UNCERTAINTIES IN BIOSPHERE/ATMOSPHERE EXCHANGES: CO_2 ENHANCED GROWTH

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Introduction

Green plants need CO_2 to grow. A higher concentration of atmospheric CO_2 will stimulate the photosynthetic process, promoting plant growth and productivity. At the same time the efficiency of plant water use is increased, hence growth stimulation is possible without an increase in water demand for transpiration. On the other hand, climate warming may partly offset the direct CO_2-effects . The positive direct effect of CO_2 on plant growth is often smaller under nutrient-poor conditions, but is fully retained when water shortage limits plant growth. The effects of climatic change will not be evenly distributed over the world. In cool and temperate climatic zones plant growth will be stimulated, but in the tropics a further increase in temperature will have negative effects.

Current estimates for the amount of carbon in the terrestrial biosphere are: 450-600 10^{15} g C in living biomass and 1200-1400 10^{15} g C in soil organic matter in various forms. In the period 1800-1990 some 210 10^{15} g C of fossil carbon have been burnt, of which about 136 10^{15} g C has remained in the atmosphere and raised the CO_2-concentration from 285 to 350 ppm. The partitioning of the past and present rates of carbon release between various components of the oceans and the biosphere is still uncertain. Two contrasting hypotheses for this partitioning were investigated, using a simulation method.

Definitions

The flux of assimilated CO_2 is stored in various biospheric pools, from where the carbon is eventually recirculated to the atmosphere. A scheme for a classification of the fluxes is given in Fig. 1, and some definitions are further explained below.
Gross Primary Productivity (GPP) is the gross carbon fixation of the photosynthetically active organs (mostly the leaves), for global studies usually expressed in 10^{15} g of C yr^{-1}. This flux is hard to estimate, but probably between 80 and 200 10^{15} g C yr^{-1}.
Net Primary Productivity (NPP) is equal to GPP minus the respiratory losses of the plants themselves. It is equal to the flux of plant material that becomes available to the other organisms that live on it (heterotrophic consumption), e.g. by grazing or by decomposition of dead material. This flux is estimated to be 40-60 10^{15} g C yr^{-1}.
Net Ecosystem Production (NEP) is equal to NPP minus the heterotrophic consumption. It presents the net growth of an ecosystem during an undisturbed period. Globally this flux is about 4-7 10^{15} g C yr^{-1}.
Net Biospheric Uptake (NBU) is equal to NEP minus loss by fire and direct human disturbance. This flux is between 0 - 1 10^{15} g C yr^{-1}, which means that the biosphere is a sink, notwithstanding burning of forests.

Reference hypothesis

This "Reference Hypothesis" (Table 1) is roughly identical to the one described by Goudriaan and Ketner(1984) and by Goudriaan(1989). According to this Reference Hypothesis, the total terrestrial biosphere has shown a decrease of 33 10^{15} g C over the last 200 years and 109 10^{15} g C was absorbed by the oceans. At present the biosphere is a net sink for carbon and not a net source (Table 1), in contrast to conclusions of other researchers (Bolin,1986).
These authors have based their figures on statistics of land reclamation, and multiply the rate of land reclamation with the carbon surface density, characteristic for deforested land.

Decrease in soil carbon is also taken into account. This method results in an estimate of the global rate of release of about 1.2 10^{15} g C yr^{-1} (on basis of 15 Mha yr^{-1} and a change in surface density of 0.08 10^{15} g C Mha^{-1}, or of 8 kg C m^{-2}).
This method however ignores reforestation and widespread regrowth on abandoned land. It also ignores the slowness of release of soil carbon. These factors reduce the release rate to a second estimate of 0.5-0.8 10^{15} g C yr^{-1}.
The third factor, which turns the biosphere from a source into a sink (Fig. 2), is the worldwide stimulation of photosynthesis by rising atmospheric CO_2 concentrations, the so-called CO_2-fertilization effect. Many experimental data (Kimball,1983; Goudriaan and Unsworth,1990) show that this effect may be as large as a 0.5% stimulus per % increase of total atmospheric CO_2. At present, the rate of increase of atmospheric CO_2 is 1.5/350 or about 0.4 % per year. A relative stimulus of 0.5 would result in an increase of 0.2% per

Balancing the atmospheric budget

Tans et al. (1990) have recently published a detailed analysis of the global atmospheric budget of CO_2, and the potential role of the oceans as a sink. Their models were constrained not only by the gross atmospheric budget, but also by the observed latitudinal gradient of pCO_2(atm). This latter constraint is particularly important, since it can only be satisfied if the bulk of the CO_2 sink is in the Northern hemisphere. Tans et al. concluded that the mean ΔpCO_2 implied for the Northern hemisphere oceans is unrealistically large, and that there must in addition be a large terrestrial CO_2 sink in the Northern hemisphere in order to balance the atmospheric budget.

It should, however, be recognised that it is extremely difficult to assign realistic confidence limits to estimates of air-sea flux of carbon dioxide based on oceanographic data and integrated in the manner of eqn. (3). The values of K_z and ΔpCO_2 used are necessarily averaged over large spatial and temporal scales. The calculations reported by Tans et al. averaged ΔpCO_2 over a 2° x 2° spatial scale, and for two periods of the year. Wind speeds applied to the 2° boxes were monthly averages. While this represents the state of the art in terms of currently available data, it is clearly inadequate when integrating the product of two parameters (K_z and ΔpCO_2) which can have spiky, episodic distributions in both space and time. In certain areas, much of the air-sea flux may be associated with storm events (high K_z), or with spring phytoplankton blooms (which result in high ΔpCO_2 as rapid primary production reduces pCO_2(water); see Fig. 2).

These events will be poorly represented in mean values averaged over periods of months, particularly if the episodes themselves have not been adequately sampled. Some of the problems involved can be illustrated with reference to Fig. 2. The hatched areas of the pCO_2 plots correspond to the two periods of the year (January-April, July-October) over which Tans et al. averaged pCO_2: it can be seen that it is possible to miss a significant part of the air to sea flux using this type of averaging procedure.

It may be argued, of course, that the area of the North Atlantic which has received detailed attention from the JGOFS programme, and on which the model of Fig. 2 is based, may not be representative of the temperate waters of the world ocean. However, Minster et al. (1990) recently reported modelling studies based on data collected at Ocean Weather Station P in the North Pacific, including a model of the seasonal cycle of pCO_2. This model was used to compute the net annual air to sea flux of CO_2 in the manner of eqn. (3), albeit on an extremely limited spatial scale. This was then compared with flux estimates based on limited sampling of pCO_2 values from the model. The general conclusion was that monthly measurements of pCO_2 represented the minimum frequency necessary to obtain a reliable flux estimate. This indicates that current integrations of the global air/sea flux of CO_2 according to eqn. (3) should be assigned large uncertainties.

Conclusions

In assessing the fate of CO_2 released to the atmosphere, the uptake of CO_2 by the oceans represents a major area of uncertainty. Current state of the art estimates suggest that the oceanic sink for CO_2 may only be about half that required to balance the atmospheric budget, challenging the widely held view that the oceans represent the major sink. Either the estimate of the oceanic sink is substantially in error, or there is a very large, unidentified, terrestrial sink, or both. It is clear from a brief review of the procedures by which the oceanic sink has been estimated that the seasonal cycle and spatial distribution of pCO_2 in surface ocean waters constitute the major source of uncertainty. The Joint Global Ocean Fluxes Study (JGOFS) is already beginning to tackle some of these problems, and additional field measurements will be carried out on cruises of the World Ocean Circulation Experiment (WOCE). However, field measurements alone can never provide the necessary spatial and seasonal coverage. This can only be achieved by developing models of the seasonal cycle of pCO_2 appropriate to different regions of the ocean, and making full use of sea truth and satellite measurements to calibrate and verify the models.

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year of the storage capacity in the terrestrial biosphere, corresponding to about 4 10^{15} g C additional storage capacity per year. However, this increased capacity is not instantaneously realized, because slow compartments lag behind. Numerical simulation shows that the differences in longevities from leaves to resistant soil carbon reduce the realized CO_2 fertilization effect to about 1.5 10^{15} g C yr^{-1}.

In combination with the estimate for regrowth, the global terrestrial biosphere is estimated to exhibit a release rate of -0.75 10^{15} C yr^{-1} or, in other words, to act as a net sink of about 0.75 10^{15} g C yr^{-1}.

Two variants of this reference hypothesis can be formulated. In one of them the CO_2 fertilization effect is not expressed as increased productivity per unit surface area, but as decreased decomposition of wood and soil organic matter. In the other variant the vegetated areas are increased, instead of the carbon surface densities.

These three mechanisms (increased surface productivity, decreased decomposition rates, and increased vegetation areas) may occur simultaneously, and can replace each other in model calculations. It is remarkable that the global mean concentration of carbon isotope in the major pools hardly differ for these variants. However, it is to be expected that a further analysis of isotopic records in the different geographic and structural pool components will enhance the possibilities to discriminate between the hypotheses.

Hypothesis 2

Tans et al.(1990) have concluded on basis of the North-South gradient of atmospheric CO_2 that biospheric carbon uptake must be larger and ocean uptake must be smaller than hitherto believed. A possible realization of this hypothesis is given in Table 1. Global NPP must grow by 0.35% per year instead of by 0.25% per year. This rate corresponds with a hypothetical CO_2-fertilization effect of 0.7% which is a very high figure, in fact too large to attribute to CO_2 alone. Other factors such as global eutrophication, should also contribute for such a large stimulus to occur.

As before, the distribution of the stimulus of growth rate over surface NPP, increased longevity and increased vegetated area is immaterial for the values of concentrations in the atmosphere.

Surprisingly, the ^{13}C isotope figures cannot serve to discriminate between Hypothesis 1 and 2, at least if only their global means are considered. The insensitivity of the isotope record to partitioning of uptake between ocean and biosphere is due to two compensating factors:

a) When the ocean absorbs less carbon, its ability to dilute the isotopically depleted fossil carbon is also less, and the isotopic record should show a faster decline.

b) On the other hand, the biosphere preferably takes up the lighter C-isotope, and with a faster biospheric growth isotopically enriched CO_2 will remain in the atmosphere. This effect will reduce the downward trend of the atmospheric isotope content.

However, the ^{14}C record, especially after the nuclear tests, did show clear differences (Table 1). For hypothesis 2 the simulated rate of return of the peak of radiocarbon in the atmosphere was too slow, at least during the first decade around 1970. For unknown reasons, during the last decade the observed rate of return has slowed down a bit, and both hypotheses can probably be reconciled with the data.

More geographic and structural detail in isotopic data will be needed to clarify some of these inconsistencies.

Conclusions and discussion

Even a slight imbalance in the growth of terrestrial ecosystems on a global scale is sufficient to absorb the carbon released by deforestation (Lugo & Brown, 1986). Such an imbalance may be caused by the fertilization effect of increasing atmospheric CO_2, as assumed here, but other environmental factors may be involved as well. Notably, the soil can store significant amounts of carbon. For instance, a 3 % increase in carbon content (relative to carbon, not to soil weight) results in a carbon sequestering of 50 10^{15} g C. Detection of this fertilization effect by sampling methods in the field is extremely difficult, because of the large natural heterogeneity that exists on practically every spatial scale.

Deforestation for permanent human use is significant, releasing CO_2 at a rate of about 0.5 to 1 10^{15} g C yr^{-1}. On the other hand, this rate of release can be more than compensated by global stimulation of growth by atmospheric CO_2. From the point of view of the activity of the biosphere, a net biospheric uptake of 0.5 - 1.5 10^{15} g C yr^{-1} is a plausible range. We still do not fully understand how a higher biospheric (and lower ocean) uptake can be reconciled with the observed record of ^{14}C in the atmosphere.

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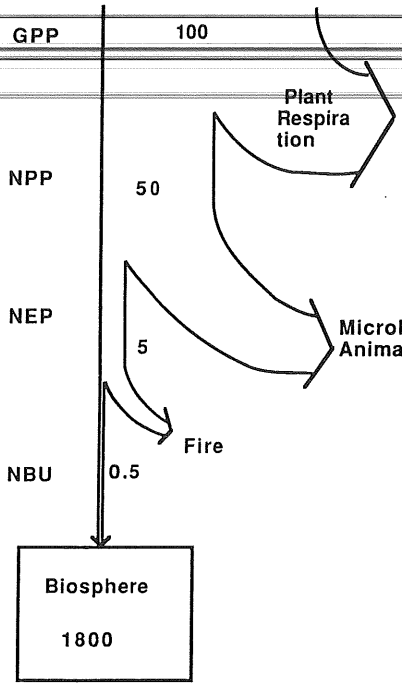

Fig. 1. The major types of terrestrial carbon fluxes in 10^{15} g C yr^{-1}, as consumed by the plants themselves, by heterotrophic organisms, by fire, and eventually used for net storage.

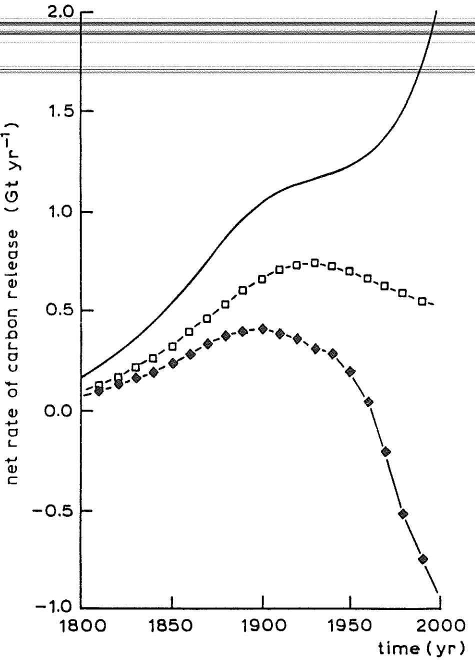

Fig. 2. Net rate of terrestrial release of carbon when only deforestation is considered (——), when regrowth worldwide is also considered (-□-□-), and when CO_2-fertilization worldwide is also considered (-◆-◆-).

TABLE 1. Two simulated Hypotheses for the year 1990. In the Reference Hypothesis the relative stimulus of atmospheric CO_2 with respect to terrestrial net photosynthesis had a value of 0.5, in Hypothesis 2 it was set at 0.7, and the exchange rate at the air-sea interface was halved to arrive at the same atmospheric CO_2-concentration.

Variable	observed	Reference Hypothesis	Hypothesis 2	
F_{fossil}	5.80	5.80	5.80	10^{15} g C /yr
F_{atm} ->sea	?	2.32	1.81	10^{15} g C /yr
F_{atm}->biosph	?	0.75	1.28	10^{15} g C /yr
d_{atm}/dt	2.7±0.2	2.73	2.72	10^{15} g C /yr
$[CO_2]_{atm}$ (285 in 1780)	350±0.5	349.7	349.8	ppm
$^{13}\delta_{atm}$ (-6.0 in 1780)	-8.0±0.2	-7.93	-8.18	promille
$^{14}\delta_{atm}$ (-23.0 in 1780)				
1950:	-46±3	-46.9	-35.7	promille
1970:	450±20	533	667	promille
1980:	220±20	216	349	promille
1990:	?	93	199	promille
Biosphere (1894.5 in 1780)	?	1861.9	1887.0	10^{15} g C
increment	?	-32.6	-7.5	10^{15} g C
Ocean 1)	?	38894.5->39004.1	38727.0->38811.3	10^{15} g C
increment	?	109.6	84.3	10^{15} g C

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1) The initial ocean profile and total content of carbon depends on the assumed surface exchange rate. F_{atm}->sea flux should be zero in the starting year 1780.

Calculation of fluxes and data situation

The present models include these pools and fluxes. The calculations are performed regionally, i.e. they are based on a global grid. It is generally not possible to characterize fluxes in the models by distinct values since these fluxes are too divers in space and time and only very limited numbers of measured data are presently available. Therefore attempts were made to relate the fluxes to their driving functions. Those driving functions are mainly climate elements, soil attributes, and others, which are commonly available as global grid-based data sets.

Thus (relatively scarcely measured) biospheric fluxes are calculated in the models from readily available environmental variables. Empirical functions relate those environmental variables to the fluxes or flux coefficients. The reliability of the functions reflects the reliability of the data set used to calibrate the functions and the experience of the persons who selected the data sets.

Processes influenced by forest clearing and land-use changes

The productivity of agricultural areas is considerably lower than the productivity of the replaced natural vegetation types in most countries of the world. Based on the yield data published in the FAO yearbooks, the productivity of agricultural crops may be calculated by use of conversion factors yield to productivity which are available for important crops. Commonly the agricultural productivity does not exceed 15-20% of natural productivity. If natural vegetation is cleared the productivity is subsequently reduced to very low values.

The cleared phytomass is either burnt or left behind on the fields and decomposed naturally. In either case the carbon pool of the phytomass is converted to CO_2 and emitted into the atmosphere with timescales of days up to a few years. If charcoal is produced the lifetime is considerably longer.

The reduced productivity of fields in contrast to natural vegetation also reduces the production of litter and soil organic carbon. Because the depletion of those pools of dead organic matter is probably not influenced this leads to a loss of soil organic matter and humus compounds.

Since the principle biospheric processes are affected by these human activities it is important to know quantitatively the cleared areas and the sites where clearing occurs. The latter is the most important factor. It is not sufficent to know the vegetation type affected, since with a particular vegetation type very different carbon fluxes may actually be correlated on different sites. Moreover, the change of areas and sites influenced by humans in the past 130 years must be known and scenarios must be available for projections into the future.

Data sets on a country basis are available which include the distribution of agriculturally used areas and their changes in the past. These are mainly based on evaluation of statistical data. According to these data the global agricultural area has developed almost linearly. Data on changes in the past 10 years are particularly uncertain since these generally not distinguish between actually cleared areas (which may have been cleared earlier already) and those which are definitely transformed from natural stands to other forms of land use (i.e. shifting cultivation).

Model results

Carbon turnover by fluxes

The terrestrial biosphere binds carbon at a rate of approximately $50\ 10^{15}$ g [10^9 t]/yr. A similar amount is emitted to the atmosphere by biospheric decomposition processes. Roughly 2/3 of the decomposed amount of carbon originates from the litter pools, about 1/3 from decomposition of soil organic carbon.

The observed temperature rise since 1860 (circa 0.6-0.8°C) has caused an additional emission of CO_2 due to enhanced decomposition processes which probably amounts to $10\ 10^{15}$ g.

Carbon content of biospheric pools

The global phytomass contains circa $650\ 10^{15}$ g carbon. From this pool only $3\ 10^{15}$ g C are due to agricultural crops.

In the period 1860-1950 the global phytomass showed a net reduction of about $40\ 10^{15}$ g C. Since 1950 a minor increase of about $10\ 10^{15}$ g is modelled. The reason for that behavior is discus- sed below.

The litter pool contains about $100\ 10^{15}$ g of carbon. The soil organic carbon adds up to about $1500\ 10^{15}$ g globally.

Considering the fluxes the mean residence time of carbon in the different biospheric pools is 13 years for phytomass, 3 years for litter, and 140 years for soil organic carbon.

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UNCERTAINTIES IN THE DYNAMICS OF THE BIOSPHERE WITH THE ACCENT ON DEFORESTATION

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Introduction

The carbon balance of the terrestrial biosphere is the most complex part of the global carbon cycle. The high diversity of contributing organisms from different life zones, the complexity of space-time scales of the relevant processes, and the high degree of intercorrelations of fluxes and control relations complicate the understanding of the system. Some processes like land-use changes and forest clearings and all processes related to soil organic carbon must be considered especially uncertain.

The entire terrestrial biosphere contains probably three times the amount of carbon in the atmosphere. Roughly 2/3 of the carbon belongs to the soil organic carbon. Circa 50×10^9 tons of carbon are annually fixed through the flux net primary productivity of land surfaces. Decomposition processes eliminate about the same amount and return this to the atmosphere. Medium to long-term disturbances of this production-decomposition equilibrium cause sources or sinks of carbon in terrestrial system, while short-term disturbances which occur during the annual cycle do not contribute to biospheric sources or sinks. The models thus have to quantify small disturbances of large fluxes, while a strong annual cycle is present.

This paper is mainly based on results of the Osnabrück Biosphere Model which calculates the relevant terrestrial processes on a 2.5 degrees grid.

Processes considered by the models

Actual models of the terrestrial carbon cycle are "balancing" models. The changes of carbon pools in those models are calculated by balancing the related fluxes. Single fluxes or groups of closely related fluxes are considered as processes.

Pools

The principal carbon pools of the terrestrial biosphere include:
- Phytomass (carbon pool in living plants).
- Litter (carbon in dead but not yet decomposed plant material).
- Soil organic carbon (the heterogenous pool of carbon contributing to the soil humus).

Those pools are generally subdivided into different compartments which react differently in relation to the fluxes. Litter for example is commonly partitioned into the slowly decomposing polyphenolic compounds (like lignin) and the faster decomposed compounds carbohydrates, proteins, and others.

Fluxes

The principle fluxes which transport the carbon between the biospheric pools and give rise to exchange between biospheric and non-biospheric pools include:
- Net primary productivity (net flux atmosphere → green plants).
- Litter production (flux living phytomass → litter).
- Litter depletion (flux litter → atmosphere).
- Production of soil organic carbon (flux litter → soil organic carbon).
- Depletion of soil organic carbon (flux soil organic carbon → atmosphere).
- Leaching of soil organic carbon (flux soil organic carbon → groundwater → rivers → ocean).