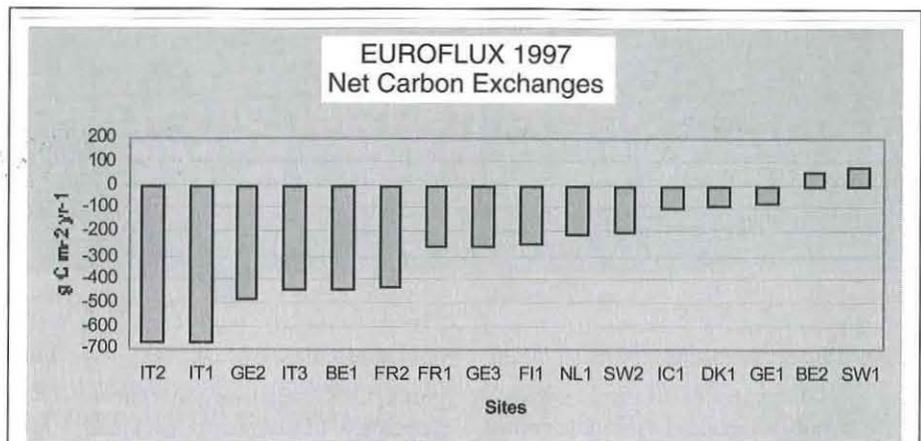


Figure 3. Long term measurements of the net carbon exchange rates of the EUROFLUX sites. Almost all of the EUROFLUX forests were sinks of carbon in 1997. Indeed the range of carbon annual uptake goes from about 600 gCm⁻²yr⁻¹ for the beech and evergreen forest in Italy to about 80 gCm⁻²yr⁻¹ for the beech forest in Denmark. There are two sources of carbon for 1997 (negative sign), they are a pine forest in Belgium (about -60 gCm⁻²yr⁻¹) and the Norunda site in Sweden (about -70 gCm⁻²yr⁻¹). These data are rather preliminary but, interestingly, it is evidence for a latitudinal trend in carbon exchange rates of different ecosystems across the European continent. (Beech = IT1, DK1, FR1; evergreen macchia = IT2; spruce = SW1, IT3, BE1, GE2, GE3, GE1; pine = FR2, NL1, SW2, FI1, BE2) (IT = Italy, FR = France; GE = Germany; BE = Belgium; SW = Sweden; FI = Finland; NL = Netherlands; DK = Denmark)

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Global transfer of carbon by rivers

by Michel Meybeck and Charles Vörösmarty

The global system of rivers is increasingly being recognized as a major component of the biogeochemistry of our planet, as demonstrated nearly 30 years ago in the pioneering work of Garrels and Mackenzie (1). Rivers indeed serve an important role in the terrestrial water cycle, regulating the mobilization and transport of constituents from the continental land mass to the world's coastal oceans. Riverine constituent fluxes arise from a complex suite of physical, biotic, and anthropogenic processes that are well-exemplified by the sources, transport, and fates of waterborne carbon. Although riverine C fluxes are a minor component of the global carbon circulation, they are very sensitive to regional and global change. Dissolved Inorganic Carbon (DIC), derived from silicate weathering and linked to tectonics, is also believed to be a major control of atmospheric CO₂ over geological time frames (2).

The basic nature of riverine carbon

Rivers carry multiple forms of carbon, including particulate organic (POC) and inorganic (PIC) carbon, dissolved or-

ganic (DOC) and inorganic carbon (DIC, generally in the form of HCO₃⁻) and dissolved CO₂. Their origins are multiple (1, 3-9) (see Table 1). This transport has been particularly studied in the 1980s for many major world rivers within the SCOPE-Carbon Programme (10). For POC the major source is mechanical erosion of carbonated rocks (i.e. limestone and loess) and of carbonaceous sedimentary rocks (i.e. shales, loess) containing highly resistant kerogens. For DIC chemical weathering of carbonate rock is also important, providing about half; the other half comes from atmospheric and soil CO₂. POC and DOC arise from leaching and erosion of topsoil and peat, as well as direct atmospheric CO₂ exchange within water bodies, regulated by pH. Organic carbon in rivers also arises from autochthonous production of organic matter in aquatic systems (POC), sometimes associated with *in situ* calcite precipitation and, more recently, direct organic waste discharge of DOC and POC from agriculture, cities, and industries.

River carbon "ages" (9), measured as the elapsed time since the initial atmospheric CO₂ uptake (see Table 1), range from a few hours for the short-term re-

gulation of dissolved CO₂ to some hundreds of millions of years for the weathering of ancient carbonate rocks. "Total Atmospheric Carbon" (TAC), of special interest for the global change research community, has been defined as the sum of dissolved CO₂, DOC, the part of DIC originating from soil CO₂, autochthonous POC and PIC, soil POC, and organic pollution (9). River TAC is thus of relatively recent age, 10⁰ to 10³ years. At the global scale riverine TAC represents only a few percent of the net primary productivity of the continents (4). The regional pattern of this fraction is not yet known – in poorly drained river basins it is probably much higher. The concentration of total riverine carbon (TC) ranges from less than 5 mg L⁻¹ for some sub-Saharan rivers devoid of carbonated rocks (e.g. Gambia) up to 800 mg L⁻¹ for the Huang He basin in China, which erodes the carbonated loess (age 50,000 yr). For basins like the Gambia, TAC/TC = 100%; for the Huang He, where mechanical erosion is maximum, this ratio is only 5% including the rarely found autochthonous PIC. TAC export rates typically vary over one order of magnitude while sediment transport rates vary over 2 to 3 orders of magni-

Table 1. Riverine carbon transfer and global change

	Sources	Age (y)	Flux #	Sensitivity to global change					
				A	B	C	D	E	F
PIC	Geologic	10 ⁴ -10 ⁸	170	1					1
DIC	Geologic	10 ⁴ -10 ⁸	140		1	1			1
	Atmospheric	0-10 ²	245		1	1			1
DOC	Soils	10 ⁰ -10 ³	200			1			1
	Pollution	10 ⁻² -10 ⁻¹	(15)?					1	
CO ₂	Atmospheric	0	(20 to 80)		1	1	1		
POC	Soil	10 ⁰ -10 ³	(100)	1					1
	Algal	10 ⁻²	(<10)				1		1
	Pollution	10 ⁻² -10 ⁰	(15)					1	
	Geologic	10 ⁴ -10 ⁸	(80)	1					1

● present global flux to oceans mostly based on (8) and (9), 10¹²gCy⁻¹

A = Land erosion; B = chemical weathering; C = Global warming and UV changes; D = eutrophication; E = organic pollution, F = basin management

tude (8-9).

There are several natural controls on C concentrations and fluxes in rivers, including parent rock lithology, soil type, climate, river flow velocity, river runoff, aquatic primary production and bacterial respiration (5) (11), UVB exposure (12), and river pH (5). Nonetheless, it has been found that river runoff acts as the prime controlling factor for carbon export, on which several of the current generation of global models have been based (13-17).

The changing nature of riverine carbon flux

There are numerous physical, geologic, biotic, and anthropogenic forces that have shaped the status of riverborne C over geologic and historical times. Since the Last Glacial Maximum the spatial organization of the continental land mass and its connection to the world's oceans has changed greatly. These changes are reflected in several geomorphometric indices, including the ratio of exorheic: endorheic land mass (flowing to oceans vs. internal drainage), rheic: arheic area (flowing vs. non-flowing), the extent of continental shelf exposed to weathering, ice cover, and land cover (13). In addition, the availability of continental runoff, which is sensitive to climate change, regulates the horizontal transport of water and hence C to the various ocean and internal receiving waters (18). Permafrost melting and leaching of post-glacial peat deposits are also major sources of DOC in Arctic rivers, highly sensitive to climate variations.

Anthropogenic change may be an especially important factor in the future, although gradual increases in atmospheric CO₂ might not themselves be critical in chemical weathering which is more related to soil pCO₂. Accelerated permafrost melting and change of UVB irradiance, which enhances DOC bacterial degradation after photolysis (12), will be key players in the future of global river C as well. In addition, land-use and land-cover changes, such as wetland filling and the decrease of organic soil carbon content through industrial fertilization of agricultural land, will be important. Land erosion will accelerate particulate carbon transfer but most of it may not ultimately reach the ocean due to storage on slopes, in floodplains, lakes and reservoirs. Lake and reservoir eutrophication may also store particulate carbon for 10² to 10⁴ years (19-22). Direct

waste emissions of organic material into rivers represents a large potential C source since the sewage treatment rate does not yet match overall population growth. However, this organic matter is mostly labile and most of it is degraded within some weeks or even days, as shown on the Seine River downstream of Paris (11). River eutrophication, now widely developed in low-turbidity, nutrient-saturated rivers, may add up to 6 mg L⁻¹ of algal POC, highly labile, which can create near-anoxic conditions when reaching turbid coastal waters like the estuaries of Western Europe. A global data base for large reservoirs has already demonstrated a "runoff aging" up to 2 years for some basins (23), which allows for more in-basin aquatic processing of riverine carbon, as well as an enhanced sediment storage, estimated now to be at least 25% of global river flux (24).

Future carbon transfers through river basins will be accelerated with respect to both sources and sinks. However, the final global trend is not yet known and the evolution of regional problems will probably show counteracting tendencies, making for an interesting and challenging global change question. A careful accounting of the key controls is now being pursued by several teams using process studies and modeling (11) as well as global GIS and multiple regression analysis where lithology, relief and runoff are key factors (13-17). A set of working scenarios for future river response to all global changes has already been proposed by R. Stallard (21), taking into account various land-use practices. New global data bases have been established or are planned within IGBP through PAGES, BAHC, and LOICZ (25) to estimate riverine carbon and allied biogeochemical constituent fluxes.

Using these IGBP activities as a focal point, several key issues relating to riverborne C could be considered. Estimates of present-day fluxes of total DOC, total POC and DIC are now converging, although the breakdown of these in various sources is still not well known (see an attempt in Table 1) nor mapped at the global scale. A hotly-debated question concerns the quantity of recycled fossil POC originating from sedimentary rocks. It has been proposed that it could constitute up to 55% of total POC flux (8, 9), and, from ¹⁴C analysis, it was estimated to be 70% in one highly eroded sedimentary basin (26). One important goal

of forthcoming riverine carbon studies could be the reconstruction of the spatial distribution of river fluxes at various periods from the last glacial maximum to the present and into the future. Direct human impacts from organic waste inputs and eutrophication on DOC, POC and dissolved CO₂ fluxes are not well known at the global scale. Although these fluxes are probably minor compared to the other TAC components (see Table 1), their impact on local oxygen balance in rivers, lakes and estuaries is enormous. A study of these fluxes is thus a legitimate part of the larger global change question, encompassing not only global biogeochemistry, but also human and ecosystem health. Current IGBP activities targeted at river case studies, process modelling, and drainage basin typologies will yield a geographically-specific picture of riverine C response to climate and anthropogenic change at the global scale and form a critical linkage within emerging Earth Systems Models (25, 27-30).

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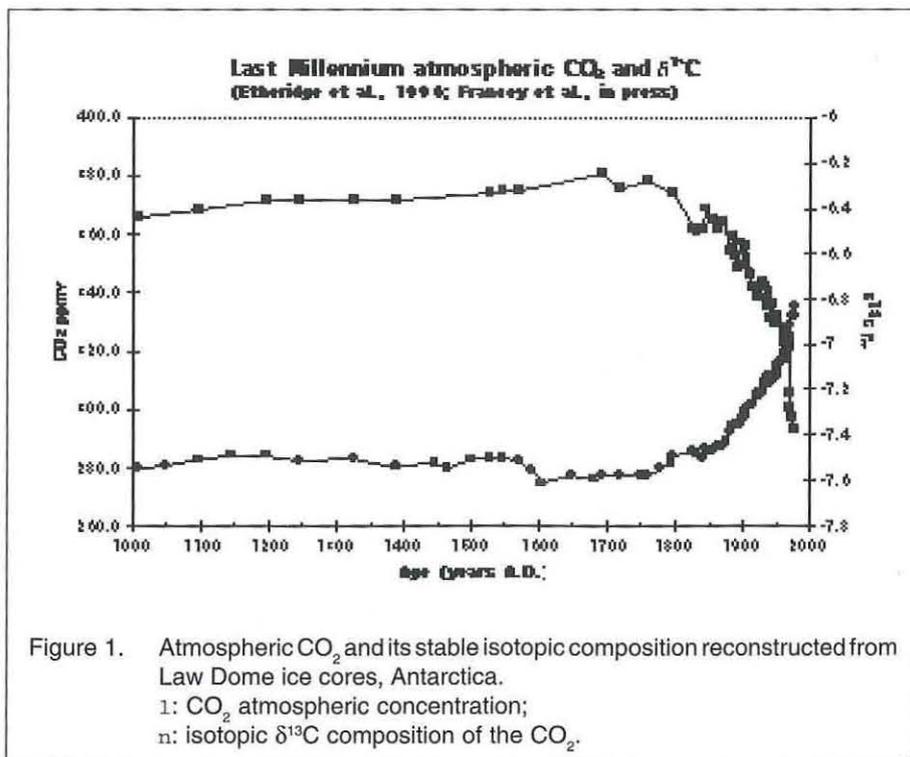
Last millennium atmospheric CO₂

by Elisabeth Michel

The first continuous measurements of atmospheric CO₂ (1) indicated that its concentration was increasing as a result of human activities. Since then, the impact of this increase on our environment, and more specifically on the future climate, has been investigated using 1-D to 3-D models of different complexity. In the 1980s, records from ice core archives of the atmospheric CO₂ and of its stable isotope composition since 1750 A.D. (2, 3) revealed the exponential increase of its concentration and the correlated decrease of δ¹³C (Suess effect). Using these records, model studies have often assumed a pre-industrial equilibrium state before 1750 A.D., with a constant atmospheric carbon dioxide concentration of 280 ppmv. However, to predict future impact of the anthropogenic perturbation on the carbon cycle, it is necessary to document past natural changes. First, this will allow us to check that models reliably represent the global carbon cycle by reproducing these changes, and second, the anthropogenic

perturbation interacts with the natural variations so it is necessary to take the latter into account to predict the future environment.

Over the Pleistocene glacial-interglacial cycles, climate and atmospheric carbon dioxide have been closely linked. Ice core records have shown that during glacial periods the atmospheric CO₂ concentration was reduced to two-thirds compared to warm interglacials (4). On a smaller scale, during the last millennium the Earth has undergone climate changes that have influenced human societies. There are now ice core records from Antarctic sites indicating that CO₂ concentrations in the air bubbles underwent changes on the order of 10 ppmv during this period (5, 6). However, ice core records are not direct atmospheric records. Beside physical processes occurring in the firn before the trapping of air bubbles, diffusion and gravitation, small CO₂ production *in situ* due to chemical reactions with impurities (7, 8, 9) possibly occurs and alters by a few



ppmv the original signal. The impurities concentrations are much lower within Antarctic than Greenland cores, so the probability of artefacts within records the last millennium records from Antarctic ice cores should be rather small.

For the beginning of this period, from 1000 to 1400 A.D., the two CO₂ records (5,6) have a lower resolution and they possibly show a different behaviour, so it is difficult to assess the real atmospheric CO₂ variations during that time. Other records would be needed to document the interesting medieval warm period. In the more recent part of the records, both indicate lower atmospheric CO₂ concentrations by up to 6 ppmv during the 17th and 18th centuries. This period corresponds to the "Little Ice Age" well documented in Europe (10). The Little Ice Age is marked by regional temperature decrease within the northern hemisphere over the continent as well as for sea surface (11, 12).

On Law Dome ice core the isotopic variation $\delta^{13}\text{C}$ of the CO₂ from the air bubbles has also been measured but with a lower resolution (13). Before the decrease since 1800 A.D. attributed to human perturbation, the isotopic record also exhibits variability. During the Little Ice Age, while CO₂ atmospheric concentration was lower by 6 ppmv, its isotopic composition was enhanced.

A global sea surface decrease during the Little Ice Age would produce a decrease of the atmospheric CO₂ but also a decrease of its isotopic composition $\delta^{13}\text{C}$ due to the temperature dependence of the isotopic fractionation during air-sea exchange.

As for the terrestrial biosphere, a lower temperature could also produce a decrease of atmospheric CO₂ due to a larger decrease for soil respiration than for net primary production. In this case enhanced isotopic $\delta^{13}\text{C}$ values would go with the lower CO₂ concentration of the atmosphere. Thus the CO₂ isotope ice record is coherent with regional cooling over the land and is not consistent with a global cooling of the sea surface temperature (13, 14).

The beginning of the CO₂ increase around 1750 A.D., as revealed by the first ice core record (2), has often been attributed to anthropogenic fossil fuel use. In the light of these new records giving the atmospheric CO₂ and $\delta^{13}\text{C}$ variations over the last millennium, it appears that the first part of the increase was rather the recovering from the Little Ice Age (14, 15), the human influence on

the CO₂ concentration of the atmosphere becoming obvious shortly before 1850 A.D.

These new data documenting the last millennium offer a great opportunity to understand the natural variability of the atmospheric CO₂ on the decadal to centennial time scale. The increasing precision of these ice core data on the more recent period gives new boundary conditions for the carbon cycle model studies. A few other higher resolution records are needed to complete our knowledge of the natural variability over century time scale, in particular to pre-

cisely document the Medieval Warm Period. The anthropogenic effects on the carbon cycle are overprinted on such variations and may interact with them, involving the land biota as well as the ocean behaviour. Thus model studies need to be able to reproduce and to take into account the natural variations when modelling the future of the carbon cycle.

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Terrestrial ecosystem responses to elevated atmospheric CO₂

by Pep Canadell

Increasing atmospheric CO₂ has effects on the metabolism and structure of terrestrial ecosystems, with subsequent associated feedbacks to the climate system. In recognition of the need to study responses of the terrestrial biosphere to elevated CO₂, GCTE established a network of field ecosystem experiments in 1992 (Figure 1). The experiments, 28 in 1999, include unmanaged and managed systems which use a variety of CO₂ enrichment technologies such as Free Air Carbon Dioxide Enrichment (FACE), open-top chambers, closed chambers, and other field enclosures. Several stud-

ies carried out on vegetation growing around natural CO₂ springs are also part of the network.

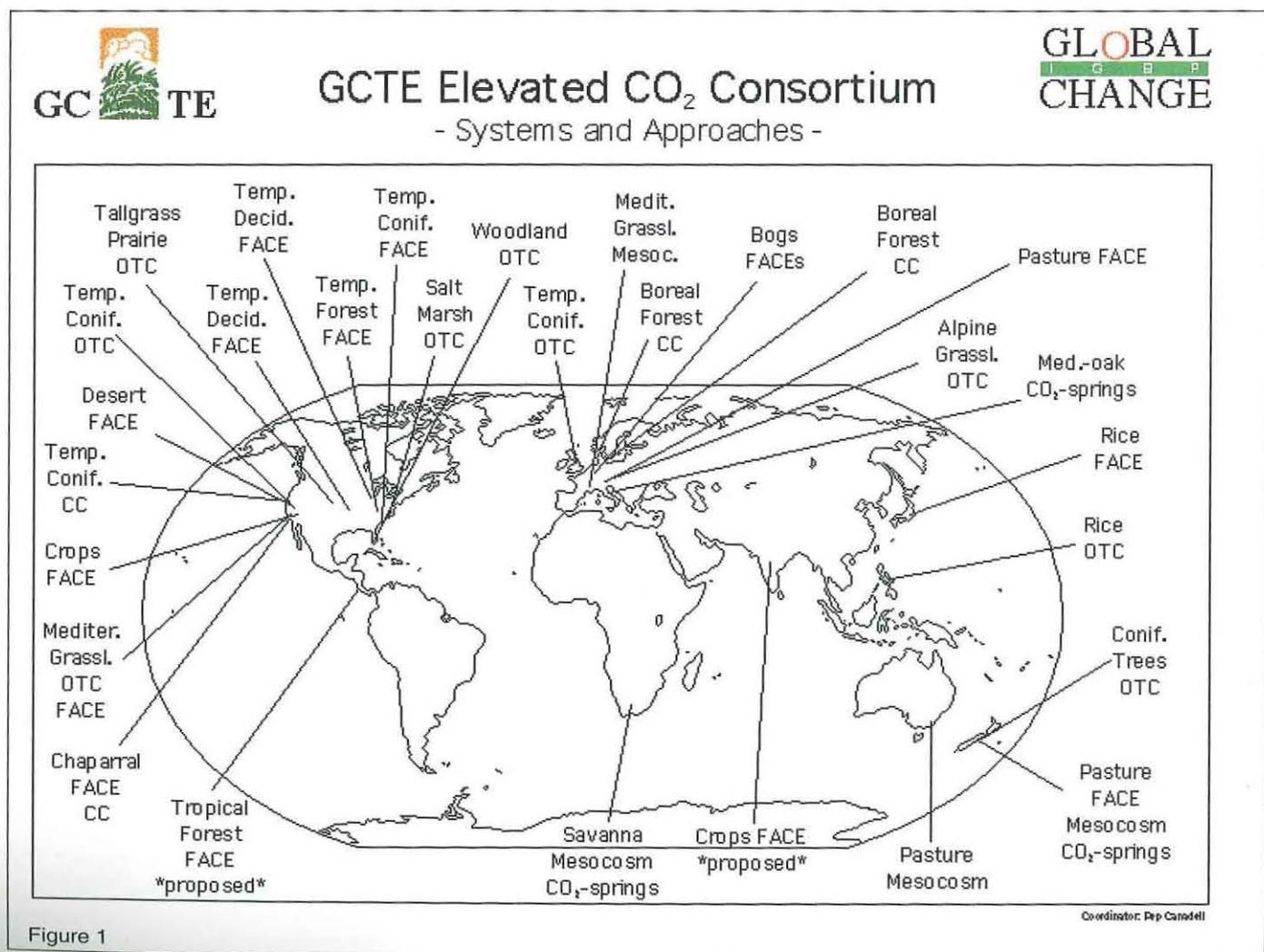
These experiments provide the necessary mechanistic and process-level understanding to test and develop ecosystem and global models. Because all experiments are confined in space (from 0.5 m² to a few 100 m²) and time (less than 10 years), there is a challenge to provide meaningful metabolic and structural information that can be used for a wide range of spatial and temporal scales.

What follows is a synthesis, based

primarily upon results from the projects of the Elevated CO₂ Network, which has been published recently in Mooney et al. (1) as part of the GCTE Synthesis.

Ecosystem carbon processes

Increased photosynthesis at the leaf-level and net canopy CO₂ uptake are probably the most consistent responses to elevated atmospheric CO₂, with values as high as 50-60%. However, grasslands growing at double ambient CO₂ showed an increase above-ground productivity



by an average of only 14%, with individual responses for a given system and year ranging from negative to positive 85%. The average increase of 14% is a much lower value than the 25-35% currently used in some biospheric models.

The wide range of the biomass results shows the highly interactive nature of the CO_2 response with other environmental factors, including water and nutrient availability, and temperature. For instance, low-temperature dominated systems, such as alpine grassland (Switzerland) and Arctic tundra (Alaska) are among the least responsive to elevated CO_2 , showing no growth response and complete acclimation after a few years of elevated CO_2 exposure in some instances.

Another strong interaction occurs between elevated CO_2 responses and soil moisture, which is commonly found in water-limited ecosystems such as Mediterranean grasslands (e.g., California and France) and tallgrass prairie (e.g., Kansas). These systems show little or no stimulation by elevated CO_2 under moist conditions, but a relative enhancement of biomass accumulation during dry years or at the end of the rainy season when soils start drying out. This interaction occurs because herbaceous species exposed to elevated CO_2 show a reduction in stomatal conductance which commonly results in increased soil moisture, and subsequent growth increase.

Less information is available on forest responses to elevated CO_2 , although a significant mechanistic understanding has been gained with the study of tree seedlings and saplings. Individuals under fertile conditions show large biomass increase under double ambient CO_2 (up to 60%) but competitive assemblages in model ecosystems show much smaller biomass response or no response in some instances. A new generation of FACE experiments has just begun to produce the first results on more mature forest stands (± 10 years old). A FACE experiment on loblolly pine stands (North Carolina, US) has shown a 16% and 19% increase in NPP over the first and second year of CO_2 enrichment (+200 ppm) respectively (2). A sweatgum FACE in Tennessee, US, showed a 19% increase in stand-level basal area during the first growing season (3). Interestingly, analysis of tree ring data from Mediterranean oaks growing around two separate natural CO_2 springs indicates that initial positive responses are gradually reduced as trees grow in size, and

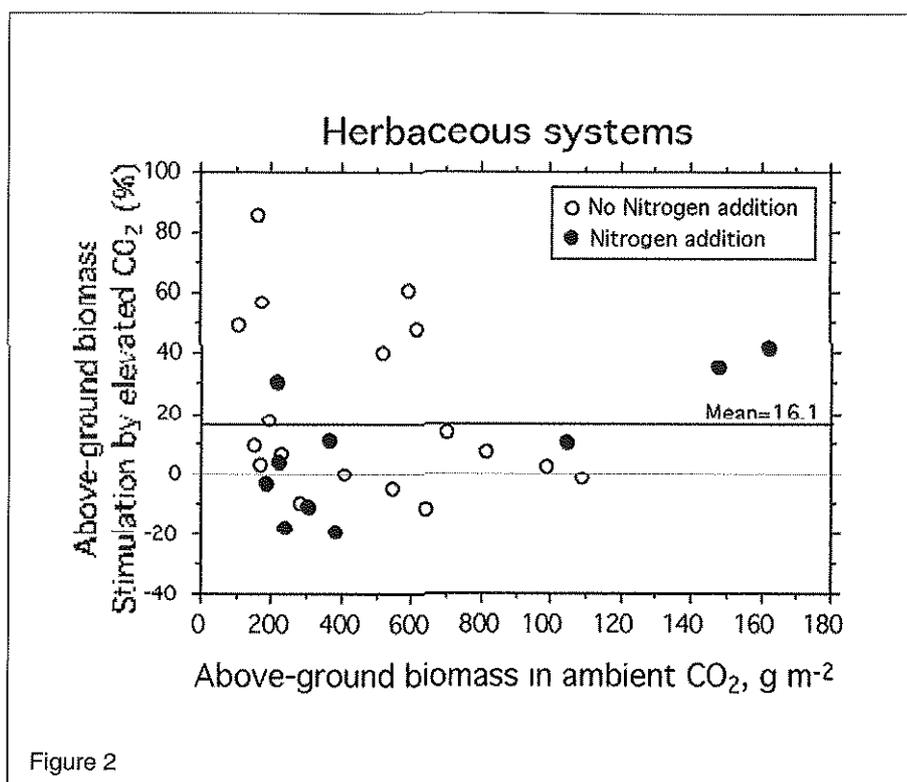


Figure 2

that the CO_2 effect is not detectable in the current-year's growth after 30 years (4). Contrary to the behaviour found in grasslands and deciduous trees, increased water use efficiency does not seem to increase in mature conifer trees, a result that has been recently confirmed for the loblolly pine FACE (5). This finding has important implications for how we model vegetation feedbacks to climate.

One of the least understood and most critical processes for future carbon fluxes is the effect of elevated CO_2 on plant respiration. Mature leaf respiration has often been reported to decrease as a consequence of the direct inhibitory effects of elevated CO_2 , although a less clear response has been found for root respiration. At the ecosystem-level, respiration either remains unchanged or increases under elevated CO_2 , the latter due to an overall increase of plant biomass.

At the ecosystem-level, one of the most critical processes to measure is net ecosystem productivity (NEP), which is the net balance between CO_2 uptake by photosynthesis and CO_2 emissions by plant and soil respiration. Only few studies have been able to measure NEP and

have shown both increases and no net carbon uptake after several years of CO_2 fumigation. Unfortunately, NEP is difficult to measure in elevated CO_2 experiments and it has not been technically resolved yet how to measure it in FACE experiments.

In the long term, changes in litter amount and its chemical composition (i.e., quality) can alter the fluxes of carbon and nutrients within the ecosystem, and hence affect plant productivity and carbon sequestration. Biogeochemical models commonly have a negative feedback on NPP due to lower litter quality produced at higher CO_2 concentrations. However, contrary to this assumption, it has been found experimentally that litter of high CO_2 -grown plants does not necessarily decompose more slowly. This is because the ratio of carbon to nitrogen in litter is no different between ambient and elevated CO_2 , despite the higher C:N in green tissues (6).

Josep Canadell
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CSIRO – Division of Wildlife and
Ecology, PO Box 84, Lyneham ACT
2602, Australia.
Email: pep.canadell@dwe.csiro.au

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6. Norby RJ, Cotrufo MF (1998). *Nature* 396: 17-18
7. For more information on the Elevated CO₂ Network visit <http://GCTE.org>
8. I thank all members of the Elevated CO₂ network for their contribution to the GCTE synthesis efforts.

Land-use change and the terrestrial carbon cycle

by Rik Leemans

During the early 1980s the global-change consequences of land-use change were often explained as the CO₂ emissions from tropical deforestation. The conversion of these forests was one of the important human sources of CO₂. Early carbon cycle models used a simple prescribed deforestation rate and emission factors to project future emissions. Land-use studies should only provide the relevant estimates.

Over the last decade, however, a much more diverse and comprehensive view on the role of land use and changes therein has been developed. This view strongly emerged after the publication of the book 'The Earth as Transformed by Human Action' (1). This book, which set the scene for the Land Use and Cover Change (LUCC) core project of IHDP and IGBP, presented many different case studies from all over the world and, from those, developed a comprehensive typology of land-use change: conversion and modification. The first is the most pronounced and directly observable: a specific land-cover class is changed into another. Tropical deforestation is a clear example. The second type involves more subtle modifications within a land-cover class. Characteristics of a land-cover type are influenced in order to increase productivity or to enhance the availability of specific species. Land degradation is an example of such modification. The book further emphasized that land-use change was not global in its actual context. Only the cumulative effect of all local and regional land-use

systems altered global systemic processes. This broad understanding led to the development of the LUCC science (2) and implementation plans (3), which focus not only on the natural-science aspects (i.e. which resources can land provide?) but also strongly on those from the social sciences and economics (i.e. how and why are these resources utilized?). Today these broad LUCC insights have become common knowledge within IGBP. In this contribution the link between these insights on LUCC dynamics and the carbon cycle will be further clarified.

Land-use change and the carbon cycle

Deforestation is still one of the most important sources of CO₂ emissions into the atmosphere. Deforestation has occurred since the evolution of early settlements and the start of agriculture but over the last decades its rate has accelerated (Figure 1). The resulting net flux from such change in land use is difficult to establish because most deforested plots are abandoned after a shorter or longer period of intensive use. In traditional shifting-cultivation agricultural systems this was common practice to sustain productivity but this pattern of deforestation and abandonment is nowadays also frequently observed in many deforested regions (5). These dynamics make the determination of carbon fluxes more complex because during forest regrowth carbon is sequestered again. If

the regional CO₂ emissions are based only on deforestation rates and not corrected for such regrowth, then the emission estimates will be much too high. Carbon dynamics also depend on the dynamics of abandonment, which are complex and depend on a multitude of socio-economic conditions and possibilities for land use, including suitability for agriculture. Such suitability can also deteriorate through longer term degradation. The actual length and intensity of the use defines the carbon that remains in the soils, and the timing of and period after abandoning defines the total carbon in vegetation. For example, if forests are converted to pastures, the soil carbon remains higher than under arable land. The actual local dynamics of sequences of land-use activities must be identified in order to scale towards regional and global process.

The evaluation of carbon dynamics under such land-use change thus requires a detailed description of activities both in time and space. Historic and current land cover and its land use have to be portrayed and changes have to be adequately monitored. The current availability of comprehensive data sets covering and integrating all these aspects is poor. This is one of the reasons that LUCC, GAIM, GCTE, and PAGES are prioritizing the development of a historic land-cover and land-use database and stimulating GCOS/GTOS to develop the necessary observation systems for monitoring land-use and land-cover change into the future. The availability of such

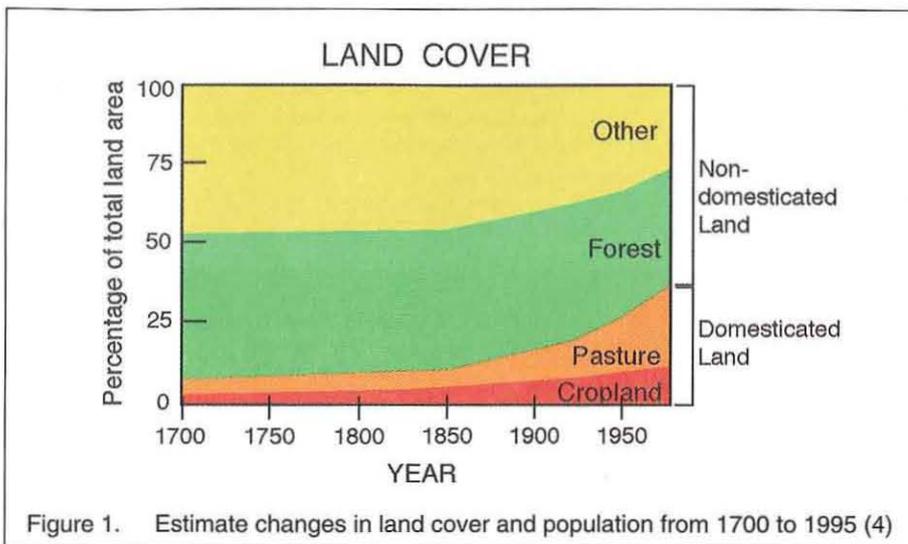


Figure 1. Estimate changes in land cover and population from 1700 to 1995 (4)

databases could also help to identify the missing carbon sink, which by many is believed to be hidden somewhere in the terrestrial biosphere.

The carbon dynamics of agricultural land are also relevant. Generally, the carbon content on soils declines under agricultural use. Only under grazing systems can the actual C-content be sometimes higher than that of the original forest. For example, conversions of marginal agricultural land to grassland, forest or wetland can increase carbon content.

The observed carbon losses in agriculture are caused by low productivity levels, inadequate fertilization, intensive tillage, removal of residuals and erosion; management is important for soil carbon dynamics. It is estimated that the application of improved management practices could sequester worldwide between 400 and 800 Mt C/yr. However, this can not be maintained for more than a century when the soil carbon becomes saturated, but it does have a significant potential for short-term mitigation of the build-up of atmospheric CO₂. This, again, strongly emphasizes the relevance of actual land-use activities for the carbon cycle. Logically, these activities are adjusted towards local and regional environmental conditions and agricultural systems, but increasingly they will need to take global environmental considerations into account.

Future land-use scenarios

IPCC is currently developing new state-of-the-art emission scenarios for its Third Assessment Report. These scenarios include emissions of all greenhouse gases and sulphur compounds from energy use, industrial activities and land use.

Besides reference scenarios (*i.e.*, no specific climate policy), specific mitigation scenarios will be developed. Although these scenarios are not yet officially published, some trends can already be observed from the IPCC review website (<http://sres.ciesin.org>), trends which include expansion of land use especially in developing regions. This expansion is much less than in most earlier scenarios. Intensification of agricultural practices

accelerates productivity, which in developing regions leads to a slow-down of agricultural expansion and in developed regions leads to an abandonment of agricultural land. The resultant, however, is still that more land will be used globally (Figure 2) and that future CO₂-emissions stemming from land use should not be neglected.

The evolving land-use patterns are strongly dependent on the assumed regional economic development, population densities, technology and consumption patterns (including diets). In general, pastures expand more rapidly than arable land and deforestation continues (Figure 2). Only in the latter half of the next century does the forested area increase again in all regions except Africa and Asia. Although there are large regional differences, these scenarios show that the expansion of arable land often results from conversion of pastures and that deforestation is driven by timber extraction (e.g. Asia) and the conversion towards pasture (e.g. Latin America). This illustrates some of the complexities in the underlying land-use dynamics. One of the important assumptions on future land use in these scenarios is fur-

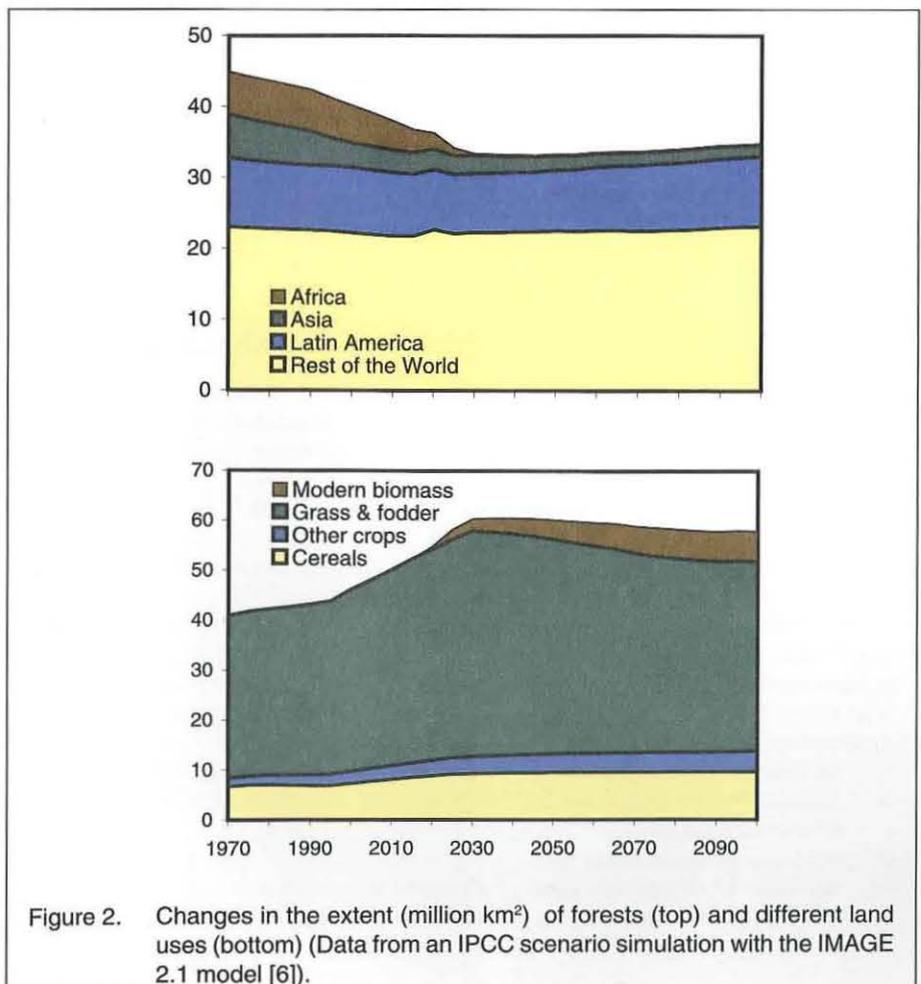


Figure 2. Changes in the extent (million km²) of forests (top) and different land uses (bottom) (Data from an IPCC scenario simulation with the IMAGE 2.1 model [6]).

ther that biomass will become a suitable commercial energy carrier, while the use of traditional fuelwoods declines. The cultivation of such biomass crops require additional land. This can be interpreted as a new type of land use competing with others. Similar changes in future land use can develop when specific carbon sequestration forests are planted as defined by the Kyoto Protocol of the UN-FCCC. Land use will respond to new needs for additional products and services.

Concluding remarks

Many studies nowadays show that land-use change is not a historic process with its most intensive peak at the end of this millennium, but that changes will continue into the future. Land use will therefore continue to exert a strong influence on the global carbon cycle. Unfortunately, it must be expected that the human use of land will become even more pronounced. This will probably reduce the total amount of carbon that is stored in the terrestrial biosphere, leaving little room for realizing the significant sequestration potential that is sought via the Kyoto Protocol.

Rik Leemans

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PAGES fellowship announcement

PAGES is pleased to announce a competition for at least three young scientists from developing countries to attend the Swiss summer school "The Dynamics of the Earth System: Processes and Records of Past Climate Change" 17.-24. July 1999. The summer school will be held in Hasliberg in the Bernese Oberland and will be coordinated by Thomas Stocker and Andy Lotter from the University of Bern. The week long program features a series of lectures by internationally renowned palaeoscientists as well as opportunities for poster presentations. Detailed information about the summer school is available from the website <http://phkup0.unibe.ch/summer/>. For scientists without access to the internet, please contact the PAGES IPO for details.

In addition to the week long summer program, it is hoped that the PAGES fellowship winners will be able to spend a week in the PAGES office in Bern making personal connections with PAGES, while at the same time raising the profile of research in their home country at the PAGES IPO. Applicants for this fellowship should send their applications materials to arrive at the PAGES IPO no later than Monday May 19th. Note that this is an extended deadline, and also a different place to submit materials than for the general summer school as listed on the website. This extended deadline is granted only to people applying for these PAGES fellowships, and is due to the relatively late announcement of this opportunity.

Application materials required for this PAGES fellowship are:

1. an abstract of your poster if you would like to present one
2. your curriculum vitae, including date of receipt (or anticipated receipt) of PhD and contact address, phone number, fax number and email if possible.
3. your list of publications
4. one letter of recommendation by a referee of your choice
5. a one page statement of why and how you would like to establish closer contact with the PAGES research community during a short stay at the PAGES IPO.

Obituary for Hans Oeschger

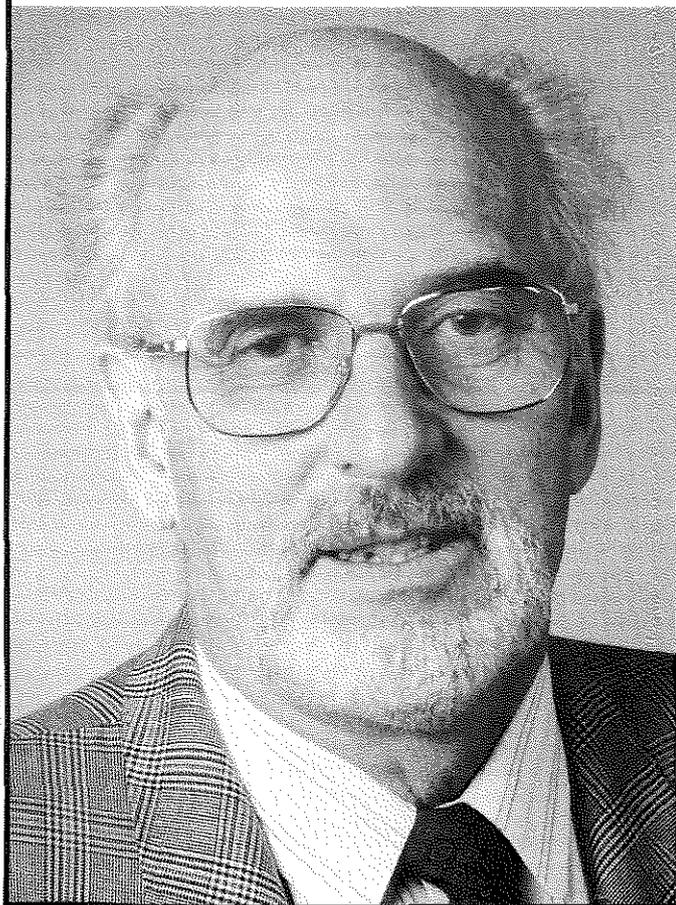
As most of the Global Change scientific community know, Professor Hans Oeschger of Bern, Switzerland, died on Christmas Day 1998. To the very last he followed with greatest interests the work of World Climate Research Programme, the International Human Dimension Programme, and the International Geosphere-Biosphere Programme for which he was a founding member. Hans Oeschger was a profound geophysicist; his science was insightful and fundamental; it was forever reaching for new knowledge and for the connections between different components of the Earth. Most importantly for Hans and for us, his scientific work and his quiet, constant, and forever effective efforts "behind the scenes" was of lasting importance to the IGBP, to the WCRP, and lately to the IHDP.

Hans Oeschger cared deeply about the changes in the Earth's environment; Global Change was not simply an area of scientific research; it was what mattered to the future. The more Hans understood about the Earth's past, the more he was concerned about its future.

In reflection, I believe that, when Hans Oeschger's younger colleague Uli Siegenthaler died, Hans redoubled all of his efforts on behalf of the science and the programmes addressing Global Environmental Change. With the loss of Hans Oeschger, our tribute to him should be to increase our commitment to understanding the Earth's changing environment and to translating that understanding into the betterment of future generations.

It is what he did; it is what he would have asked us to do.

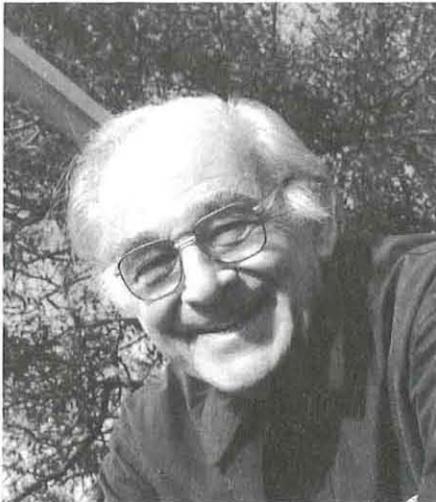
Berrien Moore III
Chair, SC-IGBP



© Photo Bucher, Bern

People and Events

New members of the Scientific Committee of the IGBP



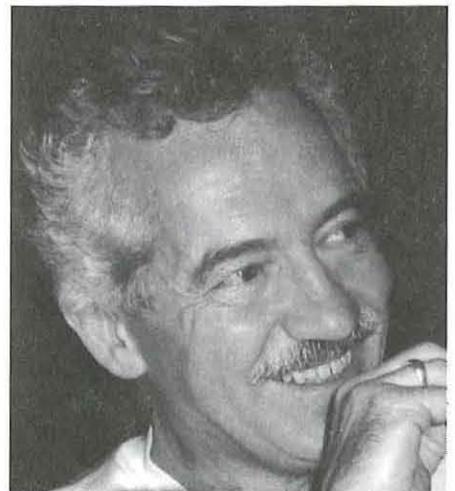
Bert Bolin

Bert Bolin is well-known in the global change community. He took part in the first assessment of the climate change issue in 1979 and led the first broad international assessment from 1983 to 1986 on request by UNEP, WMO and ICSU. He was Chairman of the IPCC from 1988 to 1997. IPCC produced its first assessment of the scientific understanding of climate change in 1990 and a supplement in 1992. In addition he was scientific advisor to the Swedish Prime Minister from 1986 to 1988 and to the vice Prime Minister from 1988 to 1991.

Subsequent to obtaining his Ph.D., Bolin worked at the University of Stockholm as Professor of Meteorology and acted from 1957-1990 as Director of the International Institute for Meteorology in Stockholm. His contributions to science have not gone unnoticed: he was awarded the Tyler Prize in 1988, the Blue Planet Prize in 1995, and an AAAS Award for International Scientific Cooperation in 1998.

Michel Meybeck is the coordinator of the new IGBP Water Group and a new member of the SC-IGBP. He is currently a senior scientist at the French National Center for Research (CNRS) and works at the University of Paris VI from which he obtained his "doctorat d'état" in 1984 and where he has been in the faculty since 1967. He has been a visiting scientist (1972-73) at the INRS-Eau, Québec Canada and at Northwestern University, Evanston, USA (1988). His research interest is in limnology, and in estuarine and river geochemistry. Working from local to global scale he raised the atten-

tion since 1979 on the global change of river fluxes. Within the GEMS-Water programme (UNEP/WHO) he has coordinated several assessments of continental water quality at the global scale and for the former Soviet Union. He is also working on the Seine river basin as an example of extreme human pressure on aquatic systems. Within IGBP he is promoting the study and typology of global river systems from atmospheric inputs to the coastal zone taking into account both direct human impacts and climate change and water uses.



Michel Meybeck



Wandera Ogana

© S. Lunter

Wandera Ogana is a Professor of Applied Mathematics and Dean of the Faculty of Science at the University of Nairobi, Kenya. He is also the Secretary of the Kenya National Academy of Sciences and a Co-Chair of the Pan-African START Committee (PACOM). His research interests are in computational fluid dynamics and mathematical modelling with applications to ecology and to global change. In collaboration with other colleagues, he recently prepared a report on the impact of climate change on fisheries resources on Lake Victoria,

with special reference to the Kenyan portion of the lake.

In addition to research, Ogana has contributed to IGBP in a number of ways. He was actively involved in the organization of the SAC-V meeting held in Nairobi last year. Together with Berrien Moore and Dork Sahagian, he helped to organize the African GAIM Modelling Workshop held in Mombasa, Kenya, in March 1997. He remains committed to promoting IGBP modelling activities in Africa.



Katherine Richardson

Katherine Richardson is Professor of Biological Oceanography at Århus University in Denmark. Originally from the USA, she obtained her Ph.D. in 1980 from the University of North Wales where she studied the role of dissolved organic material in the nutrition and survival of marine dinoflagellates. Her research interests focus on phytoplankton distribution and hydrographic features, effects of eutrophication on size distribution of phytoplankton, and oceanographic control of the *Calanus fin-*

marchicus invasion of the shelf seas.

She has served on a variety of international scientific committees, such as the ICES Working Group on Phytoplankton Ecology, the Advisory Committee on Marine Pollution, and the Living Marine Resources Panel of the Global Ocean Observing System.

14th SC-IGBP Meeting in Estoril, Portugal



© S. Lumter

From 23 to 27 February the 14th SC-IGBP was held in Estoril, Portugal, in very pleasant surroundings. The meeting was organized with the excellent help of the National IGBP Committee of Portugal, which also invited the complete SC-IGBP for a banquet with Portuguese music on the last evening. Left: during the meeting, from left to right: Chris Crossland, Han Lindeboom, Holger Hoff, Will Steffen, Berrien Moore III, Pamela Matson, and Bert Bolin. Below left: the little village of Cascais, close to the meeting site. Below right: Sofia Roger of the IGBP Secretariat and Alex Pszenny, IGAC Executive Officer, enjoying dinner after the meeting.



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IGBP Meetings

Only meetings with * are open for all scientists to attend. All other meetings are by invitation only

1999

ITASE Workshop

correlating Antarctic ice core proxy record with instrumental records
and hindcast numerical meteorological analyses for the past 100 years

April, Durham NH, USA

Contact: Ian Goodwin, SCAR - Antarctic CRC, University of Tasmania, GPO Box 252-80, Hobart, Tasmania 7001, Australia. Fax: (+61-3) 6226 7650, E-mail: ian.goodwin@utas.edu.au

LUCC Data Expert Meeting on Coastal Zones of Southern India
organized by LUCC/IGBP-DIS in collaboration with LOICZ

7-9 April, Goa, India

Contact: Veena Ravichandran, International Secretariat, COSTED, Chennai (Madras), India. Fax: (+91-44) 491 4543, E-mail: costed@giasmd01.vsnl.net.in

*BAHC Sessions on Hydrology and SVATs
at XXIV EGS Assembly

19-23 April, The Hague, Netherlands

Contact: Michael Fosberg, BAHC IPO, Potsdam Institute for Climate Impact Research, PO Box 60 12 03, 14412 Potsdam, Germany. Fax: (+49-331) 228 2547. E-mail: bahc@pik-potsdam.de

START/LOICZ/IGBP-Sri Lanka:
Workshop on Estuarine Modelling and Coastal Zone Management

28 April-1 May, Colombo, Sri Lanka

Contact: Janaka Ratnasiri, Ministry of Forestry and Environment, PO Box 1583, Colombo 00800, Sri Lanka. E-mail: janakar@sri.lanka.net

ANTIME Workshop

The problem of radiocarbon reservoir effect in the Southern Ocean

May, TBA

Contact: Ian Goodwin, SCAR - Antarctic CRC, University of Tasmania, GPO Box 252-80, Hobart, Tasmania 7001, Australia. Fax: (+61-3) 6226 7650, E-mail: ian.goodwin@utas.edu.au

IMAGES-SEAMONS

Proxies for the quantitative reconstruction of summer/winter
monsoon variability and its effects

May, Amsterdam, Netherlands

Contact: Laurent Labeyrie, Centre de Faibles Radioactivités, Laboratoire Mixte CNRS-CEA, Domaine du CNRS, Av. de la Terrasse, Gif-sur-Yvette cedex 91198, France. Fax: (+33-1) 69 82 35 68, E-mail: laurent.labeyrie@cfr.cnrs-gif.fr

Second IGBP Congress

7-13 May, Shonan Village, Japan

Contact: Sheila Lunter, IGBP Secretariat, The Royal Swedish Academy of Sciences, Box 50005, S-104 05 Stockholm, Sweden. Fax: (+46-8) 16 64 05, E-mail: sec@igbp.kva.se

GCTE Special Session at 10th ISCO Meeting

23-28 May, Purdue, USA

Contact: John Ingram, GCTE Focus 3 Office, Center for Ecology and Hydrology, McLean Building, Crowmarsh Gifford, Wallingford OX19 8BB, UK. Fax: (+44-1491) 692 313, E-mail: j.ingram@ioh.ac.uk

DAPLARCH 3 LUCC Data Organizational Needs Workshop
organized by LUCC/IGBP-DIS

May, Barcelona, Spain

Contact: Caroline Nunes, LUCC IPO, Institut Cartogràfic de Catalunya, Parc de Montjuïc, 08038 Barcelona, Spain. Fax: (+34-93) 426 7442, E-mail: lucc@icc.es

GCTE Focus 1 Workshop on How nutrient cycles constrain carbon balances in boreal forests and arctic tundra

15-18 June, Abisko, Sweden

*Contact: Peter Högberg, E-mail: peter@nana.slu.se***GCTE Focus 2.2 Workshop on Functional analysis of vegetation response to grazing**

15-17 July, Brisbane, Australia

*Contact: Sue McIntyre, E-mail: sue.mcintyre@tag.csiro.au***GCTE Session in VI International Rangeland Conference on Range management and plant functional types**

19-23 July, Townsville, Australia

*Contact: Sue McIntyre, E-mail: sue.mcintyre@tag.csiro.au***BAHC Sessions at XXII IUGG Meeting**

19-30 July, Birmingham, UK

*Contact: IUGG99, School of Earth Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK. Fax: (+44-121) 414 4942, E-mail: iugg99@bham.ac.uk <http://www.wlu.ca/~wwwiahs/index.html>***GCTE Focus 1/2 Workshop on Intercomparison of gap models and examination of how much physiology is needed in them**

July, Colorado, USA

*Contact: James Reynolds, E-mail: jfreynol@acpub.duke.edu***GCTE Soil Erosion Network: Gully Erosion**

31 July-4 August, Rio de Janeiro, Brazil

*Contact: Tony Guerra, Avenida Canal de Marapendi, 1100, apto. 608, Bloco II, Barra da Tijuca, Rio de Janeiro - RJ, CEP 22.631-050, Brazil. Fax: (+55-21) 598 3280,***START/CIRA Integrated Regional Assessment of Climate Change: Central and East European Workshop**

7-12 August, Budapest, Hungary

*Contact: CEE Workshop c/o CIRA, 248 Deike Building, University Park, PA 16802, USA. Fax: (+1-814) 865 3191, E-mail: cira@essc.psu.edu***Workshop on freshwater resources in sub-Saharan Africa with emphasis on regional scale interactions of land use and climate**

TBA, Niamey, Niger

*Contact: Michael Fosberg, BAHC IPO, Potsdam Institute for Climate Impact Research, PO Box 60 12 03, 14412 Potsdam, Germany. Fax: (+49-331) 228 2547. E-mail: bahc@pik-potsdam.de***LUCC Data Expert Meeting on Indo-Gangetic Plains organized by LUCC/IGBP-DIS**

September, New Delhi, India

*Contact: Inder Pal Abrol, Facilitation Unit, Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India. Fax: (+91-11) 581 9287, E-mail: abrol@nda.vsnl.net.in***Second International Symposium on Non-CO₂ Greenhouse Gases (NCGG-2): Scientific Understanding, Control, and Implementation organized by the Dutch Association of Environmental Professionals (VVM)**

8-10 September, Noordwijkerhout, Netherlands

*Contact: Joop van Ham, c/o VVM Section on Clean Air in the Netherlands (CLAN), P.O. Box 6013, NL-2600 JA Delft, The Netherlands; Fax: (+31-15) 261-3186; Email: j.vanham@plant.nl***Correction**

In the Global Change NewsLetter No.36 of December 1998 we reported on the SAC-V Meeting in Nairobi. In this article mention was made of the Montreal Protocol and that "the overall production of CFCs is still increasing ..." Nelson Sabogal, Programme Officer of the ozone Secretariat at UNEP, asked us to print a clarification of this:

"The overall global production of CFCs has decreased from 1986 to 1996 by 85% (see document UNEP/OzL.Pro.10/3, para.18), and the developed countries have decreased production of CFCs by 94% from over 0.9 million tonnes in 1986 to about 50,000 tonnes in 1996. The quantity of CFCs produced in 1996 were used mainly for essential uses approved by the Parties to the Montreal Protocol and for exports to developing countries to satisfy their basic domestic needs (also permitted by the Montreal Protocol).

It is the overall quantity of CFCs produced by the developing countries which has increased, by 134%, from 1986 to 1996. It should be emphasized that the developing countries will begin the implementation of their control measures in July 1999 and they will complete the phase-out of production and consumption of CFCs by the year 2010."

6th IGAC Scientific Conference jointly organized by IGAC,
the European Commission, and Consiglio Nazionale delle Ricerche
Istituto FISBAT

13-17 September, Bologna, Italy

Contact: <http://www.fisbat.bo.cnr.it/IGAC99/>

*GCTE Focus 3 Science Conference

20-23 September, Reading, UK

Contact: John Ingram, GCTE Focus 3 Office, Center for Ecology and Hydrology, McLean Building, Crowmarsh Gifford, Wallingford OX19 8BB, UK. Fax: (+44-1491) 692 313, E-mail: j.ingram@ioh.ac.uk

GCTE Focus 1 Workshop on effects of global change on fine root
physiology and turnover

19-22 October, Townsend TN, USA

Contact: Richard Norrby, E-mail: rjn@ornl.gov

GCTE Focus 2.2 and Canadian Forest Service Workshop on
Landscape fire modelling

15-16 November, Victoria BC, Canada

Contact: Mike Flannigan, E-mail: mflannig@nrcan.gc.ca

Hydrological and geochemical processes in large-scale river basins

16-19 November, Manaus, Brazil

Contact: Jean Loup Guyot, ORSTOM, CP 7091, Lago Sul, 71619-970 Brasilia DF, Brazil. Fax: (+55-61) 312 5881, E-mail: jean.guyot@apis.com.br

DAPLARCH 4 LUCC Data Systems Workshop
organized by LUCC/IGBP-DIS

December, Barcelona, Spain

Contact: Caroline Nunes, LUCC IPO, Institut Cartogràfic de Catalunya, Parc de Montjuïc, 08038 Barcelona, Spain. Fax: (+34-93) 426 7442, E-mail: lucc@icc.es

*4th LOICZ Open Science Meeting

TBA, Bahia Blanca, Argentina

Contact: LOICZ IPO, NIOZ, PO Box 59, NL-1790 AB Den Burg, Netherlands. Fax: (+31-222) 369 430, E-mail: loicz@nioz.nl

2000

*JGOFS Science Conference

13-18 April, Bergen, Norway

Contact: Roger B. Hanson, JGOFS IPO, Centre for Studies of Environment and Resources, University of Bergen, High-Technology Centre, N-5020 Bergen, Norway. Fax: (+47-55) 58 96 87, E-mail: Roger.Hanson@jgofs.uib.no

JGOFS SSC Meeting

11-12, 19 April, Bergen Norway

Contact: Roger B. Hanson, JGOFS IPO, Centre for Studies of Environment and Resources, University of Bergen, High-Technology Centre, N-5020 Bergen, Norway. Fax: (+47-55) 58 96 87, E-mail: Roger.Hanson@jgofs.uib.no



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