The regional and global quantification of sources and sinks of major biogeochemical elements such as carbon constitutes one of the ultimate goals of many IGBP endeavours. The degree to which this quantification results in a closed global budget provides a critical test of our understanding of the relevant source and sink processes, while the estimated uncertainties assigned to individual budget components highlight directions of future research. Clearly, a mere quantification per se only highlights our present state of knowledge; even more important is our understanding of how the budget changes with time as a function of natural and anthropogenic perturbations. This, in turn, requires long-term observations, detailed process studies and modelling. This article aims at providing a summary of recent developments regarding the relative partitioning of CO₂ uptake between land and sea based on old and new techniques.

The IPCC94 budget revisited.

The recent assessment by the IPCC 1994 of the different budget terms and their uncertainties (all uncertainties in this article are expressed as estimated 90% confidence intervals) is given in Table I (page 10). The listed numbers are representative of the decadal average 1980-1989. Table I has been reorganised such that all terms related to land biotic sources and sinks are listed at the end. Accordingly, emissions from fossil fuel use and cement production amount to 5.5±0.5 GtCyr⁻¹. The atmospheric increase of 3.2±0.2 GtCyr⁻¹, as determined from the background CO₂ monitoring stations, represents the best known term in the budget. The ocean uptake of 2.0±0.8 GtCyr⁻¹ is based on detailed calculations with ocean models. These include global 3-dimensional ocean general circulation models, but also simpler box model representations of the ocean. These models are either calibrated or validated by means of observations of transient tracers, such as radiocarbon, tritium and CFCs, which are to some extent analogue to the anthropogenic CO₂.

The fossil emissions, together with the increases in atmospheric and oceanic CO₂ storage imply that the terrestrial carbon pools, as a whole, must have been a very small net sink (0.3±1.0 GtCyr⁻¹) or effectively almost in balance during 1980-89. If so, any terrestrial CO₂ emissions due to land use changes (1.6±1.0 GtCyr⁻¹) must have been balanced by other terrestrial sinks e.g. regrowing forests in temperate latitudes (0.5±0.5 GtCyr⁻¹) or other processes such as fertilisation effects due to the increasing CO₂ concentration and from increased nitrogen deposition. The identification of these latter processes (often referred to as the "missing" or "unidentified sink") and their quantification on a regional and global scale represents a formidable challenge.

It is important to note, that global net fluxes between the atmosphere, ocean, and the terrestrial biosphere, are not only induced by the direct anthropogenic perturbation, i.e. by the rise in atmospheric CO₂. The global carbon cycle is also subject to interannual and longer term climate fluctuations which induce temporary imbalances in the natural exchange fluxes of carbon between the different. Depending on the approach and the time scale under consideration, climate driven fluxes may contribute considerably to a budget compilation such as given in Table I.

New Approaches

How solid are the inferences on the net balance of terrestrial biospheric carbon? Clearly the logic represented in the lines (1)-(4) of Table I hinges crucially on the ocean uptake term. Two new approaches allow an independent check on this term.

A significant advance in the last few years has been the development of measurement techniques to determine changes in atmospheric oxygen content with very high precision. Technically, the ratio of O₂/N₂ in air is measured, either by interferometric techniques or by mass-spectroscopy. Since the atmospheric content of nitrogen can be assumed to remain constant on timescales of decades to thousands of years, the O₂/N₂ ratio essentially reflects the oxygen content of the atmosphere. These measurements provide a new possibility to discriminate the contributions of oceanic and biospheric sources and sinks of CO₂. This follows from the fact that O₂ is produced during photosynthesis and consumed during any oxidation

![Figure 1: Observations of the annually averaged mixing ratio of CO₂ (left axis, circle symbols) and of oxygen (right axis, square symbols) in the northern hemisphere (solid symbols) and in the southern hemisphere (open symbols). Oxygen mixing ratios are shown as deviations from a reference value which is approximately 209,500 ppmv](image-url)
Table 1: Atmospheric CO₂ Budget 1980-89 (IPCC 1994)

<table>
<thead>
<tr>
<th>Flux</th>
<th>Value (GtC yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Fossil fuel and cement production</td>
<td>5.5±0.5</td>
</tr>
<tr>
<td>(2) Atmospheric increase (observed)</td>
<td>3.2±0.2</td>
</tr>
<tr>
<td>(3) Ocean uptake (model calculated)</td>
<td>2.0±0.8</td>
</tr>
<tr>
<td>based on observed O₂/N₂ ratio trend (1989-1994)</td>
<td>1.9±0.8</td>
</tr>
<tr>
<td>based on observations of δ¹³C/¹²C ratio</td>
<td>2.1±1.5</td>
</tr>
<tr>
<td>(4) Net balance of terrestrial biosphere</td>
<td>(1) - (2) - (3)</td>
</tr>
<tr>
<td>(5) Land use change emissions (primarily tropics)</td>
<td>1.6±1.0</td>
</tr>
<tr>
<td>(6) Regrowth of temperate latitude forests (based on forest statistics)</td>
<td>0.5±0.5</td>
</tr>
<tr>
<td>(7) CO₂ uptake by other terrestrial processes (a.o. CO₂ fertilisation effect, N-fertilisation, climate effects)</td>
<td>(4) + (5) - (6)</td>
</tr>
</tbody>
</table>

*Fluxes expressed in GtC yr⁻¹, uncertainty ranges represent estimated 90% confidence intervals.*

process in clearly defined stoichiometric ratios relative to CO₂. However, the oxygen gas is only very weakly soluble in oceanic waters, in contrast to CO₂ which is strongly chemically buffered in the oceanic carbonate system. Hence any oceanic uptake of CO₂ is not mirrored by a corresponding oxygen absorption or release from the ocean. As a consequence, the dynamical behaviour of the two gases is different and measurements of their behaviour are not redundant.

Figure 1 (page 9) shows the annually averaged records of the O₂ and CO₂ mixing ratio from representative background monitoring stations in the northern (La Jolla and Mauna Loa) and southern hemisphere (South Pole and Cape Grim) [Keeling et al., 1996]. The oxygen measurements (scale on the right) are expressed as ppmv deviations from a standard which corresponds to approximately 209,500 ppmv. It is seen that the oxygen concentration is diminishing at a slightly faster rate than the increase of the CO₂ concentration. This reflects on one hand the stoichiometric relation between O₂ and CO₂ in burning of fossil fuels of about -1.4:1 and approximately -1.1:1 with respect to photosynthesis and respiration of organic carbon. More importantly it reflects also the fact that oxygen is not buffered by the ocean. The observations of the global trends in CO₂ and O₂ provide two budget equations, which permit the determination of the oceanic and biospheric contributions in the global CO₂ balance.

The quantitative analysis using the longer O₂ record from La Jolla yields an average oceanic CO₂ uptake of 1.9±0.8 GtC yr⁻¹ (the error is the estimated 90% confidence interval) over the time period 1989-1994. With an increasing length of the record and provided that there are no problems with long-term stability of the standards, the uncertainty of the oxygen based ocean uptake rate is expected to decrease further. The oxygen analysis yields also an estimate of the global net terrestrial balance over the 1989-1994 time period amounting to 1.8±1.1 GtC yr⁻¹. This is much larger than the base period adopted by the IPCC as given in Table 1. The reason is that during the early 1990’s the atmospheric CO₂ growth rate was much smaller than during the 1980’s.

Observations of the isotopic composition of oceanic carbon, either of the temporal changes in the vertical ¹³C of or the surface ¹³C/¹²C distribution also allow an independent determination of the oceanic uptake of excess CO₂. Because of the presently insufficient database of oceanic ¹³C measurements, together with uncertainties in some of the other isotopic budget terms, the current estimates based on the ¹³C technique are subject to considerable uncertainties, yielding 2.0±1.5 GtC yr⁻¹ over the time period 1970-1990 [Heimann and Maier-Reimer, 1996].

It is reassuring that both the oxygen and the ¹³C based approaches confirm the model based ocean CO₂ uptake rates, albeit with considerable uncertainties. It is also important to note, though, that both the ¹³C/¹²C and O₂/N₂ based estimates of the oceanic CO₂ uptake refer to different times periods than the IPCC 1994 budget.

**Spatial constraints**

Figure 1 also demonstrates the gradient in the CO₂ and the oxygen mixing ratio which exists on annual average between the northern and the southern hemisphere. The primary cause of this gradient are the emissions of CO₂ and the corresponding losses of oxygen from the burning of fossil fuels taking place predominantly in the northern hemisphere. A quantitative assessment of these interhemispheric mixing ratio differences and of the more detailed spatio-temporal structures as revealed in the CO₂ records from the global monitoring station networks since the late 1970’s requires models that accurately describe the mixing of air in the global troposphere. The most conspicuous result from atmospheric modeling studies was the inference of a strong, presumably natural, CO₂ sink in the northern hemisphere, offsetting about 40% of the gradient induced from the fossil fuel source. Whilst this finding is thought to be rather robust, there remain substantial uncertainties related to modelling of the atmospheric transport as witnessed by a recent model intercomparison. Furthermore, seasonal interhemispheric exchanges also impact the mean annual mixing ratio gradient between the hemispheres. A continuation of the atmospheric transport model intercomparison and validation by means of observations of long-lived atmospheric tracers such as sulphur hexafluoride (SF₆) is currently conducted within the TRANSCOM project of IGBP-GAIM.

The nature of the northern hemisphere sink, whether of oceanic or terrestrial origin has been controversial. Again, analyses based on measurements of O₂/N₂ and of ¹³C/¹²C provide new insights. The oxygen observations allow a separation between oceanic and biospheric components in the north-south gradient. Assuming that the southern hemisphere biosphere plays a negligible role, the gradient information together with the global budget allows the determination of the net terrestrial biospheric contributions from the tropics and from the northern temperate and high latitudes. The analysis of the data for the time period 1991-1994 yields a biospheric sink of about 1.9±1.5 GtC yr⁻¹ in the extratropical northern northern hemisphere. This value, together with the global net biospheric balance of 2.0 GtC yr⁻¹ for the same time period, implies that the terrestrial equatorial regions must have been almost in balance during 1991-1994. If so, any net CO₂ releases from these regions due e.g. to deforestation must have been balanced by corresponding CO₂ uptake at other locations in the tropics. The picture provided by the oxygen measurements for the early 1990’s is grossly in accordance with a recent analysis of the interhemispheric gradient in the atmospheric ¹³C/¹²C ratio, which, however, refers to a shorter time period.

The interhemispheric CO₂ mixing ratio gradient in the 1980’s (at least 1980-87) was similar in magnitude as during the
In Search of a Language that Connects

John Stone, Richard Rockwell, and Chris Rapley

There is a need to connect the efforts of the research community working to understand our changing planet with the day-to-day concerns of the public and policy makers worldwide. In spite of substantial public interest in environmental issues, and significant media attention, there is a widespread lack of appreciation of the significance of the changes occurring around us.

It is not just that scientists often find it difficult to explain themselves in plain language, but they have a tendency to assume that the relevance of research is self-evident, when it is not.

How can we improve our effectiveness at getting the message across?

The following question and answer session, based on what we believe are deep human concerns, offers one approach:

Are we being poisoned?

Poisons involve more than eating or drinking things that make us ill or kill us. We are adding poisons to the air that we breathe. The sources include emissions from vehicles, from industry and from agriculture. Although some emissions are being controlled in some nations, the overall levels continue to increase because of growing populations and expanding economies. The problem is global. Even remote areas over the tropical ocean are found to be polluted by the products of agricultural burning on distant continents.

We can also be harmed by radiation. The Earth’s outer ozone layer protects us and our crops from damage by ultraviolet radiation. The ozone layer has been thinning for several decades due to the emissions of certain man-made chemicals. In spite of international agreements which seek to eliminate the problem, ultraviolet radiation levels are not expected to decline significantly for some years yet.

Are we damaging our life support system?

The Earth’s ecosystems provide a variety of services essential to our well-being - services for which we do not pay and which we take for granted. These include the purification of water and air, the recycling of nutrients, the generation and preservation of soils, the pollination of crops, and even the regulation of the atmosphere’s oxygen content.

Ecosystems are being damaged by human activities. We know about the effects of acid rain on forests and lakes, of toxic chemicals on fish and wildlife, of increases in ultraviolet radiation on all forms of life, and of the major impacts of changes in land use. In the longer term, shifts in rainfall and temperature patterns, resulting from climate change, will also become important.

The Earth’s ecosystems are being strained to the point where their capacity to provide services upon which we rely may be seriously impaired.

Is there a future for my children?

There is a tradition amongst some societies to “tread lightly on the Earth” - that we are only here as caretakers for our children, and that our actions must take into account the interests of future generations.

In practice the uncertainties are so great that we cannot predict the kind of future that our children will face. However, it is likely that they will experience profound changes in ecosystems, in the climate system, in the availability of water and food, and in the distribution of diseases.

When we reduce species diversity, we know that we are depriving our children of future resources. And yet we do not know enough at the moment to choose which resources to save and which to let go.

What can science contribute?

Nations, communities and individuals with the greatest understanding of global change and its consequences will be in a stronger position to take advantage of new opportunities and to adapt to the problems. Scientific research provides the best means of obtaining such understanding. Given the vast size and complexity of the Earth system, we cannot rely on the traditional methods of science. An unprecedented degree of interdisciplinary and international co-operation is necessary. To succeed will be science’s greatest challenge, but progress will depend on a wide acceptance of the importance of the goal.

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