Tellus (1993), 45B, 301–320
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TELLUS
ISSN 0280–6509

Modelling feedback mechanisms in the carbon cycle: balancing the carbon budget

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(Manuscript received 7 May 1992; in final form 16 November 1992)

ABSTRACT

Within the carbon cycle feedback, mechanisms that amplify or dampen the exchange of carbon dioxide between the different reservoirs to enhance concentrations of carbon dioxide and increase temperature from anthropogenic perturbations, play a crucial rôle. Quite a lot of these feedbacks are known, but most of them only potentially. This article evaluates the role of a number of these feedback processes within the carbon cycle. In order to assess their impact, some terrestrial feedbacks have been built into a coupled carbon cycle and climate model, as part of the integrated climate assessment model IMAGE. A number of simulation experiments have been performed with this coupled carbon cycle/climate model to compare historical atmospheric concentration values of carbon dioxide with simulated values. Also global biospheric and oceanic carbon fluxes were validated against other modelling estimates. Based on the assumptions of the IPCC's 1990 Business-as-Usual (BaU-1990) scenario, future projections of the carbon dioxide concentration have been made. A key principle in this is that we have used the modelled feedbacks in order to balance the past and present carbon budget. For atmospheric carbon dioxide, this results in substantially lower projections than the IPCC-estimates: the difference in 2100 is approximately 16% from the 1990 level. Furthermore, the IPCC's 'best guess' or 'central estimate' value of the CO_2 concentration in 2100 falls outside the uncertainty range estimated with our balanced modelling approach. Sensitivity experiments with the model have been performed to quantify to what extent the terrestrial feedback processes and oceanic fluxes influence the global carbon balance in the model. It is shown that a historical and present carbon balance can be obtained in many different ways, resulting in different biospheric fluxes and thus in considerably different atmospheric CO_2 projections.

1. Introduction

Within the carbon cycle, there is an inadequate understanding of the many potential feedbacks such as the response to increasing atmospheric carbon dioxide (CO_2) and rising temperature. These feedback processes belong to the group of biogeochemical feedbacks, which influence the uptake or emission of greenhouse gases and thereby indirectly altering the radiative characteristics of the climate system. The other group of feedback processes can be classified as geophysical feedbacks, which are caused by physical processes in the atmosphere-ocean-cryosphere system and directly affect the response to the radiative forcing. In general, feedback processes can amplify (positive feedback) or damp (negative feedback) the response of the climate system resulting from increased concentrations or radiative forcing. This study primarily focusses on the role of biogeochemical feedbacks within the carbon cycle.

In order to match modelled and observed atmospheric CO_2 concentrations, carbon cycle models can be used in two different way. The methodology which is usually applied is running a carbon cycle model in an inverse mode and deriving net biospheric emissions (inverse modelling), i.e., emissions due to land use changes (mainly deforestation), and other unspecified sources

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and/or sinks. Examples of this approach can be found in Siegenthaler and Oeschger (1987), Enting and Pearman (1987) and Wigley (1991). An important characteristic of those inverse models is that if the net biospheric emissions do not match with current ecological estimates for deforestation and land use changes, then other sinks are introduced in order to balance the global carbon budget. An alternative approach is to run a carbon cycle model in a forward mode, and test a biospheric source hypothesis (forward modelling). For instance Goudriaan and Ketner (1984) have done this. In this study we use a coupled carbon cycle/climate model to balance the global carbon budget. The carbon cycle model is an extended version of that of Goudriaan and Ketner, including a land use cycling model as described in Rotmans and Swart (1991).

This method is not new, because others have done this before. Harvey (1989a) and Wigley (1993) have attempted to balance the carbon budget by changing the CO_2 fertilization feedback and the ocean CO_2 flux. Wigley (1993) has used an inverse carbon cycle model in which he changed the CO_2 fertilization feedback and ocean CO_2 flux in order to balance the carbon budget and also make future CO_2 projections. We use a forward modelling approach which, additionally, includes temperature related feedback terms in order to balance the past and present global carbon budget. After generally discussing the carbon balance concept, we describe our coupled carbon cycle/climate model, followed by a description of how some of the terrestrial feedbacks are incorporated and used in our model. Then we present a series of simulation experiments with the model; finally, the results of a sensitivity analysis are presented and the results are evaluated.

2. The carbon balance concept

The natural global carbon cycle encompasses exchanges of CO_2 between 3 reservoirs of CO_2, the atmosphere, the oceans and the terrestrial biosphere, of tens of billions tons of carbon a year. The extra man-made addition through the burning of fossil fuels and changing land use is relatively small compared with some of these fluxes. However, there is strong evidence to indicate that man-made addition of carbon is the cause for upsetting the balance of the carbon cycle leading to an increase in atmospheric carbon dioxide concentrations. Such evidence includes the isotopic dilution of the atmosphere and surface oceans with respect to radiocarbon and stable carbon isotopes. In the global carbon cycle there are still considerable uncertainties in our knowledge of the present sources and sinks for the anthropogenically produced CO_2. The total anthropogenic flux to the atmosphere is surrounded by uncertainties. In fact, only the source from fossil fuel combustion is well known, in contrast with the source from land use changes, which is poorly known. The amount of carbon remaining in the atmosphere is the only well known component of the budget. With respect to the oceanic and terrestrial sink, the likely errors are of the order $\pm 100\%$. Many of the uncertainties arise from the lack of adequate data. Another important source of uncertainty is the deficient knowledge of the key physiological processes within the global carbon cycle. The uncertainties can be expressed explicitly by the formulation of a basic mass conservation equation which reflects the global carbon balance, as defined in eq. (1):

$$\frac{\mathrm{d}C}{\mathrm{d}t} = E_{\mathrm{fos}} + E_{\mathrm{land}} - S_{\mathrm{oc}} + I, \tag{1}$$

where $\mathrm{d}C/\mathrm{d}t$ is the change in atmospheric CO_2 (in GtC/yr), E_{fos} denotes the CO_2 emission from fossil fuel burning (GtC/yr), E_{land} the CO_2 emission from changing land use (GtC/yr), S_{oc} represents the CO_2 uptake by the oceans (GtC/yr). Based on best available current knowledge of the sources and sinks of CO_2, which is a mixture of observations and model-based estimates, it is not possible to obtain a balanced carbon budget. To balance the carbon budget, a rest term is introduced, I, which represents the missing sources and sinks. I might therefore be considered as an apparent net imbalance between the sources and sinks. Table 1 presents the global carbon balance over the last decade 1980-1989 in terms of anthropogenic-induced perturbations to the natural carbon cycle. Watson et al. (1990) estimate an apparent imbalance between the sources and sinks of 1.6 GtC/yr over this period. This results from a total source of 7.0 ± 1.1 GtC/yr (5.4 ± 0.5 GtC/yr by fossil fuel burning and 1.6 ± 1.0 GtC/yr by land use change) and a total sink of 5.4 ± 1.0 GtC/yr

Table 1. *Components of the carbon dioxide mass balance (Watson et al., 1990)*

Component	1980–1989[1] (GtC/yr)	
change in atmospheric mass of CO_2 (dC/dt)	3.4 ± 0.2	observed
uptake by the oceans (S_{oc})	2.0 ± 1.0	model-based
emissions from fossil fuel burning (E_{fos})	5.4 ± 0.5	observed
emissions from land use change (E_{land})	1.6 ± 1.0	observed
net imbalance ($I = dC/dt + S_{oc} - E_{fos} - E_{land}$)	-1.6 ± 1.4	

(3.4 ± 0.2 by accumulation in the atmosphere and 2.0 ± 1.0 by oceanic uptake). Three possible reasons are suggested for this imbalance over the last decade: (i) the CO_2 uptake by the oceans is underestimated, (ii) the deforestation in the tropics may be overestimated, (iii) there may be a net uptake by the terrestrial ecosystems at higher latitudes (Watson et al., 1990).

The analysis of the net imbalance in the carbon cycle has become a major issue during the last years, particularly the question how to account for very large carbon sinks in the terrestrial biosphere in the northern temperate latitudes. This interest was stimulated by Tans et al. (1990), who suggested that the oceans have taken up no more than 1.0 GtC yearly during the decade of the 1980s (1981 till 1987), making use of an atmospheric transport model with a compilation of observations of air-sea CO_2 difference. This low ocean sink would imply an even larger imbalance, which in this study is attributed to a net carbon sink in the terrestrial ecosystems in the northern temperate latitudes on the order of 1.6–2.4 GtC/yr over the 1980s. The low ocean sink of Tans et al. (1990) is less likely, because some of the high latitude ocean sink processes act on time and space scales not resolved in their analysis (Wigley, 1991). Many other studies using tracer-calibrated models estimate an ocean uptake of about 2 GtC/yr. For example, Sarmiento et al. (1992) give an estimate of 1.9 GtC/yr for the decade 1980-1989 (which is considered as a lower limit by the authors), making use of a 3-dimensional ocean model, which is validated against bomb radiocarbon observations. Quay et al. (1992) give an estimate of 2.3 GtC/yr for the period 1970 till 1990, making use of direct measurements of the relative decline in $^{13}C/^{12}C$ ratios in dissolved inorganic carbon in the ocean and carbon dioxide in the atmosphere. Furthermore, analyses of Heimann and Keeling (1986), Keeling and Heimann (1986), and Broecker and Peng (1992) indicate a flow of carbon from north to south through the ocean, balanced by a return flux through the atmosphere. The existence of this oceanic carbon pump is also inconsistent with the need of a large terrestrial carbon sink in the Northern Hemisphere, as proposed by Tans et al. (1990).

Recent findings with respect to the large terrestrial sink are summarized by the Intergovernmental Panel on Climate Change (IPCC) (Houghton et al., 1992), in which it was stated that: (1) net carbon added to the atmosphere in the tropics is less than expected from deforestation; (2) a strong Northern Hemisphere sink with an oceanic and terrestrial biospheric component, compared to a weak Sourhern Hemisphere sink must exist; (3) the likeliest terrestrial biospheric processes contributing to large sinks are CO_2 and N fertilization. The latter through increased N deposition due to air pollution and increased fertilizer use could sequester an additional amount of 1.0 GtC/yr during the last decade. Recent work of Kauppi et al. (1992), however, shows that the European forests may have been a sink for carbon in recent decades, but that this is probably not only due to the fertilization effect, but also due to regrowth at middle and high latitudes and improved forest management. The latter in turn may depend on better management and/or regrowth of the temperate and boreal forests or is possibly caused by fertilization of the forest ecosystems in general due to increasing carbon dioxide concentrations in the atmosphere.

These findings underline the importance of negative feedback processes in the global carbon cycle. In carbon cycle models one or more of these feedbacks can be used to balance the global carbon budget (e.g., Goudriaan and Ketner, 1984; Enting and Pearman, 1987; Wigley, 1993). In this study we try to balance the carbon budget for the period 1760–1990, by varying model parameters which represent the feedback processes: namely the CO_2

fertilization effect and temperature feedbacks on the rates of net primary production and respiration within the terrestrial biosphere. This is done in an iterative way such that the simulated atmospheric CO_2 values match well with historical estimates from CO_2 measurements of air trapped in ice core bubbles (Barnola et al., 1987; Neftel et al., 1985; Friedli et al., 1986) and, from 1958, with direct measurements at Mauna Loa (Keeling et al., 1989). We do not consider, however, the second possibility (lower deforestation values), because our simulated gross CO_2 emissions due to deforestation are already comparatively low, about 1.4 GtC in 1990 (Rotmans and Swart, 1991).

3. Description of the carbon cycle/climate model

To balance the global carbon budget by incorporating biogeochemical feedbacks we use a coupled carbon cycle/climate model. This coupled model is an essential part of the Integrated Model to Assess the Greenhouse Effect (IMAGE). The original version of the IMAGE model, version 1.0, is described in detail in Rotmans (1990), while we use here version 1.5. The carbon cycle model of this version is an extended version of that of Goudriaan and Ketner (1984), and consists of an ocean box-diffusion model, a terrestrial biosphere model and an atmospheric box model. The model starts running in 1760, with a time-step of 1 year, assuming a steady state initially, before the anthropogenic disturbances are imposed upon the system.

The box-diffusion model of the ocean is a slightly modified version of that of Goudriaan and Ketner (1984), see Fig. 1. Three primary processes are modelled: transport of dissolved carbon by up- and downwelling, through turbulent mixing or vertical diffusion and through precipitation of carbonates. Atmospheric carbon dioxide enters the ocean by gas exchange between the atmosphere and the two surface ocean boxes which are assumed to be well mixed. The chemical processes of gas exchange and equilibrium with CO_2 in the atmosphere are represented by the Revelle differential equation (Björkström, 1979; Rotmans, 1990).

The terrestrial biosphere is categorized into 7 types of ecosystems: closed and open tropical

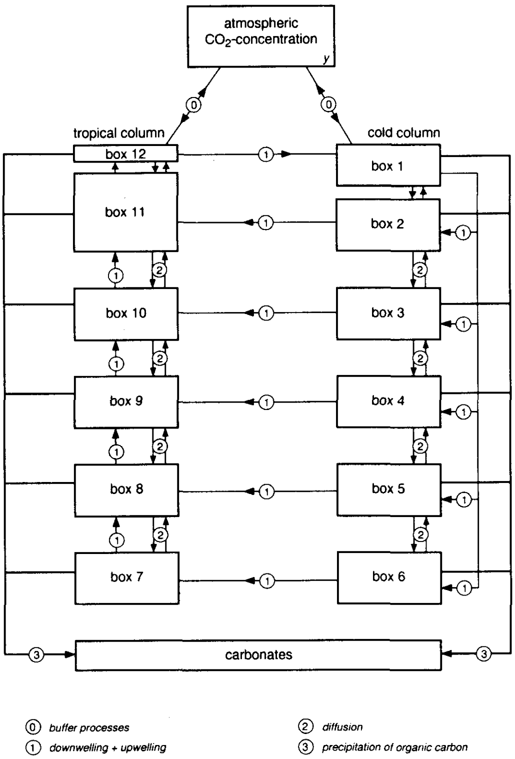


Fig. 1. Systems diagram of the carbon cycle 12-layer ocean model.

forest, temperate forest, agricultural and pasture land, human area, and semi-desert or tundra land. Each of these ecosystems is further partitioned into carbon reservoirs such as biomass (leaves, branches, stems, roots), litter, humus and charcoal, so as to represent the stages of cycling of carbon through each ecosystem. The systems diagram for a single ecosystem is given in Fig. 2, where the natural flows of carbon within a particular ecosystem are sketched. Atmospheric CO_2 is consumed in the process of net primary production and the amount of carbon transferred depends on the area of land allocated to the particular ecosystem and on the rate of exchange of carbon between the biomass reservoir in each ecosystem. The carbon thus consumed is partitioned among the structures of the plant, i.e. the leaves, branches, stems and roots. These biomass pools then decay and the carbon passes through the litter, humus and charcoal reservoirs, giving off carbon dioxide

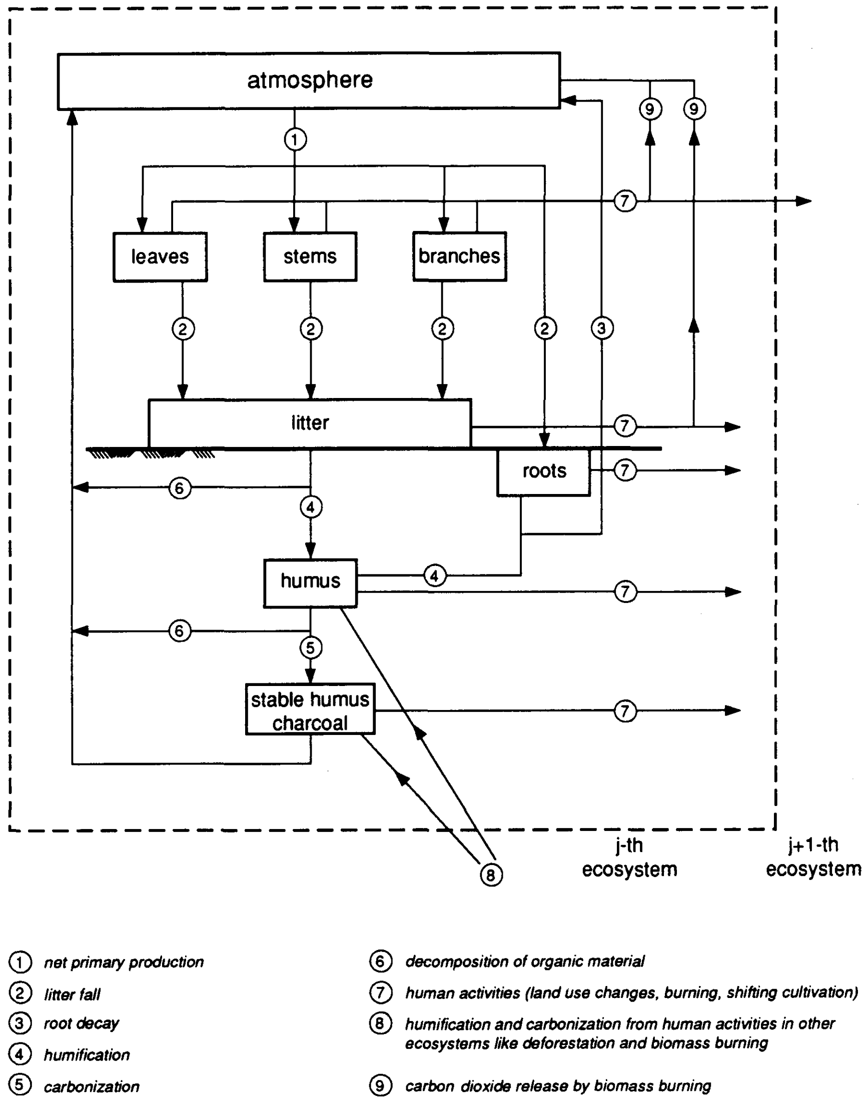


Fig. 2. Systems diagram of the *j*th ecosystem of the terrestrial biota model.

as part of the decay process, and returning carbon to the atmosphere. These natural processes are modelled as exponential decay, and are essentially linear (natural decomposition).

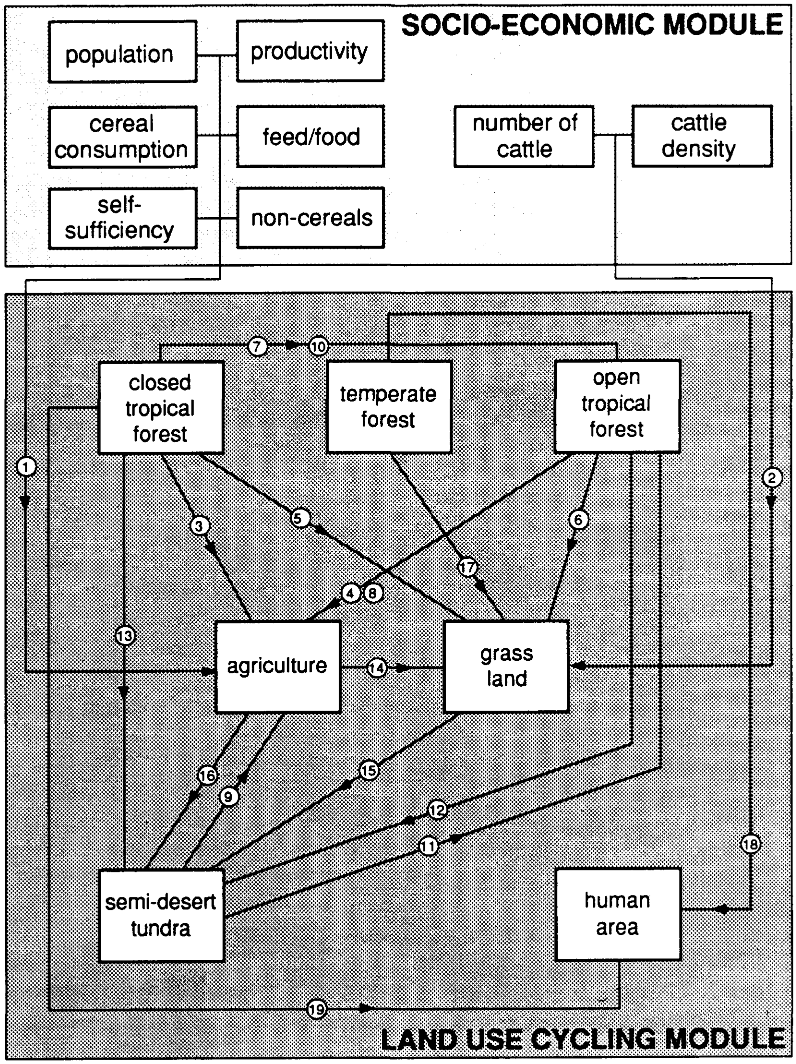
Imposed on this natural system is a reallocation of land areas through human activities like agriculture, shifting cultivation, commercial wood production, cattle breeding, fuelwood gathering, burning of forest, reafforestation and industrial activities. This affects the various carbon pools differently, and also acts to transfer humus, litter and charcoal to different land uses. In Table 2, the simulated sizes of the pools and fluxes for each of the ecosystems are presented for 1990. Next to the natural carbon flows, Fig. 2 also shows the anthropogenic component, represented by arrows flowing out to the right, indicating the flow of carbon to carbon pools in the other ecosystems.

Table 2. *Simulated pools and fluxes (in GtC) of the terrestrial part of the global carbon cycle model for 1990*

1990	Trop. closed forest	Trop. open forest	Temp-erate forest	Grass-land	Agri-cultural land	Human area	Semi-desert	Total
pools:								
leaves	6.46	2.19	5.62	5.88	4.48	0.08	1.24	25.95
branches	40.86	12.91	18.29	0	0	0.49	2.41	75.0
stems	169.0	67.90	153.53	0	0	2.66	11.35	403.5
roots	40.86	12.91	18.29	3.90	1.12	0.49	1.49	79.1
litter	16.08	4.91	14.30	8.29	3.53	0.36	3.40	50.9
humus	84.28	69.29	270.70	222.6	28.82	12.72	83.44	771.9
charcoal	234.2	95.10	138.13	213.4	71.88	15.41	57.10	825.1
fluxes:								
NPP								
leaves	6.50	2.22	2.83	7.12	5.68	0.08	1.25	25.7
branches	4.33	1.48	1.89	0	0	0.06	0.25	8.0
stems	6.50	2.22	2.83	0	0	0.08	0.25	11.9
roots	4.33	1.48	1.89	4.75	1.42	0.06	0.75	14.7
total	21.70	7.42	9.43	11.87	7.10	0.28	2.49	60.3
litter fall								
leaves	6.46	2.18	2.81	5.88	4.48	0.08	1.24	23.1
branches	4.08	1.29	1.83	0	0	0.05	0.24	7.5
stems	5.63	1.51	2.54	0	0	0.05	0.23	10.0
root decay	2.16	0.68	0.97	2.10	0.60	0.03	0.39	6.9
humification								
root	1.92	0.61	0.86	1.82	0.52	0.02	0.35	6.1
litter	6.43	1.96	4.29	2.48	0.71	0.09	1.02	17.0
carbonization	0.42	0.14	0.27	0.28	0.06	0.01	0.08	1.25
decomposition								
litter	9.65	2.95	2.86	1.66	2.83	0.09	0.68	20.7
humus	8.0	2.63	5.14	5.28	1.10	0.24	1.59	24.0
charcoal	0.47	0.19	0.28	0.43	0.14	0.03	0.11	1.65

The skew lines of Fig. 2 denote the corresponding flows from the other 6 ecosystems back into this ecosystem (humification and carbonization processes).

The land use model, consisting of a socio-economic module and a land use cycling module, is represented by the systems diagram of Fig. 3, for each of the continents of Africa, Latin America and South East Asia. All converted forests are assumed to end up as agricultural or pasture land, degraded land and semi-desert, or re-established forests (by reforestation). Deforestation is triggered by a variety of processes, which are mainly caused by a number of demands driven by growth of population and economy, see Fig. 3. At any time the expansion of agricultural land, both as permanent agriculture and shifting cultivation, is distributed over the ecosystems closed and open tropical forests and other land (semi-desert or tundra land). This distribution mechanism is done according to soil suitability, estimated by Bouwman (1989) and presented in Swart and Rotmans (1989). The expansion of pasture into closed and open tropical forest is distributed according to the ratio between the initial and current amount of closed and open tropical forest. The impact of logging on tropical deforestation is assumed to be proportional to the expected growth rate of hardwood production and the harvesting efficiency. Reafforestation is included by scenario-dependent logistic functions. Deforestation through fuelwood gathering is taken proportional to the rural population growth. Although it is very difficult to estimate, an attempt was made to quan-



1. demand for food production
2. demand for grassland
3. expansion of arable land into closed tropical forest
4. expansion of arable land into open tropical forest
5. expansion of pasture into closed tropical forest
6. expansion of pasture into open tropical forest
7. shifting cultivation in closed tropical forest
8. shifting cultivation in open tropical forest
9. expansion of agriculture land into other land
10. logging by commercial wood production
11. development of plantations
12. fuelwood gathering
13. industrial or mining projects
14. degradation of arable land
15. degradation of pasture
16. desertification of agriculture land
17. expansion of pasture into temperate forest
18. temperate deforestation
19. urbanization

Fig. 3. Systems diagram of the land use categories and processes in the land use model.

tify the impact of industrial, mining or infrastructural projects. The processes which generate the demand, how the demand is met, and the subsequent associated processes, are all described in detail in Rotmans and Swart (1991).

The simulated land use changes lead to gradual transitions of one parcel of land of one ecosystem to another. In the model this exchange of land between the ecosystems is represented by a time dependent land transfer matrix of which the elements indicate the annual transfers of land from one ecosystem to another. Shifting from an ecosystem which contains much carbon to one with little carbon, as is the case with deforestation, results in a net release of CO_2 from the terrestrial biota to the atmosphere.

The net relase of CO_2 resulting from conversion of tropical forest land into another ecosystem depends on the area transferred, the carbon density in biomass and litter of the ecosystems considered and the amount of carbon in biomass and litter that is channeled to the atmosphere (determined by carbonization and humification fractions). The total deforestation flux equals then the sum of the contributions from the conversions of areas of tropical forests into agricultural and pasture land, and human and semi-desert/tundra area.

The climate model which is coupled to the carbon cycle model is an energy balance box upwelling-diffusion model, based on Wigley and Schlesinger (1985) and Wigley and Raper (1987). The climate model includes a land box, an ocean box and atmosphere boxes over land and ocean. This model fully parameterizes the exchange of heat between the different boxes. The thickness of the mixed ocean layer is 75 meter, while the thickness of the deep ocean layer is 4000 m, consisting of 40 layers of 100 m. The thermal diffusivity is assumed to be constant and is used as a substitute for complex circulation process that transport heat. Vertical upwelling is parameterized by a globally averaged vertical velocity of 4 m/yr.

4. Model description of the terrestrial feedbacks used

4.1. Introduction

Enhanced atmospheric CO_2 concentrations and increased temperatures affect various components of a plant's carbon budget, including: photosynthesis, respiration, biomass accumulation and allocation (Melillo et al., 1990). For a more general description of these biogeochemical feedbacks we refer to Watson et al. (1990), Lashof (1989) and Harvey (1989b). In this study we consider the following terrestrial feedback processes: the CO_2 fertilization effect and the temperature effects on net primary production and respiration of soil and litter. Although we have implemented a highly parameterized oceanic feedback on vertical diffusion and an ocean temperature/chemistry feedback (Den Elzen et al., 1991), we do not present variations of these oceanic feedbacks in this study. This because of the extreme uncertainties of the feedback concepts in the ocean, and also because the first experiments with these positive feedbacks in our coupled carbon cycle/climate model showed the effects to be negligible in comparison with some of the terrestrial feedbacks. Fig. 4 gives an overview of the terrestrial feedbacks modelled in the coupled carbon cycle/climate model. Below we describe the modelling backgrounds and assumptions of the various terrestrial feedbacks which are incorporated in our model.

4.2. Carbon dioxide fertilization

Short-term experiments under controlled conditions show for most plants an increasing photosynthetic rate, water use efficiency and plant growth (thus fixing more carbon) at enhanced CO_2 levels (Strain and Cure, 1985). The few experiments done at the ecosystem level, however, show a diverse response. The response of a single species is shown to become highly modified at the ecosystem level, and is not representative for the response of a whole ecosystem (Bazzaz, 1990). If increased CO_2 concentrations enhanced the productivity of natural ecosystems, more carbon may be stored in woody-tissue or soil organic material. In general the response of forests, with their high contribution to global photosynthesis, is of high importance (Luxmoore et al., 1986), but so far no experiments have yet been done in forested systems.

We modelled the CO_2 fertilization process by using the logarithmic relationship between elevated CO_2 and net primary production (NPP), as used by Gifford (1980) and Goudriaan and Ketner (1984). In this relationship the global biotic growth factor (or fertilization factor) β

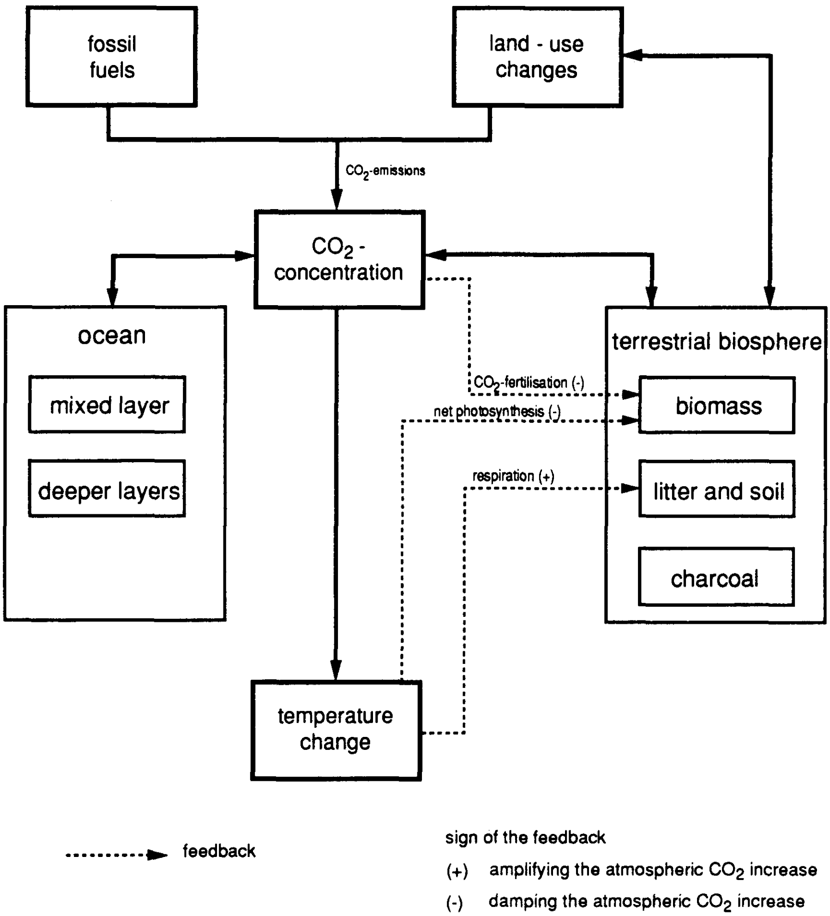


Fig. 4. Biogeochemical feedbacks within carbon cycle.

reflects the fractional increase in NPP due to a fractional increase in atmospheric CO_2 concentration.

$$\frac{\mathrm{dNPP}}{\mathrm{NPP_{ic}}} = \beta * \frac{\mathrm{d}p\,\mathrm{CO_2}}{p\,\mathrm{CO_2}}. \tag{2}$$

where dNPP is the change in net primary production [GtC/yr], NPP_{ic} the initial primary production in 1760 [GtC/yr], β the biotic growth factor, $dpCO_2$ the change in the atmospheric CO_2 concentration [ppmv/yr] and pCO_2 the atmospheric CO_2 concentration [ppmv]. Although our terrestrial biota model is divided into seven ecosystems, we use only one, global, β-factor for the net primary production. The value of this β-factor varies greatly in the different carbon cycle models, because it is usually used as a tuning factor to get a balanced carbon budget. Kohlmaier et al. (1989) decouple soil and litter respiration and net primary production, and let a global β-factor ($=0.375 \pm 0.225$) affect both processes. Goudriaan and Ketner (1984) use a β-factor of 0.5, necessary to reproduce the measured atmospheric CO_2 trend over the period 1958 to 1980. Bacastow and Keeling (1973) indicate a range of 0.2 to 0.6 for simulating the correct CO_2 build-up over the period 1959 to 1969. Experiments on single plants in greenhouses under optimal supply of nutrients, show values of the biotic growth factor up to 0.7 (Goudriaan and de Ruiter, 1983). At such ideal growing conditions Gates (1985) measured a

β-factor of 0.5–0.75 for a variety of plants at 340 CO_2 ppmv, decreasing to 0.3–0.5 at 680 ppmv. Taking into consideration the foregoing estimates of the β-factor, and after having compared our modelling results with the observed atmospheric CO_2 values by a trial and error analysis, we adopt a 'best guess' or 'central estimate' value of 0.40, with an uncertainty range of 0.1 to 0.5.

4.3. *Temperature feedbacks*

In this study, we take account of two terrestrial temperature feedbacks: the temperature feedback on the net primary production (net photosynthesis minus respiration of non-photosynthetic plant parts) and the temperature feedback on the respiration of soils and litter. A global temperature increase results in an increasing net primary production (negative feedback), while the effect on soils and litter respiration will be a release of carbon to the atmosphere (positive feedback). A key point of discussion in the literature is the sign of the total temperature effect on respiration and net primary production (see, e.g., Harvey, 1989b). Watson et al. (1990) state that the temperature effect on respiration will dominate the temperature effect on the net primary production, and thus will amplify global warming. Estimates of this additional flux vary from one to a few GtC per year. Recently Jenkinson et al. (1991) underscored the potential importance of this enhanced soil respiration feedback.

In many regions, however, the effects of precipitation changes and moisture availability are at least as important as the temperature effects on net primary production. Because it is currently impossible to project future precipitation in a global way we do not consider precipitation related feedbacks, although this is a serious shortcoming of our approach. Harvey (1989b) considers a temperature feedback on the net photosynthesis and a temperature feedback on the translocation of non-photosynthetic products from non-woody to woody tree parts. In our analysis both feedbacks are embedded in the temperature feedback on the net primary production. In our carbon cycle model, the net primary production is partitioned among the four major components: leaves, branches, stems and roots according to fixed partitioning coefficients (Goudriaan and Ketner, 1984). The temperature effect on these coefficients, also a part of the temperature feedback on translocation, as proposed by Harvey (1989b), is assumed to negligible.

Net primary production. Both photosynthesis and respiration are stimulated by a temperature increase. The magnitude of this effect is dependent on the temperature domain. Above 0°C, gross photosynthesis initially responds rapidly to temperature, but slows down in the optimum range (20–35°C). In contrast, the response of respiration is relatively slow below 20°C, but at higher temperatures it accelerates rapidly up to 40°C (Melillo et al., 1990). As a result of these processes the response of the net photosynthesis to temperature increases from zero to an optimum value (at 20–35°C), and then decreases to zero at higher temperatures.

The general response of plant growth shows a similar pattern (Fitter and Hay, 1981). Although the processes of photosynthesis and respiration are described by a parabolic and exponential function of temperature, respectively, here the temperature-dependence of these metabolic processes is taken to be exponential for both and is expressed by a Q_{10} value, indicating the rate of increase of each process at a 10°C temperature rise. We assume this Q_{10} formulation be valid, while the temperature changes are small compared to the present climate. The temperature effect on net primary production is modelled by adding to eq. (2) the Q_{10} value and the global surface temperature increase (ΔT_s):

$$\mathrm{NPP} = \mathrm{NPP}_{\mathrm{ic}} \left(1 + \beta * \ln \frac{p\mathrm{CO}_2}{p\mathrm{CO}_{2,\mathrm{ic}}}\right) \times \exp\left(\frac{\Delta T_s}{10} \ln Q_{10}^{\mathrm{npp}}\right), \tag{3}$$

where $pCO_{2,ic}$ denotes the initial atmospheric CO_2 concentration (in 1760).

To account for spatial variations in temperature, we allow Q_{10} to be temperature dependent. To do this, we have schematized photosynthetic and respiration response data of Fitter and Hay (1981), by defining eight different temperature domains of 5 degrees, represented as $[1 \cdots 5]$, ..., ..., $[36 \cdots 40]$°C, respectively. The $Q_{10}^{\mathrm{nnp}}(\tau)$ then represents the Q_{10}-value for net primary production, valid within the temperature range τ, where τ indicates the 8 different temperature domains of 5 degrees. Using the NPP data of Olson et al. (1983), den Elzen et al. (1991)

derive the following Q_{10} value for net primary production:

$$Q_{10}^{\mathrm{npp}} = \left[\sum_{\tau=1}^{8} \mathrm{NPP}_{\mathrm{ic}}(\tau)\, Q_{10}^{\mathrm{npp}}(\tau) \right] \Big/ \mathrm{NPP}_{\mathrm{ic}}, \qquad (4)$$

where $\mathrm{NPP}_{\mathrm{ic}}(\tau)$ [GtC/yr] is the initial net primary production of all territories where the average annual temperature lies within the temperature range τ. The resulting weighted average Q_{10} value (Q_{10}^{npp}) for the net primary production is 1.4. Many others have derived Q_{10} values for net primary production. Harvey (1989b), for instance, assumed an effective Q_{10} value for net primary production of 1.4, based on a Q_{10} value for the net photosynthesis of non-woody tree parts of 1.53 and a Q_{10} value for the respiration of woody tree parts of 2.0. Other estimates vary between 1.0 to about 2.0, also dependent on the temperature domain and type of ecosystem considered (Webb et al., 1983; Esser, 1987; Kohlmaier et al., 1990). Given these reported values, we consider a range of Q_{10} values, from 1.0 to 2.0 (see Table 3), with a central estimate value of 1.4.

Litter and soil respiration. The Q_{10} value for the soil and litter respiration varies greatly in the literature. Kohlmaier et al. (1990) estimate the Q_{10} value of this respiration between 1.3 and 4.0, substantially more than the Q_{10} value for net primary production. Harvey (1989b) adopts a Q_{10} value of 2.0, with an uncertainty range from 0.77 to 3.1, where the smaller values correspond with lower moisture availability. Based on these estimates we use a central estimate value of 2.0, with an uncertainty range between 1.0 and 3.1 (Table 3). In the model the litter and soil respiration directly affects the net ecosystem production (NEP), which is the net growth of an ecosystem:

$$\mathrm{NEP} = \mathrm{NPP} - (\mathrm{d}L + \mathrm{d}H) \times \exp\left(\frac{\Delta T_s}{10} \ln Q_{10}^{\mathrm{res}}\right) - \mathrm{d}C - \mathrm{d}B, \qquad (5)$$

where $\mathrm{d}L$, $\mathrm{d}H$, $\mathrm{d}C$ and $\mathrm{d}B$ denote, for each ecosystem, the decay of litter, humus, and charcoal, and the changes in biomass by the decay of roots [GtC/yr], respectively. Q_{10}^{res} represents the Q_{10} value for the respiration of soils and litter.

5. Results

5.1. Past CO_2-concentration changes

To examine the role of the feedbacks modelled, we use the historical concentration values of carbon dioxide, from 1760 to 1958, as indicated from measurements on air trapped in ice from Siple Station, Antarctica (Neftel et al., 1985; Friedli et al., 1986), and measured at Mauna Loa from 1958 to 1990 (Keeling et al., 1989). As a first experiment we run our model with no feedbacks. The resulting simulated atmospheric CO_2 values are depicted in Fig. 5, together with the observed CO_2 values. Comparing both trends shows us that the simulated atmospheric CO_2 concentrations are higher than the observed concentrations, implying an apparent imbalance in our model. In 1990 the simulated CO_2 concentration is 374 ppmv, whereas the observed annual average value for 1990 is 353 ppmv (Watson et al., 1990). For the period 1850–1990 (the starting year 1850 is chosen, because this year is also used by Watson et al. (1990) in their cumulative carbon fluxes) there is

Table 3. *'Best guess' or 'central estimate' values and uncertainty ranges for the various feedback parameters*

Feedback parameter	Min	Central est.	Max
Q_{10}^{npp} = factor by which the net primary production increases for a 10°C temperature increase	1.0	1.4	2.0
Q_{10}^{res} = factor by which the litter and soil respiration increases for a 10°C temperature increase	1.0	2.0	3.1
β = fertilization factor	0.0	0.40	0.5

Table 4. *Components of the modelled carbon dioxide mass balance of our study with and without feedbacks*

Component	1980–1989 (GtC/yr) no feedbacks	1980–1989 (GtC/yr) with feedbacks	1850–1989 totals (GtC) no feedbacks	1850–1989 totals (GtC) with feedbacks
observed change in atm. CO_2 (dC/dt)[a]	3.4	3.4	144	144
modelled change in atm. CO_2 (dC/dt)[b]	4.25	3.4	188	144
uptake by the oceans (S_{oc})	2.5	2.15	135	117
emissions from fossil fuel burning (E_{fos})	5.4	5.4	219	219
emissions from land use change (E_{land})	1.35	0.15	104	45
apparent net imbal. ($I = dC/dt + S_{oc} - E_{fos} - E_{land}$)	−0.85	0.0	−44	−3

[a] The historical concentration values of carbon dioxide from 1750 to 1958 are based on measurements on air trapped in ice from Siple Station, Antarctica (Neftel et al. 1985a; Friedli et al. 1986), and from 1958–1989 measured at Mauna Loa (Keeling et al., 1989).

[b] In the model calculations this net imbalance is stored in the atmosphere, leading to higher CO_2 concentrations than the observed values over the historical period.

an apparent imbalance of carbon of about 44 GtC in our model (see Table 4). Wigley (1993) obtains a central value for the imbalance of about 80 GtC over 1850–1989. This difference can be explained by the higher estimates of land use changes (123 GtC, based on the 1850–1986 estimate of Watson et al. (1990)) and lower ocean uptake (113 GrC) in Wigley's model. Over the 1980s (1980–1989) our model gives an annual apparent imbalance of about 0.85 GtC, which must be stored either in the oceans or in the terrestrial biosphere.

From this experiment, it can be concluded that the observed values can be simulated with the model only if an additional sink is introduced. We therefore consider for this unbalanced case the global fluxes between the oceans and the atmosphere, and the terrestrial biosphere and the atmosphere. Fig. 6 shows the global fluxes produced by the model which represent the CO_2 uptake by the oceans, the net release of CO_2 due to land use changes (encompassing deforestation) and the emissions of CO_2 by fossil fuel combustion. Analysing these

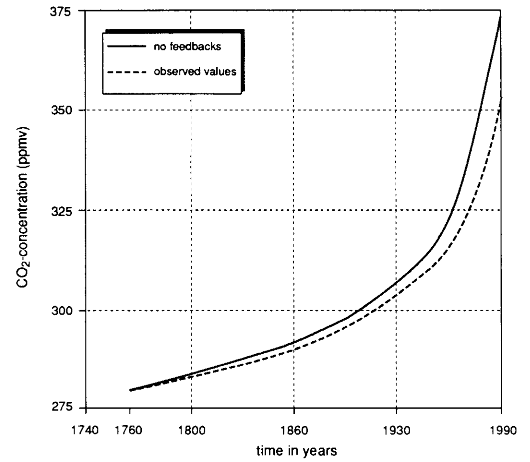


Fig. 5. CO_2 concentration over the period 1760 to 1990 (no feedbacks).

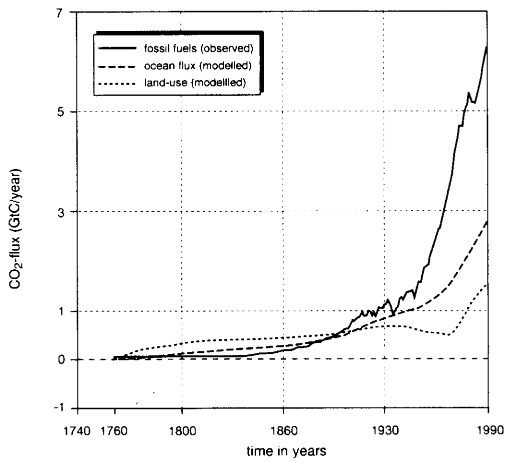


Fig. 6. Components of the carbon budget over the period 1760 to 1990 (no feedbacks).

fluxes shows that, when running the model with no feedback processes, the ocean CO_2 uptake, directly obtained from the model, is rather high (approximately 2.5 GtC/yr during the 1980s, being higher than the sparsely measured ocean uptake of CO_2). The cumulated oceanic CO_2 flux over the period 1850–1990 is 135 GtC, which is also relatively high compared to the central value of 113 GtC given by Wigley (1993) (see Table 4, case without feedbacks). On the other hand, the magnitude of the terrestrial flux to the atmosphere generated by the model is about 1.35 GtC/yr during the 1980s. The cumulated land use flux over 1850–1990 amounts to 104 GtC, which is lower than Wigley's central estimate value of 123 GtC based on Watson et al. (1990). Our simulated land use flux in Figure 6 shows a trend which is similar to the biospheric carbon flux presented by Houghton and Woodwell (1989); although, in general, the magnitude of our flux is somewhat smaller than that of Houghton and Woodwell. This may be due to our maybe too conservative socio-economic assumptions which trigger the land use changes in our land use model. These results indicate that, under the condition that we do not change the source in our model, the surplus of carbon should be stored by the creation of a terrestrial sink in the model, rather than by raising the already high CO_2 uptake of the oceans.

These conclusions lead us to experiments in which we explore the rôle of feedback processes. For these experiments, the central estimate values for the various feedback parameters are chosen, which are based on recent literature for the temperature related feedbacks and on a trial and error balancing analysis for the fertilization feedback.

Table 3 shows the central estimate values as well as uncertainty ranges considered here for the various feedback parameters. Starting with the observed value at $t = 0$, and taking the central estimate values, the simulated curve fits well with the observed atmospheric CO_2 concentrations, as is shown in Fig. 7.

Table 4 summarizes the simulated values of the different components of the carbon dioxide mass balance for the 1980s, as well as the cumulated values over the period 1850–1989. This Table shows that, when feedbacks are taken into account, the carbon budget balances over the 1980s, which implies that the CO_2 flux resulting from modelled feedbacks is about 0.85 GtC/yr (i.e., the apparent net imbalance of the carbon budget when no feedbacks are considered). It should be noted, however, that the balance is not perfect, but rather quite close. For example, the relative difference between observed and modelled atmospheric CO_2 during the 1980s is about 0.25% (or 1 ppmv). If in the following, the difference is on that order of magnitude, it is denominated as 'well-balanced'. Over the period 1850–1990 the

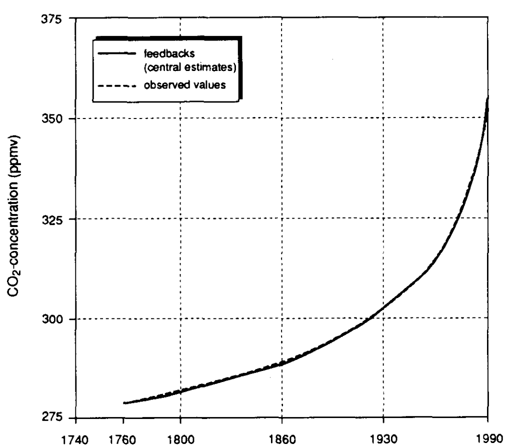


Fig. 7. CO_2 concentration over the period 1760 to 1990 (with feedbacks).

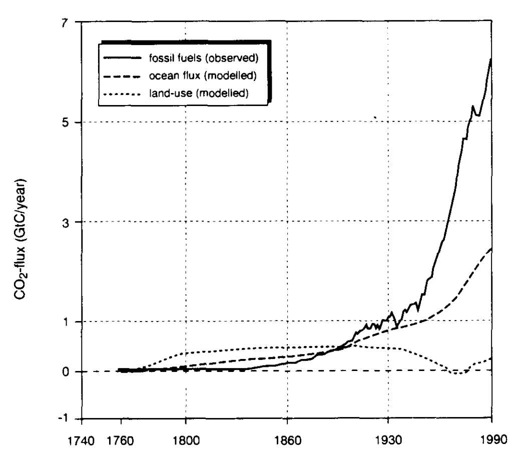


Fig. 8. Components of the carbon budget over the period 1760 to 1990 (with feedbacks).

cumulated flux due to the feedbacks (CO_2 fertilization effect) amounts to 44 GtC, i.e., the apparent net imbalance in the case without feedbacks).

Global fluxes for the period 1760–1990 are pictured in Fig. 8. Taking account of the terrestrial feedbacks leads to a global terrestrial biosphere flux that is much smaller than in the unbalanced case (Fig. 6). The biospheric carbon flux shows a decreasing trend in the 20th century, which is in contrast with the biospheric flux extimates of Houghton and Woodwell (1989), but within the uncertainty range of the past net biospheric emissions given by Siegenthaler and Oeschger (1987). Houghton and Woodwell (1989), however, do not take into account the potential carbon uptake by CO_2 fertilization, while Siegenthaler and Oeschger (1987) estimate the net biospheric flux including possible feedbacks. Comparing our model flux estimates with those of Wigley (1991) gives a similar pattern. Over the period 1900–1980, Wigley (1991) estimates a biospheric flux of only 14 GtC, while our model gives about 20 GtC. For the period 1960–1980 our model generates a net biospheric CO_2 sink, which is comparable with the net biospheric sink over the interval 1950–1983 presented by Wigley (1991). In this balanced case the simulated ocean flux is now around 2.15 GtC/yr during the 1980s, wich is in better accordance with Watson et al. (1990).

5.2. *Future CO_2-concentration projections*

We now calculate future atmospheric CO_2 concentrations for the IPCC's 1990 Business-as-usual (BaU–1990) scenario, which is described in detail in IPCC (1991). We use in these calculations the central estimate values for the feedback parameters, since these lead to a well-balanced carbon budget over the period 1760–1990. Starting with a well-balanced budget in 1990, our atmospheric CO_2-concentrations for the BaU–1990 scenario are compared with the IPCC-results (Figure 9). Furthermore an uncertainty range is presented in this Figure which is based on variations of the feedback parameters and ocean fluxes. This means that the feedback parameters and ocean fluxes are set on their minimum or maximum levels (see Table 3 and Table 7, of which the latter is explained in the section on sensitivity experiments). The sets of parameter combinations used here result in a well-balanced carbon budget, so they represent a balanced uncertainty range. Our central estimate value is lower than the IPCC-value: in 2100 our simulated CO_2 concentration is 761 ppmv, while the IPCC's central estimate is 827 ppmv, a difference of approximately 16% from the 1990 level. The scenario assumptions we use for BaU–1990 are similar to those made by the IPCC (IPCC, 1991). The fossil fuel inputs are equal to the IPCC-values, while the socio-economic assumptions in our land use model (described in Rotmans and Swart, 1991) are such, that our gross deforestation trend is comparable with the (rather strange) IPCC–1990 deforestation trend. This is shown in Fig. 10. The cumulated

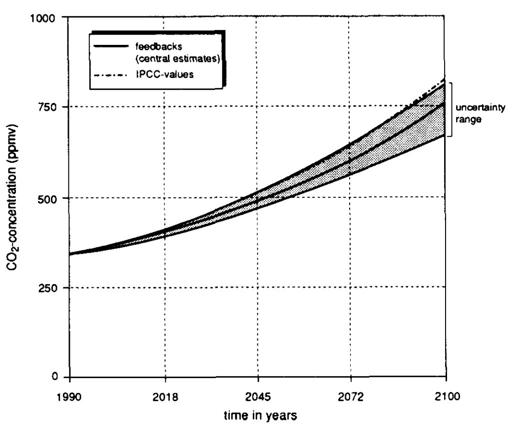


Fig. 9. CO_2 concentration for the IPCC's 1990 Business-as-Usual scenario; the uncertainty range is based on a variation of the feedback parameters.

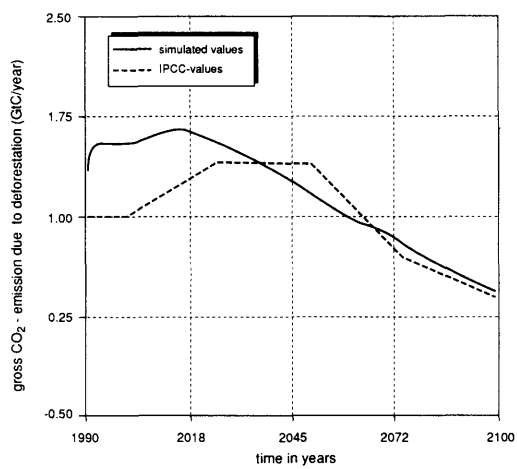


Fig. 10. Gross emission due to deforestation for the IPCC's 1990 Business-as-Usual scenario over the period 1990 to 2100.

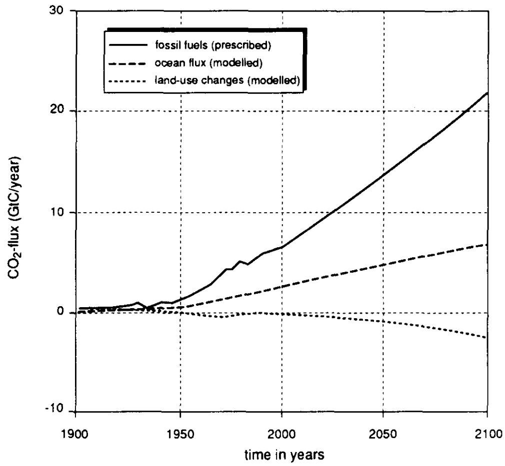


Fig. 11. Components of the carbon budget over the period 1900 to 2100 for the IPCC's 1990 Business-as-Usual scenario (with feedbacks).

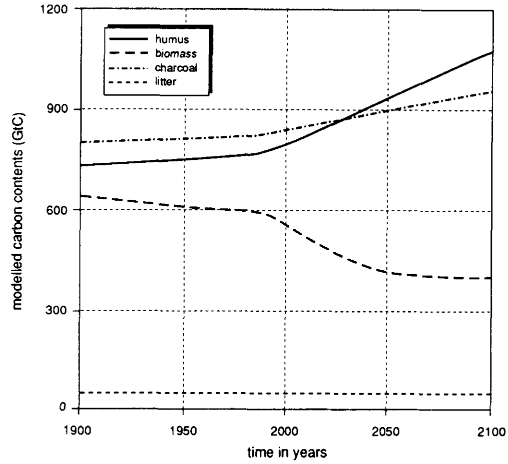


Fig. 12. Modelled carbon contents of biospheric components for the IPCC's 1990 Business-as-Usual scenario.

difference between the two deforestation curves amounts to 13 GtC, or 6 ppmv. This implicates that only a small part of the difference in future atmospheric CO_2 concentrations can be explained by the difference in input data. This leads to the conclusion that the major part of the difference is due to the fact that the IPCC-estimates are based on models that either have an unbalanced carbon budget, or if they are balanced, the simulated terrestrial fluxes do not match well with the observed values. Most models used by the IPCC ignore feedback processes. Therefore these models require a somewhat unrealistic total source of CO_2 of 6.2 GtC in 1990, while the present value is probably around 8 GtC (Table 3). Ignoring these feedback mechanisms leads to overestimated future CO_2 concentrations as pointed out by Wigley and Raper (1992).

For the central estimate parameters, the different carbon budget components (ocean flux, fossil fuel emissions and land use change flux) are presented in Fig. 11. Fig. 12 presents the corresponding total amounts of carbon sequestered in reservoirs such as biomass (leaves, branches, stems, roots), litter, humus and charcoal. The simulated carbon content in the biomass pool shows a decreasing trend, since the decay processes and litter fall dominate the net primary production. The carbon content in the litter pool slightly decreases (although it looks constant in Fig. 12), because the flow out of the litter pool through decay processes and litter humification is larger than the input flow by biomass. For humus and charcoal, the input sources by humification and carbonization dominate the output flows (decay processes and carbonization). This leads to an

Table 5. *Components of the modelled carbon dioxide mass balance of our study with and without feedbacks for the period 1990–2100*

Component	1990–2100 totals (GtC) no feedbacks	with feedbacks
change in atmospheric CO_2 mass (dC/dt)	1085	865
uptake by the ocean (S_{oc})	570	515
emissions from fossil fuel burning (E_{fos})	1500	1500
emissions from land use change (E_{land})	155	−120
net imbalance ($I = dC/dt + S_{oc} - E_{fos} - E_{land}$)	0	0

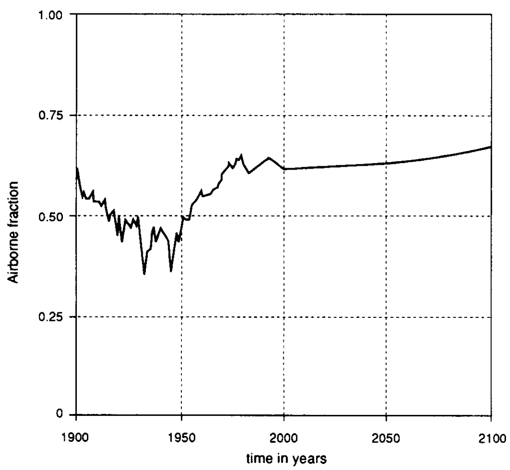


Fig. 13. Airborne fraction for the IPCC's 1990 Business-as-Usual scenario.

increasing trend in the carbon storage in humus and charcoal. The fairly high carbonization factors in the model, combined with a large turnover time of 500 years, cause a relatively large (semi)-sink of carbon in the form of a charcoal pool. This results in a very slow decay of the charcoal pool. The storage of carbon in the different reservoirs is summarized in Table 5, which gives the components of the carbon dioxide mass balance, cumulated over the period 1990–2100 for the case with feedbacks and with no feedbacks. The latter is treated in the section that deals with the sensitivity analysis.

For the case with feedbacks the resulting net airborne fraction, defined as the fraction of the total CO_2 emissions from fossil fuels and terrestrial biosphere that remains in the atmosphere (Rotmans, 1990), is represented in Fig. 13.

5.3. Sensitivity analysis

A number of sensitivity analyses have been performed with previous versions of the coupled carbon cycle/climate model (which contained only one feedback process, the fertilization effect, represented by a global biotic growth factor, or fertilization factor), using statistical techniques (Rotmans, 1990). The set of techniques used for the sensitivity analyses consists of least quares curve fitting, regression analysis, and factorial designs. For a detailed description of how to use these techniques we refer to Kleijnen et al. (1992). These studies indicate the importance of the fertilization factor, and to a lesser extent the charcoal fractions, humification factors and the residence times of humus. The present version of the coupled carbon cycle/climate model includes more feedbacks, and was not yet subjected to a complete sensitivity and uncertainty analysis. To investigate to what extent the terrestrial feedbacks affect the outcomes we have carried out a simple one-factor sensitivity analysis, by varying one feedback parameter at a time for the period 1990 to 2100. The results are presented in Table 6.

It should be noted that the temperature related terrestrial feedbacks are triggered by a global temperature increase of about 3°C for the period 1990–2100, calculated by the model. In the first run the feedbacks are switched off, resulting in a simulated CO_2 concentration of 865 ppmv in 2100. For this case the cumulated carbon storage in the different reservois is given in Table 5. This high value of 865 ppmv compared to the 827 ppmv of the IPCC can only partly be explained by the differences in gross CO_2 emissions through deforestation and net CO_2 emissions due to land use changes (28 ppmv or one third of the difference); this implicates that two thirds of the difference is

Table 6. *One-factor sensitivity analysis*

	Run 0	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Q_{10}^{np}	1.4	1.0	1.4	1.0	1.0	1.0	2.0	1.4	1.4	1.4	1.4
Q_{10}^{res}	2.0	1.0	1.0	2.0	1.0	2.0	2.0	1.0	3.1	2.0	2.0
β	0.4	0.0	0.0	0.0	0.4	0.4	0.4	0.4	0.4	0.0	0.5
pCO_2[a]	761	865	821	918	756	805	712	712	790	875	736

[a] pCO_2 is the simulated atmospheric CO_2 concentration in the year 2100 (in ppmv).

due to our relatively low CO_2 uptake by the oceans (570 GtC), but we do not know precisely the cumulative CO_2 uptake by the oceans used by the IPCC–1990.

Switching on the feedbacks leads to a considerably lower atmospheric CO_2 concentration of about 761 ppmv, mainly caused by the net CO_2 uptake of 120 GtC by the terrestrial biosphere and the soils. The emissions have primarily gone into the temperate and tropical forests, with a partitioning between about 30% in biomass, 55% in humus, 5% in litter, and 10% in charcoal.

In the next three experiments (runs 2, 3 and 4) we run the model by setting only one feedback parameter on its central estimate value, ignoring other feedbacks. In the following 6 experiments (runs 5 to 10) one feedback parameter is set on its maximum or minimum value, fixing the other feedback parameters on their central estimates. These experiments show that the CO_2-fertilization feedback effect appears to be dominant (runs 4, 9 and 10), while the photosynthetic and plant respiration effect seems to counterbalance the soil and litter respiration effect (runs 2, 3, and 5 to 8). This means that in the model the temperature effect on biomass growth and on the decrease of carbon in soils is about equal.

The next sensitivity experiments are meant to produce well balanced carbon budgets for various combinations of feedback parameters and ocean fluxes for the whole period 1760–2100. Table 7 shows the different combinations of the feedback parameters and ocean fluxes and the resulting atmospheric CO_2 concentrations. In order to quantify the "goodness of balance" we have calculated for the different balancing experiments the root mean square concentration error (rmse) over the period 1760–1990. The concentration error is the difference between the modelled and the observed atmospheric CO_2 concentrations. The rmse value indicates a measure of the dispersion of modelled CO_2 concentrations around the observed CO_2 concentration values. The differences between the different rmse values turn out to be small, certainly in comparison with the rmse-value of 5 for the 'no feedbacks' case. The table also gives the ratio between the rmse and the root mean square observed concentrations, which are also small, between 0.1–0.2% (1.5% for the 'no feedbacks' case).

In the 1st 4 runs (run 1 to 4), only the terrestrial feedback parameters are varied in order to get a balanced carbon budget. These experiments result in outcomes which lie between 747 and 762 ppmv. In particular, run 2 shows that the fertilization effect largely determines the historical balance; for this case the resulting atmospheric CO_2 concentration in 2100 of 760 ppmv is about the same as the simulated value of 761 ppmv for the central estimate case. In runs 5 and 6, we vary the atmo-

Table 7. *Balancing sensitivity experiments*

	Run 0	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Q_{10}^{np}	1.4	2.0	1.0	2.0	1.2	1.8	1.4
Q_{10}^{res}	2.0	3.1	1.0	1.0	2.5	1.2	2.5
β	0.4	0.35	0.4	0.1	0.5	0.5	0.1
rmse	0.4	0.4	0.45	0.68	0.35	0.7	0.6
rel.*	0.13	0.13	0.14	0.22	0.11	0.22	0.19
$dC/dt^{a)}$	3.4	3.4	3.35	3.5	3.3	3.4	3.4
$S_{0c}{}^{b)}$	2.2	2.2	2.2	2.2	2.2	1.5	2.7
$E_{land}{}^{a)}$	0.15	0.15	0.1	0.3	0.0	−0.5	0.7
$E_{fos}{}^{a)}$	5.4	5.4	5.4	5.4	5.4	5.4	5.4
$pCO_{2\,23}{}^{c)}$	761	751	760	747	762	670	815

* Ratio between the rms value and the rms of the observed concentration (%).
[a)] for the period 1980–1989 (in GtC/yr).
[b)] S_{oc} is the simulated atmosphere-ocean flux during the 1980s (in GtC/yr).
[c)] pCO_2 is the simulated atmospheric CO_2 concentration in the year 2100 (in ppmv).

sphere-ocean flux during the 1980s between 1.5 and 2.7 GtC/yr, which is in between the upper and lower boundaries (between 1 and 3 GtC/yr during the 1980s) given by Watson et al. (1990), by varying the diffusivity and the rate of precipitation of organic material. Table 7 shows that variations in the ocean flux strongly influence the projected CO_2 concentration range in our model.

Based on these balancing variations of the terrestrial feedback parameters and ocean fluxes, an uncertainty range, which is only indicative and not representative for the full range of uncertainty, varies from about 670 ppmv to 815 ppmv.

In spite of all uncertainties which surround the global carbon cycle, the results obtained from experiments with our model are of interest. The first point of interest is that, if we keep the atmosphere-ocean flux constant, the fertilization feedback determines the balancing and dominates the temperature related feedbacks. To put it differently, balancing by changing only the fertilization feedback gives similar results in terms of future atmospheric CO_2 concentrations as balancing by changing both fertilization and temperature feedbacks. The second is that variations in the atmosphere-ocean flux strongly influence the balancing, and thus the projected CO_2 concentration. Balancing by changes in both ocean flux and fertilization feedback will lead to different historical biospheric fluxes, resulting in substantially different atmospheric CO_2 projections, which was also pointed out by Harvey (1989a) and Wigley (1993).

6. Conclusions

Although not pretending to give a comprehensive picture of the potential rôle of the biogeochemical feedbacks within the carbon cycle, we have tried to evaluate the role of some terrestrial biospheric feedbacks in balancing the carbon budget. Simulation experiments with a coupled carbon cycle/climate model show that excluding feedbacks in our model leads to an apparent net imbalance in the past and present carbon budget. For the period 1850–1990 there is an apparent imbalance of carbon of about 44 GtC in our model. Over the 1980s our model produces a yearly imbalance of about 0.85 GtC. From these experiments it follows that in our model a balanced carbon budget can only be created if a terrestrial sink is introduced. In order to create balanced carbon conditions for the period 1760–1990 we included in our model the CO_2 fertilization effect and the temperature related feedbacks on net primary production and respiration of soil and litter. Although these feedbacks are only parameterized representations of very complicated biogeochemical processes and should be modelled in a spatially-explicit manner, it seems to be a reasonable first step in considering the role of feedback processes in the carbon cycle, given the uncertainties and the lack of geographically-defined data.

Choosing so-called 'central estimate' values for the feedback parameters, which are based on current insights from recent literature and partly on trial and error balancing experiments, leads to a well balanced carbon budget. This implies that the balance is quite close, but not perfect (a perfect balance cannot be created with our forward modelling approach). The resulting historical biospheric flux falls within the uncertainty range of the past net biospheric emissions presented in recent literature. For the period 1960–1980 a net biospheric sink is generated by the model, which is in accordance with results of other carbon cycle models.

Sensitivity experiments show that in our model a well balanced carbon budget can be obtained in many different ways. The fertilization feedback appears to determine the balancing and dominates the temperature related feedbacks, while the net primary production feedback seems to counterbalance the soil and litter respiration feedback effect. It is also shown that variations in the atmosphere-ocean flux strongly influence the balancing. Different balances by changing the atmosphere-ocean flux and the fertilization feedback lead to different historical biospheric fluxes and to different atmospheric CO_2 projections.

Future projections based on the IPCC's BaU-1990 scenario show that our estimated CO_2 concentrations are considerably lower than the IPCC-values: in the year 2100, our estimate is 761 ppmv, whereas the 'central estimate' value of the IPCC is 827 ppmv. This is mainly due to the dominating role of the fertilization feedback effect. As we have shown the differences in input data cannot account for this significant difference of about 16% from the 1990 level. The difference can be explained by the fact that most global carbon cycle models used by the IPCC were unbalanced, while the balanced models do not produce terrestrial fluxes that correspond to observations. The imbalance in the models that the IPCC used is caused by the fact that feedback processes, which must be included in order to obtain balanced conditions, are ignored in these models. This results in overestimated future atmospheric CO_2 concentrations.

Finally, sensitivity analysis experiments show that, under the condition of a balanced carbon budget, the IPCC's central estimate of 827 ppmv falls beyond our estimated uncertainty range of [670 to 815] ppmv, based on variations of both modelled terrestrial feedback parameters as well as the ocean flux.

7. Acknowledgment

The authors thank Martin Middelburg for drawing the pictures.

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