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Understanding and managing the global carbon cycle

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Summary

1 Biological carbon sinks develop in mature ecosystems that have high carbon storage when these systems are stimulated to increase productivity, so that carbon gains by photosynthesis run ahead of carbon losses by heterotrophic respiration, and the stocks of carbon therefore increase. This stimulation may occur through elevated CO_2 concentration, nitrogen deposition or by changes in climate.
2 Sinks also occur during the 'building' phase of high carbon ecosystems, for example following establishment of forests by planting.
3 New methods have been developed to identify biological carbon sinks: ground based measurements using eddy covariance coupled with inventory methods, atmospheric methods which rely on repeated measurement of carbon dioxide concentrations in a global network, and mathematical models which simulate the processes of production, storage and decomposition of organic matter. There is broad agreement among the results from these methods: carbon sinks are currently found in tropical, temperate and boreal forests as well as the ocean.
4 However, on a global scale the effect of the terrestrial sinks (absorbing 2–3 billion tonnes of carbon per year) is largely offset by deforestation in the tropics (losing 1–2 billion tonnes of carbon per year).
5 The Kyoto Protocol provides incentives for the establishment of sinks. Unfortunately, it does not provide an incentive to protect existing mature ecosystems which constitute both stocks of carbon and (currently) carbon sinks.
6 Incentives would be enhanced, if protection and nature conservation were to be part of any international agreement relating to carbon sinks.

Key-words: carbon sinks, carbon sequestration, Kyoto Protocol, Plan Vivo

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Introduction

Environmental change on a global scale became a matter of public concern in the 1960s. Before then, the more widely perceived environmental problem had been urban pollution, which affected human health and the quality of life of so many people, but only on a local scale. The perception that the environment is changing rapidly at the global scale as a result of human actions is relatively recent. In the 1960s I was one of many people who read Rachael Carson's book, *Silent Spring* (Carson 1962). It drew attention to the long-range transport of harmful chemicals, and inspired a generation of environmental scientists and ecologists to investigate such things in a scientific manner. The debate was fuelled in 1972 by two notable publications: *The Limits to Growth* (Meadows *et al*. 1972) and *The Blueprint for Survival* (Goldsmith *et al.* 1972). It was not only scientists who were concerned about global change. The issue became part of the political agenda, and the status of ecology as a scientific discipline as opposed to a political movement seemed jeopardised. In the same year there was a meeting of Heads of Government in Stockholm, organized by the United Nations Environmental Programme, to discuss environmental issues (one of the key events listed in Appendix 1). Attention was drawn to the acidification of lakes and rivers, global warming caused by trace gases, the destruction of the ozone layer, likely deficits in the supply of food and resources, destruction of rain forest, changes in land use (resulting in species extinctions), biological invasions, and the imbalance in the natural cycles of many of the elements (notably nitrogen and carbon).

By the 1980s and 1990s it was clear that ecologists ought to be addressing such issues, and at a large scale.

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This change in emphasis was marked by the launch of a number of ecological journals dealing with large-scale phenomena, such as *Ambio*, *Global Change Biology* and later, *Ecological Applications*, complementing those already flourishing in the geophysical sciences. By the late 1980s interest in climatic warming had become intense. The Intergovernmental Panel for Climate Change (IPCC) was founded in 1988 to provide expert advice to governments and policy-makers. The inauguration of the International Geosphere-Biosphere Programme (IGBP) in 1992 was an important milestone, enabling international co-ordination of the scientific effort. In 1992 the political leaders of the world met in Rio de Janeiro to set out an agenda to address the environmental, economic, and social challenges facing the international community. Two years later, the United Nations Framework Convention on Climate Change came into force, aimed at stabilizing atmospheric concentrations of greenhouse gases at a level that would prevent human-induced actions from leading to 'dangerous interference' with the climate system. In 1997 the Kyoto Protocol was unveiled; dealing predominantly with greenhouse gases, it was the largest and most ambitious piece of environmental legislation ever seen.

If we are to use scientific principles to manage the planet's biogeochemical cycles, we do have to be very sure of our grounds. The cycles as they appear in text books are invariably incomplete and the fluxes are uncertain. More importantly, they interact in ways which we are only now beginning to understand. Moreover, the observational requirements to capture the knowledge are considerable and expensive; at least comparable to that of establishing the global meteorological network.

The carbon cycle (Fig. 1) has received particular attention because 60% of the observed global warming is attributable to the increase in carbon dioxide concentration from about 280 µmol mol^{-1} in the pre-industrial period to today's 360 µmol mol^{-1}. In fact, the realization of a rising trend in the carbon dioxide concentration of the atmosphere seems to have first been made as long ago as 1896 by Swedish chemist Arrhenius. He measured the concentrations of CO_2 in the ocean and atmosphere, and noting that the ocean had a slightly lower concentration than the atmosphere he inferred the presence of an ocean sink. Modern recording of the atmospheric CO_2 signal was started in 1958 by Charles Keeling of the Scripps Oceanographic Institute in the USA. These data are of paramount importance. They were first used to demonstrate that only about half of all the CO_2 emitted from fossil fuel burning remains in the atmosphere, and by inference,

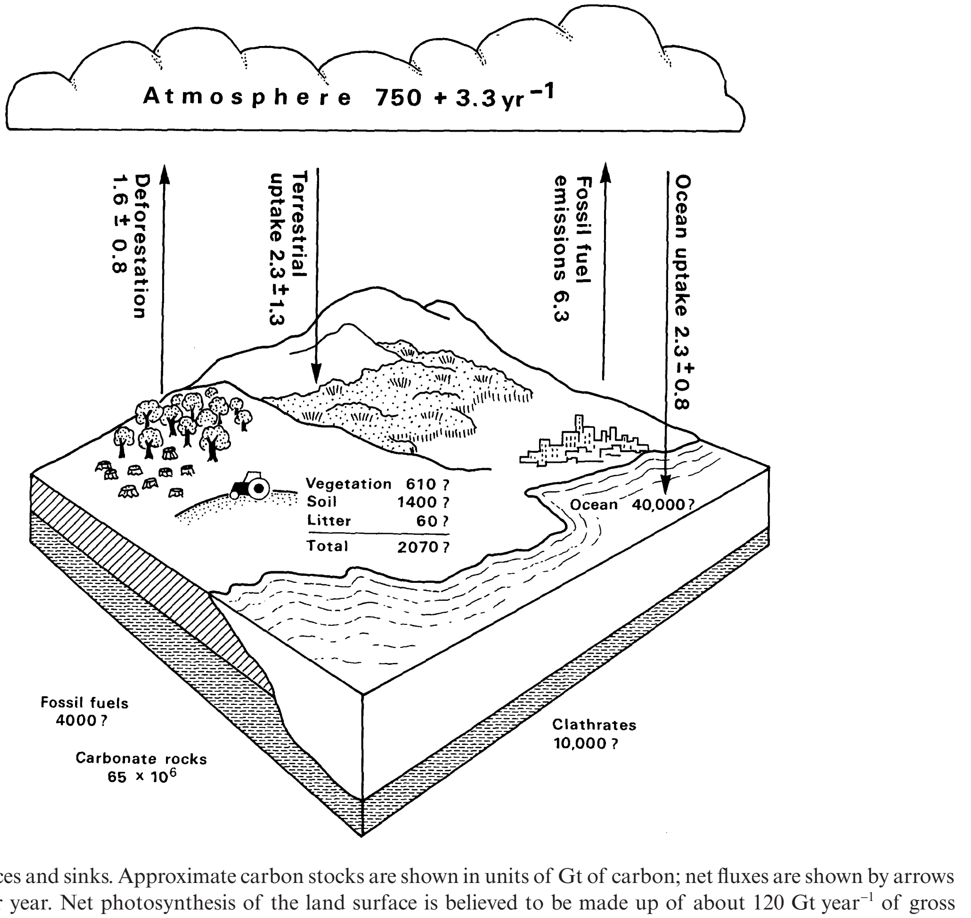

Fig. 1 Carbon sources and sinks. Approximate carbon stocks are shown in units of Gt of carbon; net fluxes are shown by arrows in Gt of carbon per year. Net photosynthesis of the land surface is believed to be made up of about 120 Gt year^{-1} of gross photosynthesis and about 60 Gt year^{-1} of autotrophic respiration, whilst heterotrophic respiration ('decomposition') is about 60 Gt year^{-1}. The sinks shown in the diagram are consistent with inferences from atmospheric concentrations, and calculations referred to later in this article.

that there must be carbon 'sinks' in the ocean or on land. It was later observed that this airborne fraction varies from year to year, and the interannual variability is associated with variations in the climate, particularly those caused by El Niño and major volcanic eruptions (Keeling *et al.* 1995). The records also show the annual seasonal draw-down of carbon dioxide caused by photosynthesis in the northern hemisphere, demonstrating the importance of the biota in the carbon cycle.

One of the most important questions that we face today is how to prevent the relentless rise in the atmospheric concentration of CO_2 and other greenhouse gases which collectively cause climate warming. Global Circulation Models (GCMs) point to the dire consequences of continuing CO_2 emissions at their present rate (IPCC 2001), and provide an increased motivation for making GCMs more realistic. Although these models are still rudimentary in their representation of several important issues (cloud formation, global photosynthesis and respiration, and feedbacks), they provide a 'crow's nest' view of what may be on the horizon for humankind. The conclusion from these models is that global climate change poses a substantial threat, as many food-producing regions are vulnerable to drought and much of the world's human population is vulnerable to natural disasters involving extreme weather. Moreover, the rate of change of temperature will be too fast for many species to adapt or migrate. Already, there are demonstrations of this from alpine regions where temperature increases have alarmingly been faster-than-average (Nagy *et al.* 2003).

Integrated research on the carbon cycle had been stimulated by an early controversy surrounding the question of whether the global biota is a source or a sink of carbon. This controversy raged over 20 years ago, mostly in the pages of *Science*. Woodwell *et al.* (1978) claimed that as a result of human disturbance, the terrestrial ecosystems were a net source of carbon to the atmosphere, but Broeker *et al.* (1979) thought otherwise, and drew attention to the disparity between the known emissions of CO_2 and the much lower rate at which the gas appeared in the atmosphere. He spoke of the 'missing CO_2'. Moreover, Ralston (1979) suggested that Woodwell's estimate of deforestation had been much too high and careful carbon book-keeping by Houghton *et al.* (1983) proved the point. Later papers of Tans *et al.* (1990) and Siegenthaler & Sarmiento (1993) consolidated our knowledge and provided the foundation of work over the next decade. Simply put, of the 7–8 Gt C emitted annually by burning fossil fuels and removing forest, only about 3 Gt C appeared in the atmosphere (1 Gt = 1 Gigaton = 1 billion tons = 10^9 tons = 1 Petagramme = 1 Pg = 10^{15} g). Of the remaining 5 Gt C some 2 Gt C was dissolved annually in the ocean (according to models), still leaving 2–3 Gt C unaccounted for, and presumed to be absorbed by the terrestrial ecosystems of the world. The important question was, where? In the early 1990s the search for the 'missing sink' gathered pace.

Land-based measurements of the terrestrial carbon sink

EDDY COVARIANCE

Eddy covariance is a micrometeorological technique that measures the total exchange CO_2 and H_2O at the ecosystem scale. There were early eddy covariance systems for measuring fluxes of water vapour, but in the 1990s reliable fast-responding CO_2 analysers became widely available and in several centres the technique was developed to measure CO_2 fluxes. Eddy covariance provides an opportunity for researchers to determine whether particular ecosystems are sources or sinks of CO_2. Previously, that had scarcely been possible. For typical conditions, with the sensor mounted on a tower above a forest canopy, the area 'seen' by the sensor is 0.1–1 km^2 (Aubinet *et al.* 2000). The resulting flux of carbon dioxide is called the Net Ecosystem Exchange or Net Ecosystem Productivity (abbreviated NEE or NEP), and it really is our best estimate of the extent to which the ecosystem is removing carbon from the atmosphere.

NEP is related to the familiar ecological terms Gross Primary Productivity (GPP) and Net Primary Productivity (NPP), but more readily measured than both of them. The overall flux, NEP, has familiar constituents: the photosynthetic rate; P, respiration rates by plants, R_p; and respiration rates by heterotrophs, R_h:

$$\mathrm{NEP} = P - R_p - R_h$$

$$\mathrm{NPP} = P - R_p$$

$$\mathrm{GPP} = P$$

Generally, a flux site has ancillary measurements of 'soil respiration' and leaf, stem and root gas exchange using chambers or some other type of enclosure, with inventory measurements of plant growth, so that NEP may be disaggregated to obtain NPP and GPP.

There are important limitations to the eddy covariance technique. The underlying micrometeorological assumptions require turbulent airflow over large flat areas of more-or-less homogeneous vegetation, and thus preclude use of these techniques in many areas of ecological interest. Moreover at the global or regional scale there are disturbances including fire and harvesting which operate over long time scales and effectively reduce the carbon sink well below what we measure as NEP. For example, in Canada there are some years where biomass burning releases almost as much carbon dioxide as that from fossil fuel burning. Using the symbol D to indicate the disturbance flux, we may define the Net *Biome* Production (Steffen *et al.* 1998) which more properly represents the C flux at larger spatial and temporal scales (10 to several 10^6 km^2 and decades or centuries):

$$\mathrm{NBP} = P - R_p - R_h - D$$

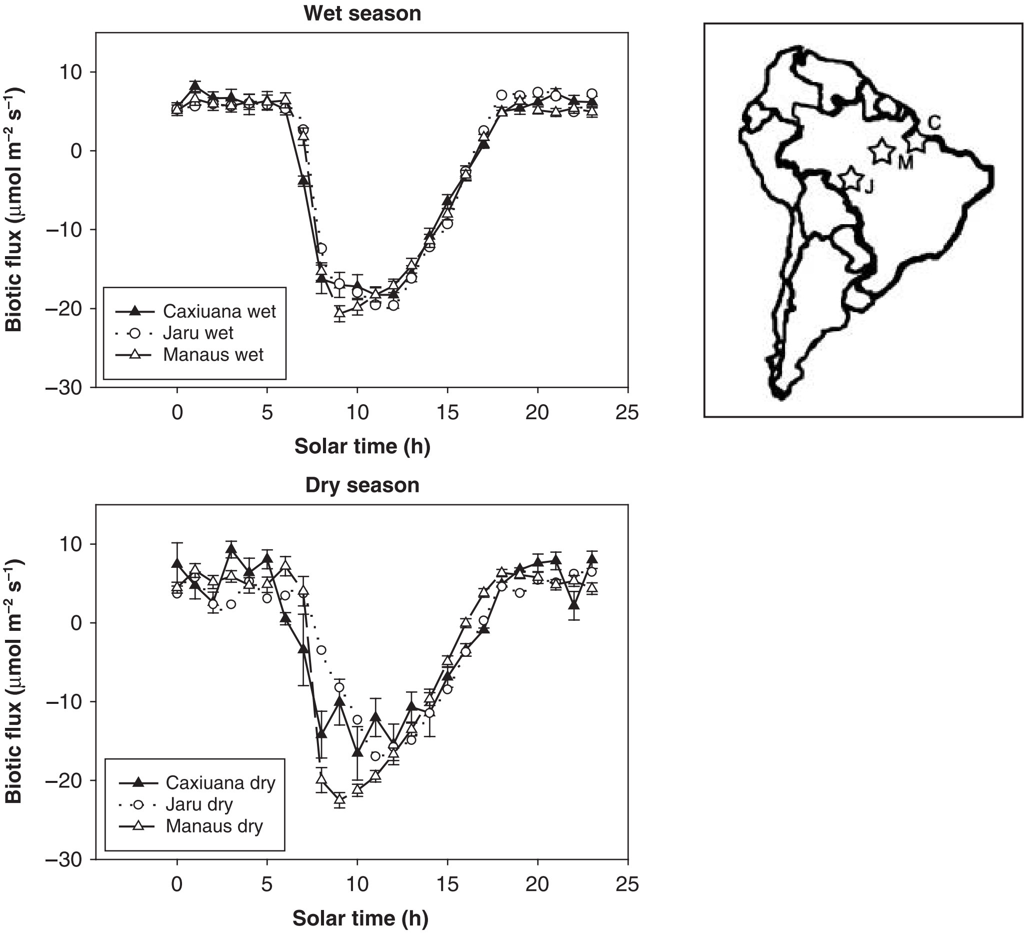

Fig. 2 Fluxes of CO_2 over three rain forests in Amazonia: Caxiuana (north-east), Manaus (central) and Jaru near Ji Parana (south-west). The fluxes are given as biotic flux (the NEP has been corrected for storage of CO_2 in the canopy). Sign convention: negative denotes uptake. Each site is represented by data obtained over many days representing the wet and dry seasons. Bars are standard errors. Overall, all three sites show more uptake than loss, i.e. they are carbon sinks. (Reproduced with permission from Andreae *et al.* 2002.)

A great strength of the eddy covariance technique is that it allows us to model the sensitivity of the carbon fluxes of a given ecosystem to changes in the environmental variables, a prerequisite for modelling, scaling-up and prediction (Lloyd *et al.* 1995; Williams *et al.* 1998). It also provides insights into the eco-physiological controls, which is particularly important as the H_2O flux may be used to estimate the canopy stomatal conductance. Moreover, it is possible to monitor sites more or less continuously for periods of several years to explore interannual variability (Lindroth *et al.* 1998) and to use a global network of hundreds of flux towers deploying the same (or equivalent) instrumentation (Falge *et al.* 2002).

Eddy covariance measurements of CO_2 fluxes over undisturbed tropical forests in three parts of the Amazon, all presumed to be climax forests, show them, remarkably, all to be carbon sinks (Grace *et al.* 1995; Malhi *et al.* 1998; Andreae *et al.* 2002; Fig. 2). This does not of course mean to say that every rain forest is necessarily behaving as a sink (Saleska *et al.* 2003), nor does it mean that the observed sink is necessarily a consequence of elevated CO_2 as most people would presume. We may be witnessing a response to trends in rainfall, for example, or some other trend in climate (for example, Nemani *et al.* 2003 calculate that net primary production on a world scale has increased by 3.4 Gt of carbon over 18 years as a result of changes in solar radiation, precipitation and rainfall).

Such data remain somewhat controversial because there are still some uncertainties in the eddy covariance technique (Kruijt *et al.* 2004). However, there are other, more traditional techniques that may be brought to bear on the problem. Repeated inventory data from the above-ground component of the biomass (excluding soil organic matter) also suggest that Amazonian forests are usually carbon sinks, up to about 3 t C ha^{-1} year^{-1}, but on average 0.5–1 t C ha^{-1} year^{-1} (Phillips *et al.* 1998).

We may contrast the rain forest with managed forests. Forests that are actively managed, such as those in Europe, are of course very likely to be carbon sinks, as they are maintained in their building phase. Valentini *et al.* (2000) measured the C fluxes by eddy covariance over middle-aged (20–80 year old) European forests and demonstrated a latitude-dependent CO_2 flux, from a sink of 6 t C ha^{-1} year^{-1} in Italy to a small source in Sweden (where the forest was on an organic soil which had been drained). Other data sets, perhaps unsurprisingly, show managed forests to be sinks. A more interesting analysis would include the off-site decomposition of forest products. The true sink strength would be approximately equal to the rate at which carbon accumulates in the soil plus any long-lived forest products, for example structural timber.

Most analyses of ecosystem carbon fluxes are inevitably incomplete. For example, all vegetation emits volatile organic compounds (VOCs) which require an additional measurement system to that used for CO_2 fluxes. There are many kinds of VOCs. For instance, conifers are well known for their production of a range of terpenes which give them their characteristic 'fresh' smell beloved of manufacturers of air-fresheners and deodorants, but isoprene (C_5H_8) is quantitatively more significant and, in terms of global carbon fluxes may be as much as 1% of the respiratory flux (Guenther *et al.* 1995).

In evaluating terrestrial carbon sinks, it is the decomposition of the soil organic matter that is least understood and the most difficult to measure and model. Most models assume a standard temperature sensitivity based on laboratory experimentation (Lloyd & Taylor 1994; Cox *et al.* 2000), but this does not explain the singular lack of variation in soil respiration rate observed across Europe or in the tropics (Liski *et al.* 1999; Giardina & Ryan 2000; Grace & Rayment 2000). More probably, when viewed over long periods of time, the soil respiration is a constant fraction of NPP, being controlled at the larger scale by the quality and supply of organic matter. There is undoubtedly a recalcitrant fraction that is resistant to decay as a result of its chemical composition, and perhaps there is an occluded fraction which does not decay because it is associated with clay or minerals, and protected by the ped structure of the soil.

Atmosphere-based measurements of the terrestrial carbon sink

Larger scale estimates of carbon sinks may be obtained from atmospheric samples taken over the landscape by measuring concentrations from an aircraft (Styles *et al.* 2002) or over entire continents and the world, simply by measuring their concentration with great precision (Keeling *et al.* 1996; Gurney *et al.* 2002). Here we describe the approach used in the continental or global analysis. The atmosphere 'sees' the result of all carbon transactions including photosynthesis and respiration. This includes the fossil fuel emissions and also the decomposition of the many products of ecosystems. Some of these products are short-lived (e.g. newspaper, food) whilst others endure for decades (e.g. structural timber). The signal appears as a change in the concentration and isotopic composition of CO_2, CH_4 and CO in the atmosphere, and so in principle a time series of accurate measurements of these gases should be useful in deriving the location and strength of sources and sinks. Sampling is currently carried out manually, using flasks which are filled on a regular basis and shipped to a common laboratory for analysis. So far, the global network of sampling stations is barely adequate to enable robust calculations to be made.

The sinks are inferred from the draw-down in CO_2, using an atmospheric transport model to correct for the 'smearing' that occurs because of atmospheric motion. Uptake of carbon by terrestrial ecosystems and the ocean may be distinguished from the isotopic composition of carbon: terrestrial photosynthesis discriminates against $^{13}CO_2$ but oceanic uptake does not. An important advance towards discriminating between the land and ocean sink was made by Ralph Keeling, who developed an interferometric oxygen analyser sufficiently precise to be able to measure the one-to-one exchanges of oxygen which inevitably accompany the exchanges of CO_2 in photosynthesis, respiration and fossil fuel burning (Keeling *et al.* 1996; Keeling & Garcia 2002), but which are absent when CO_2 dissolves in the ocean. Using all available atmospheric signals, sinks have been detected in North America and Europe, whilst the tropical region is often near to equilibrium (Gurney *et al.* 2002). The recent study by Rödenbeck *et al.* (2003) shows an analysis based on 20 years of concentration data (Fig. 3). After losses of CO_2 from

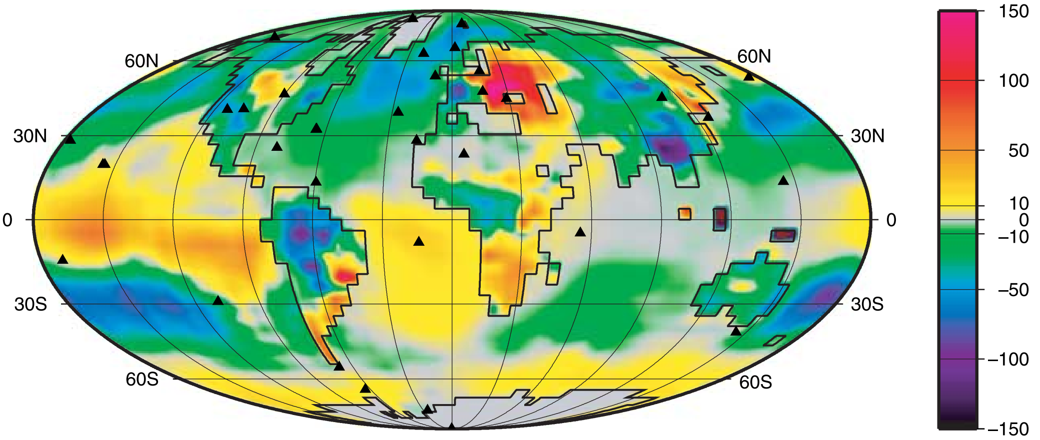

Fig. 3 Net Ecosystem Exchange inferred from 20 years of CO_2 concentration data measured at sample stations scattered across the world (triangles). Units are g C m^{-2} $year^{-1}$ and negative fluxes (blue and green) denote carbon sinks. (Reproduced with permission from Rödenbeck *et al.* 2003).

tropical deforestation are taken into account, temperate, boreal and tropical zones all reveal themselves as carbon sinks. According to one synthesis report, the temperate and boreal regions constitute a sink of 1.3 ± 0.9 Gt C year^{-1} whilst the tropical sink is 1.9 ± 1.3 Gt C year^{-1} (Royal Society 2001). Interannual variability, associated mainly with El Niño, is large, and contributes to the uncertainty. Modelling studies suggest the tropics to be the main cause of the interannual variability, a consequence of the large stocks of carbon that are held there, and the effect of temperature on the balance between photosynthesis and respiration.

Attempts have been made to reconcile continental estimates of the sink inferred from atmospheric measurements with those from scaled-up ground-based studies based on eddy covariance and inventories Land based estimates are 'consistent' with atmospheric estimates, but both have wide uncertainties (Pacala *et al.* 2001; Janssens *et al.* 2003). Following this comparison, one may attempt some continental summaries: the USA has an overall sink strength of 0.30–0.58 Gt C year^{-1} (Pacala *et al.* 2001), whilst that in Europe is between 0.13 and 0.20 Gt C year^{-1} (Janssens *et al.* 2003).

Model-based estimates of the terrestrial carbon sink

There is a simple and ingenious method of estimating the sink strength of a biome or an ecosystem (Lloyd & Taylor 1994). NPP is on the increase because of fertilization by CO_2 and deposition of active nitrogen, but heterotrophic respiration which is related to temperature and therefore is also increasing, does not keep pace with NPP due to the residence time of carbon in the vegetation and soil. The sink occurs because heterotrophic respiration lags behind the breakdown of organic matter, especially in ecosystems where there are significant stores of carbon. Lloyd & Taylor (1994) and Saugier *et al.* (2001) assumed heterotrophic respiration at time t is equal to the NPP at time $t - t_r$ where r is the residence time (estimated as carbon in vegetation plus soil divided by NPP):

$$R_h = \text{NPP}(t - t_r)$$

Assume that NPP is increasing linearly in response to rising CO_2 concentration.

$$\text{NPP}(t) = \text{NPP}_o(1 + at)$$

Based on experiments on woody plants grown at twice-normal CO_2 it is reasonable to propose that a doubling of CO_2 would increase the NPP by 30% (Wullschleger *et al.* 1995; Idso 1999) and so the observed annual increase of CO_2 of 0.4% per year might cause an annual proportional increase in NPP of $a = 0.0012\ \text{year}^{-1}$.

By definition, Net Ecosystem Productivity, NEP = NPP – R_h.

$$\text{NEP} = \text{NPP}(t) - \text{NPP}(t - t_r) = \text{NPP}_o a t_r$$

We can see from this analysis that rising CO_2 causes an increase in sink strength that is proportional to the residence time of carbon in the plant-soil store. Applying the above equation to the global productivity data suggests that the sinks are predominantly in forests and savannas (Table 1). Using this method we have a global terrestrial sink of 2–3 Gt C year^{-1}, depending on which values are taken for the carbon stock. This is in agreement with the error bands obtained from atmospheric methods (IPCC 2001; Royal Society 2001).

Later, Lloyd (1999) developed a more realistic model of the carbon fluxes (NEE) to terrestrial vegetation, explicitly considering the effect of elevated CO_2 and nitrogen deposition on photosynthesis, and considering respiration to be a function of temperature. This exercise suggested a strong C sink in the tropical regions and a weaker sink in North America and Europe (Fig. 4).

Table 1 Carbon fixed by the Earth's vegetation, as Net Primary Productivity NPP (Saugier *et al.* 2001), and the possible sink strength by the Taylor & Lloyd (1992) method. The total C pool includes vegetation and soil organic matter. See text for the assumptions. The average sink strength (final column) is obtained by dividing column 6 by the biome area (column 3)

Biome	NPP (t C ha^{-1} year^{-1})	Area (million km^2)	Total carbon pool	Total NPP (Gt C year^{-1})	Estimated total sink (Gt C year^{-1})	Average sink per ha (t C ha^{-1} year^{-1}) (Gt C)
Tropical forests	12.5	17.5	553	21.9	0.66	0.37
Temperate forests	7.7	10.4	292	8.1	0.35	0.34
Boreal forests	1.9	13.7	395	2.6	0.47	0.34
Arctic tundra	0.9	5.6	117	0.5	0.14	0.02
Mediterranean shrublands	5.0	2.8	88	1.4	0.21	0.75
Crops	3.1	13.5	15	4.1	0.20	0.15
Tropical savanna and grasslands	5.4	27.6	326	14.9	0.39	0.14
Temperate grasslands	3.7	15	182	5.6	0.21	0.14
Deserts	1.2	27.7	169	3.5	0.20	0.07
Ice		15.3				
Total		149.3		62.6	2.85	

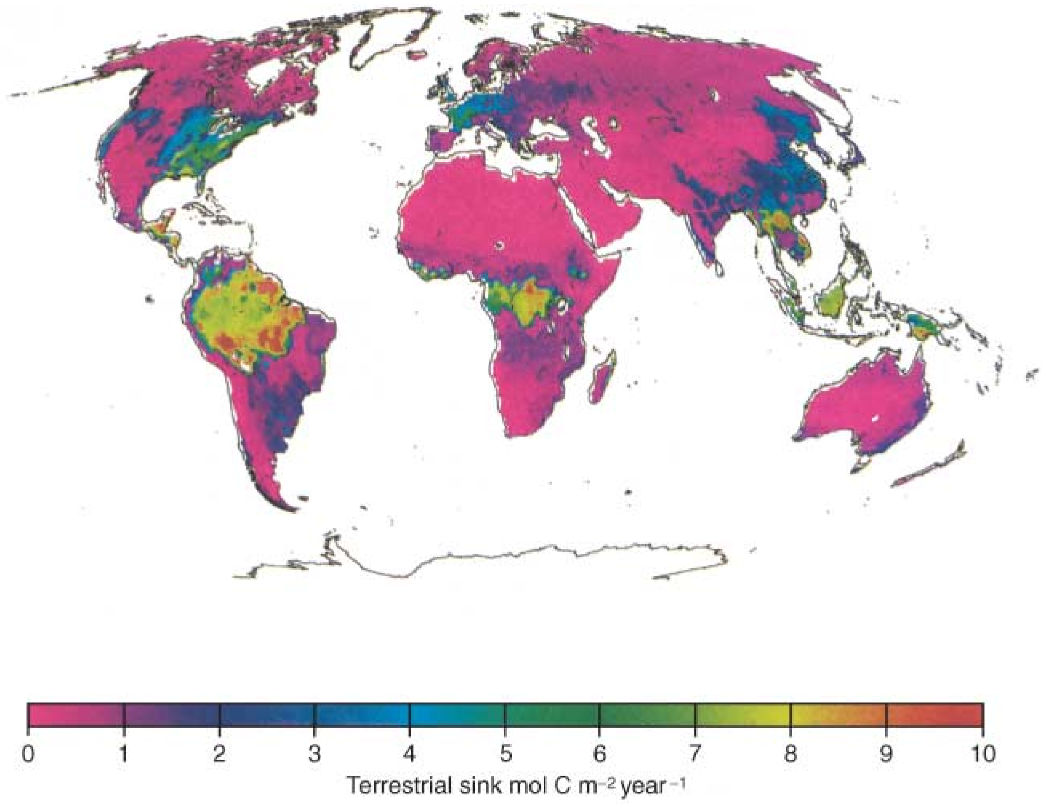

Fig. 4 The terrestrial carbon sink according to the model of Lloyd (1999). To be compared to Fig. 2 (noting that 1 mol CO_2 m^{-2} $year^{-1}$ = 12 g C m^{-2} $year^{-1}$). (Reproduced with permission from Lloyd 1999.)

A note on carbon losses from deforestation

Substantial carbon is transferred from the terrestrial reservoir to the atmosphere as a result of deforestation. Deforestation occurred in Europe over many centuries as the population increased. For example, Stewart (2003) draws attention to the very low percentage cover of forest in Scotland already by the late 1500s, as portrayed in the first maps of that land made by the intrepid Timothy Pont from 1585 to 1596. In North America a similar deforestation occurred following colonization by Europeans (McNeill 2000). Deforestation of the humid tropics is a relatively recent phenomenon, and is of great concern because its scale is likely to influence the global climate system, as well as threaten the rich diversity of species and the lives of indigenous people. In many tropical countries, development plans require substantial deforestation (Laurance *et al.* 2001a; Laurance *et al.* 2001b) and it is likely that tropical deforestation will continue into the foreseeable future, ceasing only when people realize the heritage value of the forest, as has happened in Europe.

Measuring tropical deforestation is difficult and controversial. In the 1970s and 1980s the published rates of deforestation tended to be exaggerated. The best data on global deforestation have been those derived from official national data sets collated by the Food and Agriculture Organization (FAO), giving a deforestation rate of 6.4 million hectares per year, equivalent to 0.55% of the total tropical forest per year (Table 2). However, the often-quoted data from Dixon *et al.* (1994) suggests 15.4 million hectares per year. Assuming the average carbon content of rain forests to be 152 t C ha^{-1} the FAO figure implies a transfer of carbon to the atmosphere of only 0.97 Gt C $year^{-1}$ whilst Dixon's figure suggests 2.34 Gt C $year^{-1}$. Other recent estimates produce an even lower figure than the FAO value (Achard *et al.* 2002; De Fries *et al.* 2002).

Table 2 Deforestation data from the FAO and the TREES project (Achard *et al.* 2002). The census year for columns 2 and 3 was 1990, and the period for columns 4 and 5 was 1990–97. The area of tropical forest shown here is far lower than the estimate by Dixon *et al.* (1994), which is 1760 million hectares

	Area (10^6 hectares)		Annual loss (10^6 ha) (percentage value in parentheses)	
	TREES	FAO	TREES	FAO
Southeast Asia	283	302	2.0 (0.71)	2.5 (0.82)
Africa	198	218	0.7 (0.35)	1.2 (0.55)
Latin America	669	652	2.2 (0.33)	2.7 (0.41)
Global	1150	1172	4.9 (0.43)	6.4 (0.55)

Changes in forest cover are estimated from satellite. Satellite remote sensing using optical methods can distinguish readily between forest and non-forest, and has enabled monitoring of forest cover for over two decades, with increasing levels of sophistication. Data collected annually by Brazil's Space Research Institute, INPE, for instance, provide a good impression of the progressive decline in Brazil's Amazonian rain forest, but do not detect illegal logging, which merely degrades the forest without removing it (Nepstad *et al.* 1999). For much of the period in the 1980s and 1990s, Brazil's deforestation rate was 20 000 km^2 $year^{-1}$, starting from a forest with an initial area of about 4 million km^2. Assuming a carbon density of 152 t C ha^{-1} this implies a flux of 0.3 Gt C $year^{-1}$.

The products of biomass burning include numerous organic compounds that react in various ways in the troposphere and stratosphere in ways which are not well-understood (Andreae *et al.* 2002). Substantial quantities of black carbon are also ejected from fires, contributing to the total aerosol content of the atmosphere. Some of the black carbon is deposited in other parts of the world in snow, and reduces the planetary albedo.

Remote sensing has several applications in the study of the carbon cycle. In future it may be possible to track deforestation rates using radar remote sensing, whereby the biomass of the forest as well as its area can be estimated. Synthetic Aperture Radar has the great advantage that clouds do not obscure the signal, but more work is required to develop this promising approach. Secondly, there is a good prospect that CO_2 may be measured from satellite, using infra-red bands. This will enable emissions from fires to be quantified and also it will provide extra information for the atmospheric modelling community, even though the expected precision (3–4 p.p.m. of CO_2) will be much less than what can be achieved through laboratory analysis of the air in flasks (about 0.1 p.p.m.).

Deforestation is important not only because of the release of carbon to the atmosphere. Climate models show that Amazonian deforestation impacts on the local and regional energy balance, causing a warmer and dryer climate. Moreover, through atmospheric circulation, the impact may propagate well beyond the Amazon. Such teleconnections are widespread, and show how climatic anomalies may produce impacts which are thousands of kilometres away (Van den Dool, Saha & Johansson 2000).

The future of carbon stocks in the rain forest remains uncertain. Although most countries have protection schemes in place, illegal logging is rife, and policy is driven by the need for economic development and revenue. In Brazil, deforestation may be accelerated by new roads in a government scheme known as *Avanca Brazil* (Nepstad *et al.* 1999; Laurance 2001a,b). One possibility is for the developed countries to pay for protection of rain forests, either as part of the Clean Development Mechanism (CDM) of the Kyoto Protocol, or as industry-funded development projects. Of course, the 'value' of the forest as a global environmental service may be considerable, especially if species conservation is included in the assessment of the value (Swingland 2003). Some of these developments are to be seen already. Since 1997, the government of Costa Rica has been paying landowners for several ecosystem services: carbon sequestration and protection of watersheds, biodiversity, and scenic beauty (Costanza *et al.* 1997; Daily *et al.* 2000). The payments of about 50 \$ ha^{-1} $year^{-1}$ are financed in part by tax on fossil fuels.

The Kyoto Protocol

The Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) is the first step by the world's nations to limit the emissions of carbon dioxide and other greenhouse gases. The text of the Protocol was adopted at the third Conference of the Parties (COP3) in Kyoto on 11 December 1997.

In the Protocol, 38 of the most developed countries of the world ('Annex 1 Countries', who collectively emit about 60% of the total carbon emissions) have been given *emission reduction targets*. These targets have been arrived at by a long negotiation process (see Leggett 2000), which has attempted to take into account the 'special circumstances' of each country. For example the European Union was given a reduction target of 8%, Japan 7%, and the USA 6%, whilst Australia is allowed to *increase* its emissions by 8%. The emissions are to be counted in the period 1990 to 2010. If all these targets are met, the emissions by the Annex 1 countries would fall by 5.2%.

The greenhouse gases that are especially important are: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), all of which have been rising fast over the last few decades. Carbon dioxide is the main product of fossil fuel burning, and is quantitatively the most important. There are industrial gases too: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF6). Weight-for-weight, or molecule-for-molecule, these gases are far from equal in their greenhouse effect, and so to add them up it is necessary to use their Global Warming Potential, an index agreed upon by the Intergovernmental Panel on Climate Change (IPCC). The index takes account not only their infra-red absorbing power, but also their longevity in the atmosphere.

To become law, 55 countries must ratify the Protocol, and those 55 must account for 55% of emissions. However, under the leadership of President Bush, the USA announced its intention not to ratify the Protocol in March 2001. Since USA emits over one-third of the global C-emissions this was a massive set-back for the Protocol. At the time of completing this article (December 2003), 101 countries accounting for 44% of emissions had ratified. Australia has also decided not to ratify the Protocol (even though its recent severe droughts have been considered by many people to be one of the outcomes of global warming), and Russia is currently prevaricating, with President Putin stating publicly that warming would be useful in such a cold country.

The Protocol allows Annex 1 countries to count the following practices, known as 'flexible mechanisms', towards their emissions reductions.

1 Planting new forests and thus creating 'sinks' for carbon (from 1990) and adopting new agricultural practices that reduce emissions (Article 3.3 and 3.7)

Subsequent Conferences of the Parties (COPs) were required to clarify the details of Article 3.3. At COP4 in Buenos Aires in 1998 it was agreed that Countries would be credited (or debited) with any increase (or decrease) in carbon stocks in the period 2008–12 due to afforestation, reforestation and deforestation. At COP6, held in The Hague in November 2000, it was agreed that afforestation and reforestation meant converting non-forested land to forest, and excluded regeneration of forest after logging. The potential to develop large scale afforestation schemes certainly exists, although there are doubts as to whether afforestation in the boreal region will have the desired effect on warming, because the albedo of the snow-covered landscape will fall appreciably (Betts 2000), whilst the lowered water table at many of the afforested peatland sites will encourage rapid aerobic decomposition of the stored carbon. As regards agricultural practices, many countries see opportunities to 'save' carbon by adopting low tillage agriculture. It is generally assumed that low levels of cultivation will reduce carbon dioxide losses from soil and by fossil fuel burning, and that low N-fertiliser inputs will reduce the emission of nitrous oxide. To exploit low-till or no-till agricultural systems to their full, it will be necessary to develop a new type of agriculture in which weed control is achieved through the use of crops that have been genetically engineered for herbicide resistance.

2 Carbon trading (Article 6 and 17)

An Annex 1 country may acquire from another Annex 1 country any number of emission reduction units. Where a country has exceeded its emissions reduction targets, it could sell its excess units to the highest bidder.

3 A Clean Development Mechanism, CDM (Article 12)

Through this mechanism, Annex 1 countries are meant to assist sustainable development in non-Annex 1 countries by providing 'clean' projects that create sinks or reduce emissions. These 'certified emissions reductions' may include: afforestation and reforestation, but protection of existing forests is excluded.

Whilst most countries agree to the Protocol in principle, many of the details of the flexible mechanisms are controversial, and continue to be the main concerns of successive COPs. Issues relating to carbon sinks have been especially controversial (Grace *et al*. 2003). For example, how would carbon stocks in forests be verified and by whom? Even when an increase in carbon stocks at one site has been verified, there may be an increase in deforestation elsewhere, possibly in another country (quite possibly in a tropical country, with additional, non-climatic, adverse effects on biodiversity or indigenous people). This is known as 'project leakage'. Conservationists are often opposed to the use of carbon sinks for such reasons, arguing for a real shift from a carbon-based energy supply to renewable energy and carbon taxation.

Others have pointed out that the Protocol ignores any increase in carbon emissions by the major developing countries. However, these are the countries who collectively are likely to increase sharply their use of fossil fuels over the next few decades, in order to achieve development.

Moreover, even if Annex 1 countries do achieve the target of 5.2% reduction in their emissions, it must be realized that this is a very small contribution. It amounts annually to only 0.19 billion tonnes of carbon, whilst the losses from tropical deforestation are between 1 and 2 Gt C year^{-1} and the fossil fuel emissions now exceed 6.5 billion tonnes of carbon per year and are still rising. At best, a 5.2% reduction would merely mark the start of a large-scale and long-running set of international negotiations aimed at stabilizing the atmospheric greenhouse gas content. In principle, to bring the carbon cycle back to equilibrium the world needs to reduce its emissions to match the natural sink strength (the combined terrestrial and ocean sink is about 4–5 Gt C year^{-1}). At present the combined fossil fuel and deforestation sources (8.2 Gt C year^{-1}) exceed the natural sink strength by 3 Gt C year^{-1}). According to some models, the terrestrial sink will in any case vanish in a few decades, as respiration overtakes photosynthesis (Cox *et al*. 2000), and so to achieve equilibrium fossil fuel emissions would have to cease entirely.

As I finalize this paper in December 2003, delegates are returning from COP9 in optimistic mood, with the view that it is likely that Russia will eventually ratify the Protocol and thus trigger the Protocol to become law. Some people even believe that the USA will also ratify the Protocol if there happens to be a change in government. There is other good news: the major uncertainties in the operation of the CDM have now been resolved and agreement has been reached. Moreover, the Brazilian delegation is talking about the possibility of including forest protection and conservation within the CDM, a sign that the new President of Brazil is listening to the good advice he receives from many of his own country's scientists as well as from the international community.

Informal carbon projects

Before the Kyoto Protocol, there were some firms and individuals who began to take steps to offset their greenhouse gas emissions. Consequently, small companies sprang up to deal with the need these people feel to absorb their emissions by using vegetation, typically by planting trees. Many examples are given by Orlando *et al.* (2002). Such companies will act as brokers to facilitate planting and maintenance of trees, and participate in carbon trading. In tropical countries this results in an income stream to enable rural communities to invest in long-term projects involving sustainable forestry and agroforestry. Such activity has the same effect, and is organized on the same lines, as the Clean Development Mechanism (CDM) outlined above, but at present its status is 'informal', and the Kyoto Protocol has not been ratified. It is interesting to show a 'worked example' of how this works, as follows.

> Jane Citizen drives a family saloon 15 000 km per year, and most years she and her spouse visit their family in Australia. Jane was able to determine from fuel consumption data in her car's handbook that the saloon emitted 0.85 tons of carbon in that year. Referring to published data on the emissions by long-haul civil aircraft she was able to estimate that two return flights to Australia for two people emitted about 1.9 tons of carbon. Putting aside household emissions (heating, lighting and cooking), which she considered to be unavoidable, she decided she ought to arrange for the annual absorption of 2.75 tonnes of carbon to offset transport emissions. She contacted a carbon management company who advised her that this could be done by planting 0.55 hectares of native trees in the tropics. She decided to go ahead, and was pleasantly surprised that the cost was rather small, only 25 Euro for each ton of carbon per year. A few weeks later, a rural community in South America was contacted by project manager of the company, and informed that new funding, from Jane and others, had been received from a European broker to increase the area of the plantation. As the land was currently being used only for subsistence grazing, the community agreed to go ahead and agree a schedule of payments with the project manager. Jane meanwhile was issued with a certificate, which she regards as an ethical investment, and expects to sell it in the future.

One example of how carbon may be sequestered at a local scale is provided by the experience of the Edinburgh Centre of Carbon Management. The scheme is called Plan Vivo. Farmers produce working plans to increase the carbon content of their land by planting trees, including trees for fruit and pharmaceuticals, on land that is otherwise marginal. Record-keeping involves making an accurate map of the holding (Fig. 5). Payment for carbon sequestered is made according to a schedule (some up-front payment, payment on planting, and payment when the trees have reached specific size). Hence, money flows from many Jane Citizens (also some big and well-known companies). Plan Vivo, and similar protocols, are being used in many parts of the world,

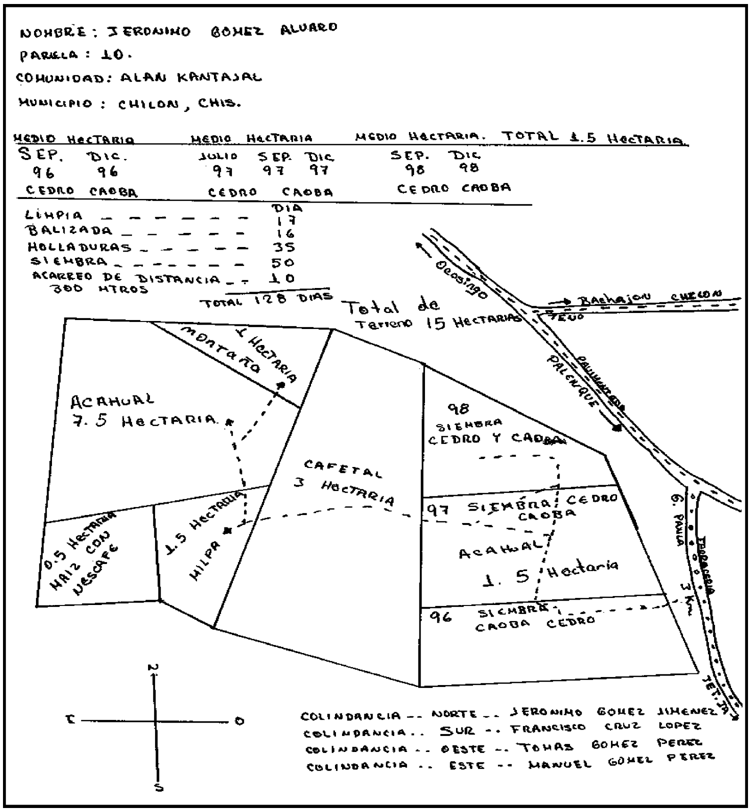

Fig. 5 Farming carbon on a local scale by the Plan Vivo. The farmer's map holds information required to estimate the change in carbon stocks: the total area of the plot, the species planted in each section, the planting density and rotation length, the intended use of the trees (fuel, timber, coffee and cocoa, fodder, fruit, poles or medicinal), and the maintenance and management requirements. (Reproduced by permission of the Edinburgh Centre for Carbon Management.)

and are likely to be adopted as part of the CDM once the Protocol becomes operational.

Can schemes like this work? In some cases they are already working. Detractors, however, point out the flaws: afforestation projects in the tropics generally have a high failure rate which needs to be factored into the calculations (Grace *et al*. 2003), and there may be project leakage. The term project leakage refers to the tendency of people to continue to fell trees, but to do it outside the project area where it may not be detected (except by satellite surveillance). Actually, in some cases *negative* project leakage occurs, whereby villagers elsewhere try to emulate the practices of those in the project zone. If such projects were to become widespread, they would result in a flow of money from rich to poor countries, an alleviation of poverty in poor countries, and a shift towards a more sustainable form of land management, whilst a significant fraction of carbon emitted in rich countries would be absorbed in tropical vegetation. Such projects could usefully be extended to cover conservation of forest (Swingland 2003). In that case the donor would pay for protection of a forest ecosystem that might otherwise have been destroyed, and with it the biodiversity and diverse ecosystem services. E.O Wilson has pointed out that conservation needs to be related to income generation for those who live near the reserves (Wilson 2002). Earning carbon credits is one of the income streams he sees, alongside ecotourism and bioprospecting. In this way, land can yield more income than logging or agriculture would on the cleared land.

Some organizations and some governments have raised ethical and political objections to projects like these, that we should not ignore. The ethical objection is not difficult to see: it is that rich countries should not export their environmental problems (carbon emissions) to other countries – establishing plantations or even protecting rain forests from illegal logging is difficult and sometimes dangerous work which provides income for the rural poor at only the lowest level; it does not really result in 'development'. Rich countries should reduce emissions at source and suffer the small reduction in lifestyle that the action brings. Similar ethical objections have often been raised to the use by multinational companies of 'cheap' labour in poor countries. The *political* argument pertains to sovereignty: the developing country wishes to retain the right to cut down rain forest and develop the agricultural potential of its land, unfettered by international agreements to sequester carbon.

To avoid some of the problems, and using the Kyoto Protocol's CDM as a guide, it is possible to grade project proposals to make sure they satisfy certain criteria (Grace *et al*. 2003):

(i) Does the project result in truly *additional* carbon uptake, or would the uptake have occurred anyway (current plantation rate in the tropics has been increasing over the last 20 years and is now about 4 million ha^{-1} $year^{-1}$)?

(ii) Is the project *sustainable* beyond the initial investment? For example, if tree planting in the tropics includes trees for fruit and medicines, or if forest protection is associated with ecotourism which provides income, then the project is likely to continue. If the local community has real ownership of the project they will generally protect it.

(iii) Have steps been taken to minimize the risks of project failure; has a risk analysis been done; is the recipient country reasonably stable?

(iv) Is the project linked to relevant technology transfer, training and capacity building? This is often best achieved through involvement of local universities, and 'training of trainers' at several levels. Examples of relevant technology and training would include: beekeeping, woodcarving, pisciculture, survey, use of carbon inventories, use of satellite remote sensing and Geographical Information Systems, taxonomy of trees, and the use of models.

Concluding remarks

It is useful to return to the 'big picture' to see whether manipulation of the vegetation on a global scale to create new biological sinks can be useful in relation to the current imbalance of the carbon cycle. We saw (Fig. 1) that fossil fuel emissions are about 6.5 Gt C $year^{-1}$, and that the deforestation flux is 1–2 Gt C $year^{-1}$. Suppose, by international agreement, attempts were made to sequester as much carbon as possible using afforestation and modified forms of agriculture; how much carbon could then be fixed? This would be a large project, requiring further training of foresters and ecologists, and the establishment of appropriate funding instruments. Cannell (2003) estimated that for the world as a whole, on the basis of land available, there is a theoretical capacity of 2–4 Gt C $year^{-1}$, a 'realistic' capacity of 1–2 Gt C $year^{-1}$ and an 'achievable' capacity of 0.2–1.0 Gt C $year^{-1}$. Clearly these quantities are useful, especially when combined with measures to develop non-biological sinks using geological strata and chemical technologies.

The Kyoto Protocol is an important first step towards developing carbon sinks, as well as reducing emissions. Without Russia or the USA, who emit 0.39 and 1.53 Gt C $year^{-1}$, respectively, it is unlikely that the Protocol could ever come into force. However, as this article was being finalized the international community was generally optimistic that Russia would indeed ratify the Protocol, despite earlier suggestions by Russian President Vladimir Putin to the contrary. Moreover, the details of the Clean Development Mechanism, which had caused so much difficulty for negotiators, were resolved at the end of 2003, and there was strong support for the inclusion of forest protection and nature conservation as part of the Mechanism in the future. If these conservation measures can be included alongside the carbon incentive, mankind may, after all, succeed in the first global ecological engineering project.

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APPENDIX 1 CHRONOLOGY OF EVENTS RELATING TO THE CARBON CYCLE

1780–1820 Industrial Revolution. Dramatic increase in the use of coal. Western Europe sees rapid technological, social and economic transformation, driven largely by the steam engine fuelled by coal. Widespread urban pollution, exploitation of workforce, occupational diseases. Humans begin to alter the composition of the global atmosphere.

1851 James Young, Scotland, discovers how to extract hydrocarbons from oil shale, and develops the process of refining oil. He establishes a paraffin industry in West Lothian, Scotland (paraffin is called kerosene in the USA) and is nick-named ‘Paraffin Young’.

1859 Edwin Drake strikes oil at 20 m in Pennsylvania, USA. Oil was soon discovered in North and South America, Mexico, Russia, Iran, Iraq, Rumania, Japan, Burma and elsewhere. Oil soon plays its part in the industrialization of the world.

1859 Irish scientist John Tyndall discovers that H_2O and CO_2 absorb specific wavebands of infra-red radiation, and suggested a role for these gases in the regulation of the Earth’s temperature.

1866 German engineers Langen and Otto patented the internal combustion engine. The manager in Otto’s factory, Daimler, made the first petrol (gasoline in the USA) engine in 1884.

1896 Arrhenius, Swedish chemist, advances theory that carbon dioxide emissions will lead to global warming, and postulates the ocean as a global CO_2 sink.

1903 Henry Ford, USA (1863–1947) establishes the Ford Motor company, makes model T Ford cars in 1908. Others would follow Ford’s idea of mass production: car ownership and consequent CO_2 emissions would increase rapidly.

1928 Mohandas Karamchand Gandhi, leader of India, questions the sustainability of the industrial age; ‘God forbid that India should ever take to industrialism after the manner of the West. If it took to similar economic exploitation, it would strip the world bare like locusts’.

1958 Charles Keeling, of the Scripps Institute in the USA begins the first reliable measurements of atmospheric carbon dioxide at Mauna Loa in Hawaii.

1962 *Silent Spring* by Rachael Carson, USA, warns of dangers of pesticides to wildlife. This best-seller inspired a whole generation of environmentalists.

1968 Satellite remote sensing starts. Pictures of Earth from deep space, Apollo 8 mission, USA; followed in 1972 by Earth resources satellite ERTS-1 carrying multispectral sensors later called Landsat. Ordinary people would soon develop a new perspective of the Earth as a result of satellite images.

1968 Sweden calls upon the United Nations to convene a special conference on the environment (it occurred four years later).

1971 Swedish scientists demonstrate long-range transport of sulphur as the cause of acidification of Swedish lakes, and predict that acid rain will damage freshwater ecosystems and forests.

1971 Russian climatologist M. I. Budyko (1920–2001) publishes a treatize *Human Impact on Climate*, providing the scientific basis for the link between human populations and climate.

1972 In the UK, publication of *A Blueprint for Survival*, warning of the extreme gravity of the global situation and criticising governments for failing to take corrective action.

1972 Publication of *The Limits to Growth* by the Club of Rome, dealing with computer simulation of global environmental change.

1972 First international conference on the environment, Stockholm, leading to the establishment of the United Nations Environment Programme (UNEP). Acid Rain was widely publicised, especially in relation to forest decline, but since then the developed world has been moving to low sulphur fuels. One of the conclusions was ‘A point has been reached in history when we must shape our actions throughout the world with a more prudent care for their environmental consequences’.

1973 Organization of Petroleum Exporting Countries (OPEC) restricted the supply of oil, forcing its price to rise five-fold and threatening the global economy.

1979 James Lovelock publishes book on the Gaia Hypothesis, suggesting that there may be mechanisms of global homeostasis.

1987 Ice core from Antarctica, taken by French and Russian scientists, reveals close correlation between CO_2 and temperature over the last 100 000 years.

1987 United Nations World Commission on Environment and Development produce the Brundtland Report, dealing with definitions of sustainability.

1988 Intergovernmental Panel on Climate Change (IPCC) is established.

1990 IPPC’s first Scientific Assessment Report, linking greenhouse-gas emissions to warming.

1992 Implementation of the International Geosphere Biosphere Programme (IGBP) to predict the effects of changes in climate, atmospheric composition and land use on terrestrial ecosystems; and to determine how these effects lead to feedbacks to the atmosphere.

1992 Earth Summit, Rio de Janeiro. Leaders of the world’s nations meet in Rio and set out an ambitious agenda to address the environmental, economic, and social challenges facing the international community.

1994 The United Nations Framework Convention on Climate Change comes into force, aimed at stabilizing atmospheric concentrations of greenhouse gases at a level that would prevent human-induced actions from leading to ‘dangerous interference’ with the climate system.

1997 Kyoto Protocol, international agreement to limit greenhouse gas emissions.

1997–8 Particularly severe El Nino causes drought and widespread forest fires in Indonesia, Malaysia, Brazil and Mexico. In Southeast Asia the large-scale fires affected 10 000 km^2 of forest, probably releasing 0.1 billion tons of carbon. This is only 1.5% of current emissions from burning of fossil fuels.

1998 The warmest year of the century, and probably of the millennium.

2000 International Coral Reef Initiative reports that 27% of the world’s corals reefs are lost, mainly as a consequence of climate warming.

2001 President Bush announces that the USA will not ratify the Kyoto Protocol.

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