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Sensitivity of global carbon pools and fluxes to human and potential climatic impacts

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ABSTRACT

Besides the emissions from fossil sources, the anthropogenic land use changes (clearings and similar influences) the CO_2 fertilization effect on the biosphere, and potential climatic fluctuations may have influenced the global carbon balance and the CO_2 concentration of the atmosphere in the period 1860–1981. A sensitivity study was carried out to compare the importance of these impacts for the behaviour of fluxes and pools in biosphere, atmosphere and ocean. The Osnabrück Biosphere Model, a regionalized carbon flux model for the terrestrial biosphere, was coupled with a box diffusion ocean model and a one-box atmosphere model. A regional land use pattern was derived from the World Atlas of Agriculture. Its dynamics were introduced using data of global land use changes. For the simulation of climatic variations, standardized changed levels as well as gradients of temperature and precipitation were used. In the period 1860–1981, land-use changes and the CO_2 fertilization effects are similarly important and roughly amount to 4/5 of the fossil source. Effects of potential climatic fluctuations may not exceed 1/5 of that amount.

1. Introduction

The rôle of the terrestrial biosphere in the global C-budget of the last 125 years has been a major topic in ecological research. It is well known that human impact on natural vegetation has given rise to CO_2 emissions in the order of magnitude of the emissions from fossil sources (Esser, 1986). Human activities through clearing of natural forests, selective wood cutting, forestry, forest and savanna pasture, fires, agriculture, generally reduce the stand ages of the vegetation in comparison to the potential natural steady state, and thus increase the turnover of carbon. Moreover, the net primary productivity (NPP), the net flux atmosphere to green plants, is reduced by agricultural production methods (Aselmann and Lieth, 1983; Lieth and Aselmann, 1983; Esser, 1986). Since the standing phytomass is a function of both NPP and stand age (Esser, 1984, 1986), the phytomass pool is reduced by human impacts.

The second point of interest has been the existence or non-existence of a CO_2-fertilizing effect on natural vegetation. The great majority of physiological investigations with C3-plants (C4-plants and CAM-plants play a minor role in the global vegetation) indicate the existence of a favourable effect of elevated CO_2-levels on the photosynthesis (see Esser, 1986; bibliography at Strain and Sionit, 1982). Recent experiments in natural environments or with model ecosystems indicate that NPP too may be increased by higher atmospheric CO_2 (Overdieck and Bossemeyer, 1985; Ostendorf, 1986; Bazzaz et al., 1985). Generally, two mechanisms for this effect are in discussion: (1) The quantum yield of photosynthetic reactions may be increased directly by suppression of photorespiration. (2) The water efficiency for plants is better at higher atmospheric CO_2-levels, since higher values of stomatal resistance become possible, without re-

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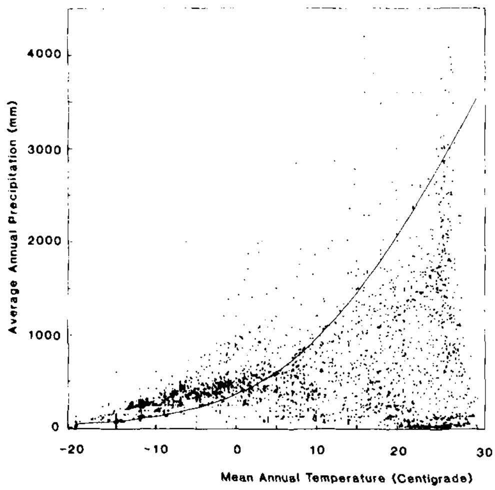

Fig. 1. Distribution of the basic climatic data "mean annual temperature" and "average annual precipitation" of the 2433 grid elements in comparison to the equilibrium function for the temperature-precipitation influence on NPP in the OBM. The majority of the grid elements having T above 5°C is limited by precipitation.

ducing the CO_2-supply of the leaf mesophyll, thus reducing water losses through transpiration. The latter effect is very important, since most of the vegetation formations are water limited (Fig. 1). Therefore a fertilizing effect of CO_2 exists even under conditions limited by the climate. Increasing NPP increases the phytomass pool (we have to assume, however, that the stand age is not influenced by CO_2) and the litter pool of dead organic material, thus causing a biospheric carbon sink.

Changes of NPP also originate from climatic changes, either of temperature or precipitation (Lieth, 1975). Changes of temperature in the order of some tenth degrees have taken place at least in parts of the world in the past 125 years (Bradley et al., 1985, Wigley et al., 1984). Little is known about changes of precipitation. We are not in a position to have regionalized data sets of precipitation data on a global scale for the past 125 years. Nevertheless, it is desirable to investigate the importance of climatic influences on biospheric fluxes and pools relative to the effects of human impact.

In this paper, we report the results of a sensitivity study using the Osnabrück Biosphere Model (Esser, 1984; Esser, 1986; Lieth and Esser, 1985) for comparison of climatic influences with CO_2-effects and human impacts. We used standardized linear gradients for temperature and precipitation changes in the period 1860–1981 as well as changed levels for temperature and precipitation for the whole period.

2. Description of the Osnabrück Biosphere Model (OBM)

2.1. *Model philosophy*

The OBM describes and quantifies the pathways of carbon through the terrestrial biosphere. For this study it was coupled to an atmosphere–ocean submodel (box diffusion model according to Oeschger et al., 1975). In the OBM, carbon transfer rates and transfer coefficients, respectively, are calculated from environmental variables such as mean annual temperature, average annual precipitation, CO_2-concentration of the atmosphere, soil fertility, related vegetation formation, and land use category. The equations are based on theoretical considerations and are then calibrated with ecological field data or data from physiological experiments. Since field data in many cases are measured as annual integrals, regression functions were used in those cases which predict the flux under consideration in annual integrals.

No adjustments of the OBM or of individual functions, except of the ocean submodel, to global data sets such as the Mauna Loa records have taken place.

The model is regionalized on a 2·5 degrees grid. 2433 grid elements are obtained for the continental area except Antarctica.

2.2. *Model data necessary as independent variables*

Data on grid element level used to run the model include: *Climatic data*: Mean annual temperature and annual average precipitation. Source: NCAR-tape (1983); Walter and Lieth (1960 ff); Müller (1980, 1982). The data were recalculated for the mean elevation of the grid element.

Potential natural vegetation: 172 vegetation units are included (Schmithuesen, 1976). The distribution pattern is in percent of the related grid element area.

Land use. (a) Distribution of 5 basic units (arable land, permanent crops, meadows and pastures, forests, rough grazing land) is included in percent of the grid element area. Source was the World Atlas of Agriculture (Instituto Geographico de Agostini 1969, 1971, 1973). (b) Yields of 17 major crops according to FAO (1980 ff) on state level for the calculation of agricultural *NPP*. (c) Factors, *FA*, for calculation of agricultural *NPP* from yields (Aselmann and Lieth, 1983).

Soils. 106 soil units according to the Soil Map of the World (FAO-Unesco 1974 ff). The distribution is in percent of grid element area.

Data not correlated to the grid. Carbon releases from fossil sources (Keeling, 1973, 1982; Marland and Rotty, 1983).

Population development 1760–1975 (Coale, 1974).

2.3. *Model structure*

In Table 1 and Fig. 2, the structure and notation used in the functions below may be found. The indices used in the functions include:

model year since model start:	$i = 1860, \ldots, 1981$
grid element:	$m = 1, \ldots, 2433$
vegetation formation:	$n = 1, \ldots, N(m)$
soil unit:	$o = 1, \ldots, O(m)$

The suffixes T and Pp relate to variables calculated from either parameter. Underlined variables relate to an entire grid element.

It is assumed that the sum of pool changes equals zero:

$$\frac{1}{dt}(d(\overline{CO_2}) + d(FC) + d(M + D) + d(S) + d(SC)) + \sum_{m=1}^{2433} \frac{dP(m)}{dt} + \sum_{m=1}^{2433} \frac{d(\underline{Lh}(m) + \underline{Lw}(m))}{dt} = 0 \quad (1)$$

The individual pool changes (eqs. (2) through (10)) equal the balances of the related input–output fluxes (output fluxes with negative prefix):

$$\frac{d(\overline{CO_2})}{dt} = CF(t) + \sum_{m=1}^{2433} (\underline{LDh}(m, t) + (\underline{LDw}(m, t)) - \sum_{m=1}^{2433} \underline{NPP}(m, t) - \frac{d(M + D)}{dt} \quad (2)$$

$$\frac{d(FC)}{dt} = CF(t)$$

Table 1. *Alphabetical list of symbols mentioned in the model equations*

Symbol	Meaning	Units
a	Stand age of a vegetation type *n*(*m*)	years
A	Weighted mean of all *a* of a grid element	years
AA	Agricultural area of a grid element in a model year	m^2
AG	Total area of a grid element	m^2
AS	Area of soil type *o*(*m*)	m^2
AV	Area of vegetation type *n*(*m*)	m^2
CF	Anthropogenic carbon production	g/year
CM	Net uptake of the ocean	g/year
CO_2	Carbon dioxide concentration in the atmosphere	p.p.m.
$\overline{CO_2}$	Total atmospheric carbon	g
D	Carbon content of deep ocean	g
DOC	Dissolved organic carbon transported in world rivers	g/year
f	Soil factor of soil type *o*(*m*)	—
F	Weighted mean of all *f* of a grid element	—
FA	Conversion factor yield to *NPP*	—
FCO_2	Fertilizing factor of CO_2 on *NPP*	—
FC	Global pool of fossil carbon	g
h	Herbaceous portion of *NPP* or *LP* of a vegetation type *n*(*m*)	—
H	Weighted mean of all *h* of a grid element	—
kh	Decomposition coefficient for herbaceous material	$year^{-1}$
kw	Decomposition coefficient for woody material	$year^{-1}$
L	*Lh* + *Lw*	g/m^2
Lh	Pool of herbaceous litter	g/m^2
Lw	Pool of woody litter	g/m^2
LDh	Decomposed amount of herbaceous litter	$g/m^2/year$
LDw	Decomposed amount of woody litter	$g/m^2/year$
LPh	Produced amount of herbaceous litter	$g/m^2/year$
LPw	Produced amount of woody litter	$g/m^2/year$
M	Carbon content of mixed layer	g
NPP	Net primary productivity	$g/m^2/year$
P	Phytomass	g/m^2
Pp	Average annual precipitation	mm
PM	World population	persons
POC	Particulate organic carbon transported in world rivers	g/year
S	Ocean sediment	g
SC	Soil organic carbon	g
T	Mean annual temperature	°C
z	Exponent for coupling of changes of *AA* to changes of *PM*	—

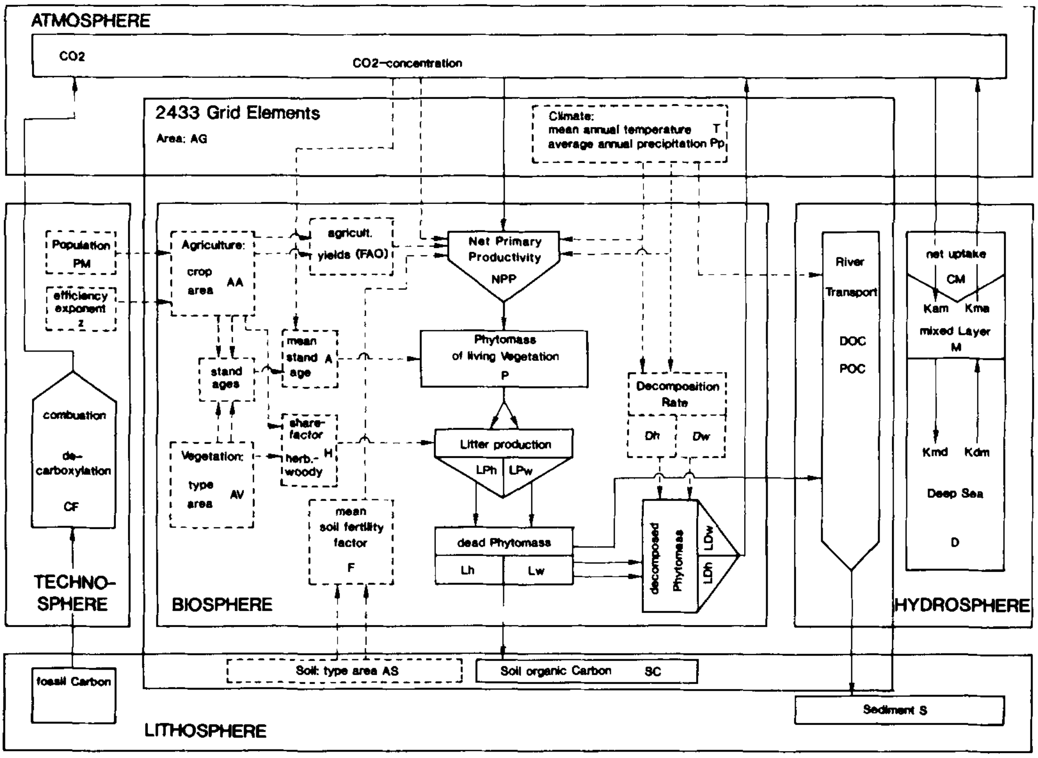

Fig. 2. Simplified structure of the Osnabrück Biosphere Model. The grid size is 2.5 degrees latitude and longitude. The fluxes and/or flux coefficients (mass relations) are calculated as functions of the control variables. The pools are balanced by input and output fluxes. The box-diffusion ocean submodel is due to Oeschger et al. (1975).

and

$$\int_{t=i-1}^{i} CF(t) = CF\,(i) \text{ from external file} \tag{3}$$

$$\frac{\mathrm{d}(M+D)}{\mathrm{d}t} \tag{4}$$

predicted by the ocean submodel (it is assumed that no exchange with the sediment occurs: $\mathrm{d}S/\mathrm{d}t = 0$)

$$\frac{\mathrm{d}(SC)}{\mathrm{d}t} = 0 \tag{5}$$

provisionally assumed to be negligible due to the low turnover rate

$$\frac{\mathrm{d}P(m)}{\mathrm{d}t} = NPP(m, t) + (-LPh(m, t) - (LPw(m, t)). \tag{6}$$

In the version of the OBM used in this study, eq. (6) is parameterized for annual steps due to (11) (see below):

$$\Delta P(i, (i-1), m) = NPP(i, m) + (-LPh(i, m) - (LPw(i, m)) \tag{7}$$

and

$$\Delta P(i, (i-1), m) = P(i, m) - P(i-1, m) \tag{8}$$

The phytomass of a year i can be calculated from NPP and stand age of the vegetation unit or land use category (Esser, 1984, 1986):

$$P(i, m) = 5.9181 \cdot 10^{-4} \cdot A(m)^{0.79216} \cdot NPP(i, m) \tag{9}$$

It is assumed here that stand age is independent of the environmental parameters climate and CO_2 concentration which is certainly a simplification. Possible effects of CO_2 on stand age have been investigated with a further version of the OBM and are discussed elsewhere (Esser, 1986).

With (7)–(9), the annual litter production (LPh, LPw) is calculated.

Litter pool:

$$\frac{d(Lh(m) + Lw(m))}{dt} = LPh(m, t) + LPw(m, t) + (-LDh(m, t) - LDw(m, t)) + (-DOC(m, t) - POC(m, t)) \quad (10)$$

The carbon fluxes are calculated from the vector of environmental influences by non-linear regression equations. The regressions predict the fluxes either directly (then in annual integrals), or compute the coefficients of the differential equations.

The net primary productivity (NPP) of natural vegetation is calculated with the Miami model (Lieth, 1975) and additional soil correction factors $F(m)$ (Hamburg model, Esser et al., 1982). The productivity of cultivated lands (NPP_{agri}) is assumed to be proportional to the yields of crops published by FAO (1980 ff). The factors FA were supplied by Aselmann and Lieth (1983). The correction factor for the influence of atmospheric CO_2 on NPP, $FCO_2(i)$, is calculated by a regression function (15) derived from a set of data measured in ecological and physiological experiments (see Esser, 1984, 1986).

The system of equations for the calculation of annual integrals of NPP per unit area of grid element m is given by (11)–(17):

$$\int_{t=i-1}^{i} NPP(m, t) = NPP(i, m) = \{(\min|NPPT(i, m), NPPPp(i, m)|) \cdot F(m) \cdot \frac{AV(i, m)}{AG(m)} + \text{yield}\,(m) \cdot FA(m) \cdot \frac{AA(i, m)}{AG(m)}\} \cdot FCO_2(i), \quad (11)$$

$$NPPT(i, m) = 3000/(1 + e^{1.315 - 0.119 \cdot T(i,m)}) \quad (12)$$

$$NPPPp(i, m) = 3000 \cdot (1 - e^{-0.000664 \cdot Pp(i,m)}) \quad (13)$$

$$F(m) = \frac{\sum_{o=1}^{O(m)} f(o) \cdot AS(m, o)}{\sum_{o=1}^{O(m)} AS(m, o)} \quad (14)$$

With (14), a soil factor $F(m)$ is calculated as weighted mean of the soil factors $f(o)$ of the soils of a grid element (m) according to the areas $AS(m, o)$ which they cover.

$$FCO_2(i) = 3.6365 \cdot (1 - e^{-0.00134 \cdot (CO_2(i) - 80)}) \quad (15)$$

The cultivated area $AA(i, m)$ of a grid element m is calculated from the value of 1970 (according to the World Atlas of Agriculture), modified by the quotient of population in year i to population in 1970:

$$AA(i, m) = AA(1970, m) \cdot \left(\frac{PM(i)}{PM(1970)}\right)^z \quad (16)$$

$$PM(i) = 3.9371 \cdot 10^7 \cdot e^{0.025(i-1760)} + 7.295 \cdot 10^8. \quad (17)$$

Regression (17) is calibrated with data from Coale (1974); i is the calendar year. With $z = 0{\cdot}8$ eq. (16) gives an increase of cultivated land since 1860 similar to the estimates from statistical data by Houghton et al. (1983) on a global scale. (A revised second version of the OBM will include a regional pattern of land use changes.) The amount of carbon released from phytomass through clearings simply is calculated from annual change of agricultural areas and natural phytomass replaced.

Litter production in the model is calculated in annual integrals by eqs. (7)–(9). Share factors for each vegetation unit are used to separate woody and herbaceous portions (Esser et al., 1982; Esser, 1984, 1986).

For calculation of litter decomposition it was assumed that the decomposed amount of litter is proportional to the litter pool:

$$\frac{dL}{dt} = -k \cdot L. \quad (18)$$

The coefficient k depends on the temperature/precipitation components of the environmental vector and on the material decomposed (woody (kw) and herbaceous (kh)):

$$kh(i, m) = \min|khT(i, m), khPp(i, m)| \quad (19)$$

$$khT(i, m) = 0.1063 \cdot e^{0.0926 \cdot (T(i,m) + 6.41)} + 0.2365 \quad (20)$$

$$khPp(i, m) = \left\{\frac{0.4436}{0.0215 + e^{4.2 - 0.0053 \cdot Pp(i,m)}} + 5.944\right\} \cdot \left\{\frac{0.094}{0.7 + e^{0.0023 \cdot Pp(i,m) - 5.05}} + 0.076\right\} \cdot \{1 - e^{-0.001 \cdot Pp(i,m)}\} \quad (21)$$

$$kw(i, m) = \min|kwT(i, m), kwPp(i, m)| \quad (22)$$

$$kwT(i, m) = 0.037 \cdot e^{0.522 \cdot T(i,m) + 31.63)} - 0.0348 \quad (23)$$

$$kwPp(i, m) = \left\{\frac{0.1927}{0.021 + e^{8.53 - 0.0095 \cdot Pp(i,m)}} + 4.9352\right\} \cdot \left\{\frac{0.126}{1.51 + e^{0.003 \cdot (Pp(i,m) - 4.65}} + 0.05\right\} \cdot \{1 - e^{-0.001 \cdot Pp(i,m)}\}. \quad (24)$$

Eqs. (20), (21), (23), (24) are calibrated with a global set of 93 field data points (see Esser et al., 1982; Esser and Lieth, 1986a). A solution of (18) for annual values of decomposed litter for herbaceous material is:

$$LDh(i, m) = (Lh(i-1, m) + LPh(i-1, m)) \cdot (1 - e^{-kh(i,m)}). \quad (25)$$

The decomposed amount of woody material per year is calculated analogously to (25) using *LDw*, *Lw*, *LPw*, and *kw* instead.

The fluxes *DOC* and *POC* of dissolved and particulate organic material transported annually by the world rivers were estimated by Kempe (1984) to amount up to 1 ± 0.4 Gt C. Kempe assumed that erosion processes from cultivated land were mainly responsible for the postulated increase of *DOC* and *POC* since preindustrial times. To investigate the effect of river transport upon the global carbon budget we assumed that the value of 1 Gt *C/a* was given in the year 1970 and that the development of river freights was proportional to the development of the agricultural area:

$$(DOC(i) + POC(i)) = 1 \cdot \frac{\sum_{m=1}^{2433} AA(i, m)}{\sum_{m=1}^{2433} AA(1970, m)}. \quad (26)$$

Eq. (26) was applied in some model runs to simulate the effects of such a sink proposed by Kempe.

3. Results for the period 1860–1981

3.1. *Model results with a standard climatic data set*

The set of climate data described in Subsection 2.2 was used together with the original parameters for the box diffusion ocean model proposed by Oeschger et al. (1975). The determination of a starting value for atmospheric CO_2 for 1860 by trial and error during several model runs to yield 340 p.p.m. of the Mauna Loa records for 1981 lead to 290 p.p.m. However, this procedure of initiation does not include any model adjustment to the Mauna Loa records.

Results of this model run are included in Table 2. For an easy survey the table only shows every 10th year except the last. The accumulated biospheric source from clearings of natural vegetation amounts to −137 Gt of carbon (Table 2, column 7) which is 4/5 of the fossil source (column 6) of −166.6 Gt C. The total source thus has been −303.6 Gt C. The CO_2 content of the atmosphere has increased by just 50 p.p.m. or 105.2 Gt C. The ocean absorbed 64 Gt C, 11.8 Gt C of which remained in the mixed layer.

Due to CO_2 fertilizing, the net primary productivity (*NPP*) of the terrestrial biosphere has increased from 43.1 Gt C per year in 1860 to 48.6 Gt C/a in 1981. This includes a considerable reduction due to lower *NPP* of the agricultural areas which expanded in the period. Thus a 17% increase of atmospheric CO_2 results in an increase of *NPP* of 13%. The value for litter production includes biomass from clearings (column 7/13). Therefore it is frequently slightly higher than the *NPP*. The decomposition coefficients in this model run are constant on grid element level (no change of climate) so that the litter decomposition follows the pool (column 5/12).

The phytomass pool is the largest pool in the biosphere. With about 600–700 Gt C it contains more carbon than the preindustrial atmosphere. The phytomass was reduced according to the model by 17.5 Gt C. This figure is a balance of −137.0 Gt C reduction by clearings and +119.5 Gt C additionally stored in the recent vegetation as a consequence of CO_2 fertilization on *NPP* according to eq. (15).

The phytomass of cultivated lands amounts to 4.5 Gt C in 1981 which is 3.3 Gt C more than 1860. The phytomass of the former natural vegetation which was replaced would have been 137.0 + 3.3 = 140.3 Gt C.

The global litter pool increased by 15.0 Gt C as a consequence of the raised litter production, partly due to the assumption that the phytomass that has been clearcut passes through the litter pool, having a turnover time of 1.9 to 4.0 years

Table 2. *Development of major global fluxes and pools of biosphere, atmosphere, and ocean in the period 1860–1981; results of a model run with standard climate and without consideration of carbon transport in rivers*

	Pools (ppm, Gt)				Accumulated fluxes (Gt)				Annual biospheric fluxes (Gt/a)			
		Phytomass					Ocean					
Model year (1)	Atmosphere (2)	Total (3)	Agricult (4)	Litter (5)	Fossil source (6)	Clearings (7)	Mixed layer (8)	Deep sea (9)	NPP (10)	Litter Product. (11)	Litter Decomp. (12)	Clearings (13)
1860	290.0	674.3	1.2	137.1	−0.4	0.0	0.0	0.0	43.1	43.1	−43.1	−0.0
1870	290.7	673.0	1.3	137.9	−1.3	−3.2	0.1	0.2	43.1	43.3	−43.2	−0.3
1880	291.7	671.8	1.4	138.3	−3.2	−7.0	0.4	0.8	43.2	43.4	−43.3	−0.4
1890	292.9	670.5	1.5	138.7	−6.2	−11.6	0.6	1.7	43.3	43.5	−43.4	−0.5
1900	294.5	669.1	1.6	139.1	−10.4	−17.2	1.0	3.1	43.5	43.6	−43.6	−0.6
1910	296.7	668.1	1.7	139.7	−17.1	−24.1	1.5	5.1	43.8	43.8	−43.8	−0.7
1920	299.3	666.9	1.9	140.8	−25.9	−32.3	2.2	7.9	44.0	44.3	−44.1	−0.9
1930	302.4	665.2	2.2	141.8	−36.1	−42.3	2.9	11.4	44.5	44.5	−44.4	−1.1
1940	306.0	661.9	2.4	143.2	−47.0	−54.5	3.8	15.8	44.7	45.0	−44.9	−1.3
1950	310.4	658.3	2.8	144.8	−60.9	−69.2	4.9	21.2	45.2	45.6	−45.5	−1.6
1960	316.7	655.4	3.2	146.4	−81.3	−87.0	6.4	28.2	45.9	46.2	−46.9	−1.9
1970	325.8	654.2	3.8	148.6	−113.1	−108.7	8.5	37.6	46.9	46.9	−46.6	−2.4
1980	338.5	656.7	4.4	151.6	−161.6	−134.3	11.5	50.7	48.4	48.2	−47.7	−2.7
1981	339.8	656.8	4.5	152.1	−166.6	−137.0	11.8	52.2	48.6	48.5	−48.0	−2.7

The fossil emission data in column (6) are due to Keeling (1973, 1982) and Marland and Rotty (1983). The ocean-submodel is the box-diffusion ocean proposed by Oeschger et al. (1975).

(Esser et al., 1982), partly due to CO_2 fertilization.

In Table 3, the total balance of carbon in the period under consideration is represented. Fig. 3 gives the curve of the CO_2 concentration in the atmosphere calculated by the OBM in comparison to the seasonally corrected Mauna Loa records after 1958. Both curves correspond excellently. Nevertheless, this is not an absolute validation of the model, since potential errors may compensate. The annual fluctuations in the Mauna Loa records are not reproduced by the model since the responsible structures probably are not yet available in this model version.

Fig. 4 shows the development of the pools expressed as the net changes in relation to the respectively lowest value in the period 1860–1981. Pool changes are generally positive except of phytomass which has a minimum in the year 1969. The positive development of the phytomass after 1969 is due to temporarily prevailing CO_2 fertilization effect over the clearings. It is obvious that further clearings will reduce the residence time of carbon in phytomass increasingly and thus again repress the fertilization effect. The biosphere in total has only been a minor source of −2.5 Gt C, while within the biosphere a shift of roughly 15 Gt C from phytomass to litter has taken place.

Table 4 gives an overview over some estimates and model results concerning global phytomass. The results differ widely and the more recent results even vary by 15–30%. The uncertainty

Table 3. *Global balance of net pool changes in the period 1860–1981 for a model run with standard climate and no river transport values; read in Gt carbon*

Net sources		Net sinks	
Emissions from fossil sources	−166.6	Phytomass	119.5
		Litter pool	15.0
Release from phytomass due to clearings	−137.0	Atmosphere	105.2
		Ocean	64.0
	−303.6		303.7*

* Differences between total sums are due to rounding errors.

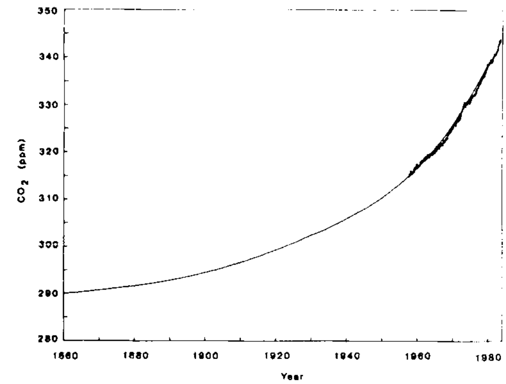

Fig. 3. Development of the atmospheric CO_2 concentration in the period 1860–1981 calculated by the OBM with a standard climatic data set in comparison to the seasonally corrected values of the Mauna Loa records (Bacastow and Keeling, 1981).

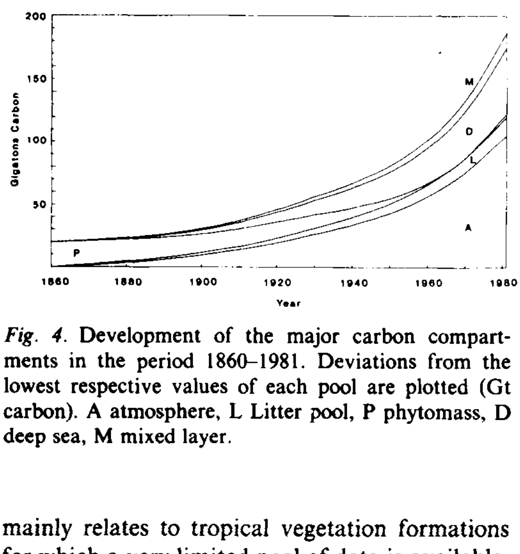

Fig. 4. Development of the major carbon compartments in the period 1860–1981. Deviations from the lowest respective values of each pool are plotted (Gt carbon). A atmosphere, L Litter pool, P phytomass, D deep sea, M mixed layer.

Table 4. *Values for the pool "global phytomass" published by various authors in comparison to the value given by the OBM extracted from Table 2; all values read in Gt carbon*

Phytomass Gt carbon	Comments	Reference
550	Early realistic estimate based on production and residence time	Schröder, 1919
300	Estimate using production and stand age	Müller, 1960
560 ± 100	Vegetation information on 0.5° grid, considers agriculture	Olson et al., 1983
560	Considers agriculture	Ajtay et al., 1979
592	Considers agriculture	Duvigneaud in Bolin et al., 1979
827	Upper limit for potential natural vegetation. Based on a high production estimate of 72 Gt C/a	Whittaker and Likens, 1973
638	Natural vegetation only	Aselmann, 1985
737	Considers agriculture	Matthews, 1984
594	Considers deforestation	Goudriaan et al., 1984
759	Potential natural vegetation	Esser, 1986
657	Considers agriculture (OBM)	Esser, this paper

mainly relates to tropical vegetation formations for which a very limited pool of data is available. The modelling of standing phytomass of undisturbed vegetation rather than estimates of the cleared areas is a principle problem since evaluations of land use changes are now done on basis of landsat images (Esser and Lieth, 1986b). The OBM requires soil factors and mean stand ages as input data for the calculation of phytomass due to eqs. (9) and (11). Either data are poorly known for tropical vegetation units.

Phytomass changes published by various authors are put together in Table 5 for the past century or recent years, respectively. Estimates of releases from phytomass due to agriculture or clearings are affected with similar problems as discussed above. Moreover some authors do not consider fertilization effects, so that "net releases" sometimes deal with releases from clearings only.

3.2. *Results without consideration of a CO_2 fertilization effect*

One could argue that eq. (15) for calculation of the CO_2 fertilizing factor has been calibrated with physiological rather than ecological data and may be unreliable if applied to natural environments. If a fertilizing factor smaller than calculated by (15) is assumed, it is necessary to assume subsequently that sinks have been underestimated or even overlooked or that clearings were overestimated. If, as an extreme case, one would not consider a fertilization factor in the

Table 5. *Some published phytomass changes during the past century or in recent years and the related values calculated by the OBM*

Time period	Statement	Reference
1860–present	Phytomass reduction 105 Gt C due to agriculture	Matthews, 1984
1880–1980	Phytomass reduction 62.8 Gt C	Goudriaan et al., 1984
1860–1970	120 G t C from clearings	Chan, 1980
1860–1970	148 Gt C net release from vegetation and soils	Moore et al., 1981
1860–1980	135–228 Gt C from phytomass	Woodwell et al., 1983
since 1958	38–76 Gt C from clearings	Houghton et al., 1983
1860–1981	137 Gt C from clearings	Esser, this paper
1860–1981	119.5 Gt C additional fixation due to CO_2 fertilization	Esser, this paper
present	trop. CO_2 source 1.3–4.0 Gt C/a	Hampicke and Bach, 1979
present	C release from phytomass must be less than 10% of fossil emission	Oeschger et al., 1980
present	+ 1.6 Gt C additional fixation due to CO_2 fertilization − 1.6 Gt C /a from clearings	Olson, 1982
1970	2.4 Gt C/a from clearings	Moore et al., 1981
1980	1.8–4.7 Gt C net release from phytomass	Woodwell, 1982
1981	2.7 Gt C/a from clearings	Esser, this paper

OBM, the biospheric source from clearings is distributed to the remaining sinks as indicated in Table 6. The ocean then takes 117.7 Gt C, the atmosphere 187.5 Gt C or +88.8 p.p.m. since 1860. The starting value for 1860 then has to be 251 p.p.m. The mean increase in the period of the Mauna Loa records would be 1.8 p.p.m./a in comparison to 1.1 p.p.m./a of the Mauna Loa curve.

Table 6. *Global balance of net pool changes 1860–1981 if CO_2 fertilizing is neglected; values in Gt carbon*

Net sources		Net sinks	
Emissions from fossil sources	− 166.6	Atmosphere	187.5
		Ocean	117.7
Release from phytomass due to clearings	− 138.2		
Litter pool	−0.4		
	− 305.2		305.2

Table 7. *Global balance of net pool changes 1860–1981 with consideration of river transport (DOC and POC)*

Net sources		Net sinks	
Emissions from fossil sources	− 166.6	Phytomass	89.4
		Litter pool	10.1
Release from phytomass due to clearings	− 137.1	Atmosphere	81.6
		Ocean	45.8
		River transport (*DOC* + *POC*)	76.8
	− 303.7		303.7

Carbon transport in the world rivers is assumed to increase from 0.37 Ct C/a in 1860 to 1.16 Gt/a in 1981 due to eq. (26). Basis is estimation of Kempe (1984).

3.3. *Effect of an assumed DOC and POC transport in rivers*

The river transport of dissolved and particulate organic carbon (*DOC* and *POC*) according to Kempe (1984) was coupled in the OBM to the development of agricultural areas by eq. (26). The annual transport increased therefore from 0.37 Gt C/a in 1860 to 1.6 Gt C/a in 1981. The total transport in the period 1860 through 1981 then amounts to 76.8 Gt C. This amount was assumed to reach a final sink and not to contribute to the exchange ocean-atmosphere.

The CO_2 concentration for 1860 is 302 p.p.m., the mean increase since 1958 is 0.9 p.p.m./a or 0.2 p.p.m./a less than the Mauna Loa records. The global balance may be found in Table 7. If compared with Table 3 it is obvious that the amount transported by rivers is to the debit of phytomass, atmosphere, ocean, and litter pool in decreasing order.

Table 8. *Influences of changed levels of mean annual temperature and average annual precipitation, respectively, on major fluxes and pools of biosphere, atmosphere, and ocean in comparison to results of the reference model run with standard climate (see Subsection 3.1 and Table 2)*

Climate (1)	*NPP* 1860 (2)	*LD* 1860 (3)	*NPP* 1981 (4)	*LD* 1981 (5)	Clearings 1860–1981 (6)	Increase of phytomass (7)	Net change of phytomass (8)	Change of litter (9)	Δ sink (10)	Ocean (11)	Atmosphere (12)	CO_2 in 1860 p.p.m. (13)	Mean increase 1958–1981 p.p.m./a (14)
Reference (*T*, *Pp*)	43.1	43.1	48.6	48.0	−137.0	119.5	−17.5	15.0	0.0	64.0	105.2	290	1.1
T+2°C, *Pp*	44.1	44.1	49.7	49.0	−139.7	122.3	−17.4	15.0	0.1	64.0	105.0	290	1.1
T, *Pp*+10%	45.2	45.2	50.8	50.3	−144.1	125.4	−18.7	14.7	−1.5	64.6	106.0	290	1.1

Fluxes in Gt/a, pools in Gt carbon unless differently indicated. $\Delta\text{ sink} = \sum_{m=1}^{2433} \Delta(\Delta P(m) + \Delta L(m))$ is the change in total biospheric sink capacity in the period 1860–1981 in comparison to the reference. *NPP* net primary productivity; *LD* litter decomposition.

3.4. *Effects of changed levels of temperature or precipitation*

Altered climates were simulated by setting T' or Pp', respectively, instead of T and Pp in eqs. (12), (13) and (19)–(24):

$$T'(m) = T(m) + 2.0$$

$$Pp'(m) = Pp(m) + Pp(m)/10.$$

The results in Table 8 show that, although the biospheric fluxes and pools are influenced considerably, the effects on atmosphere and ocean are negligible. The biospheric effects already compensate within the biosphere.

In Figs. 5, 6, regional results for the 2433 grid elements concerning the change of the biospheric sink function, $\Delta(\Delta P + \Delta L)$, relative to the model run reported in subsection 3.1, are plotted. The change of the biospheric sink function is defined as:

$$\begin{aligned}\Delta(\Delta P + \Delta L) &= \{P(T', Pp', 1981) + L(T', Pp', 1981) \\ &- P(T', Pp', 1860) - L(T', Pp', 1860)\} \\ &- \{P(T, Pp, 1981) + L(T, Pp, 1981) \\ &- P(T, Pp, 1860) + L(T, Pp, 1860)\}. \quad (27)\end{aligned}$$

The term $\Delta(\Delta P + \Delta L)$ thus indicates how sinks in phytomass and litter change under changed conditions in relation to standard conditions. Positive values indicate higher sink capacity or lower source capacity respectively than the reference.

The change of sink function is positive in regions, where the change of the climatic variable is favourable for the *NPP* and for phytomass and where only minor clearings occur. On the other side, negative changes are observed in regions, where likewise the climatic change is favourable for *NPP* and phytomass but extensive clearings have taken place in the period under consideration.

3.5. *Effect of temperature and precipitation gradients*

5 linear climatic time-gradients of either mean annual temperature or average annual precipitation or both were applied to the OBM for the model years 1860 through 1981. The annual values for the climatic variables in the five scenarios were calculated by the equations:

1. Gradient + 2°C
   $T(m, i) = T(m, 1981) - 2.0 \cdot (1981 - i)/121.$
2. Gradient + 10%
   $Pp(m, i) =$
   $Pp(m, 1981) - 0.1 \cdot Pp(m, 1981) \cdot (1981 - i)/121.$
3. Gradient + 250 mm
   $Pp(m, i) =$
   $Pp(m, 1981) + 250 \cdot (i - 1860)/121.$
4. Gradient − 250 mm
   $Pp(m, i) =$
   $Pp(m, 1981) - 250 \cdot (i - 1860)/121.$

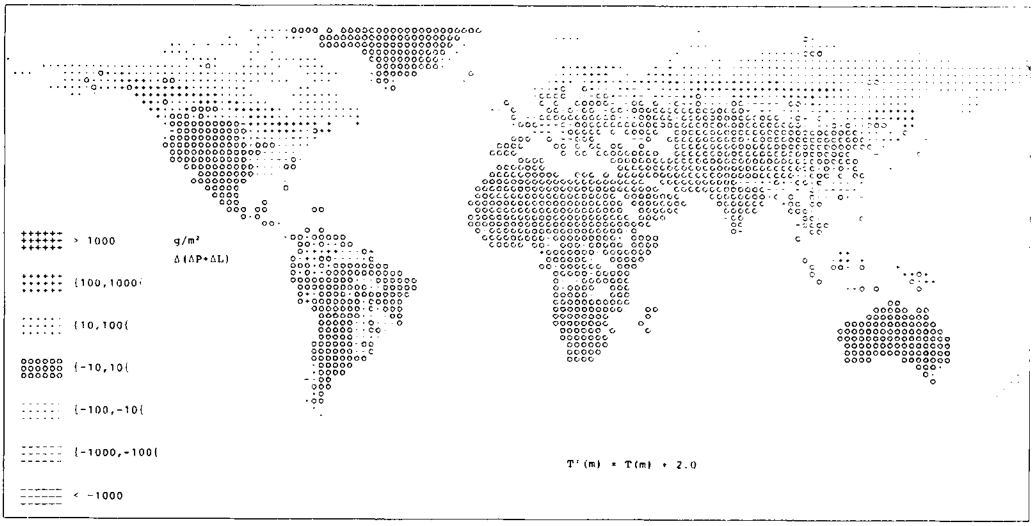

Fig. 5. Response of the regional biospheric sink capacity to altered levels of temperature of +2°C. Values in g/m² carbon for the integer period 1860–1981. Negative values indicate reductions in sink capacity or increase in source capacity respectively.

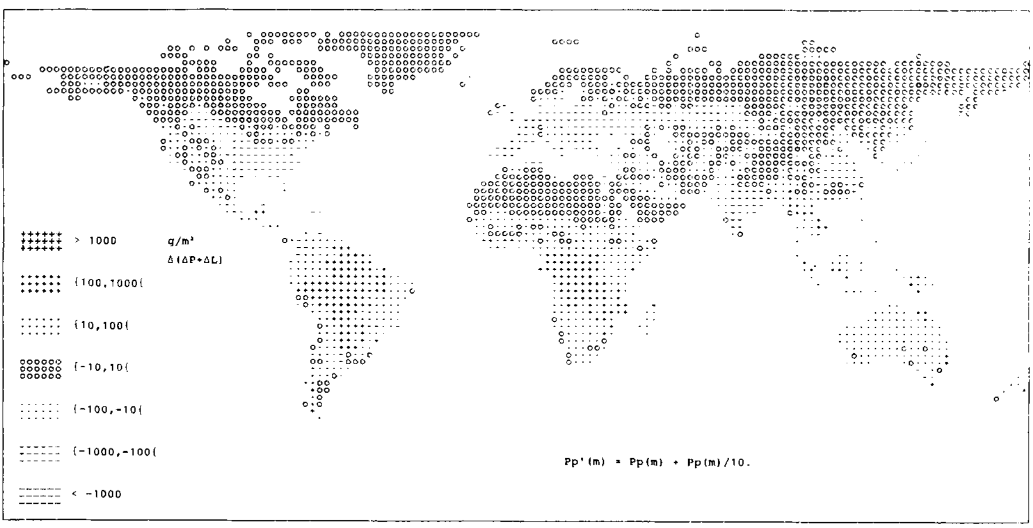

Fig. 6. Response of the regional biospheric sink capacity to altered levels of precipitation of +10%. For further explanations see legend to Fig. 5.

5. Gradient + 2°C

$T(m, i) =$
$T(m, 1981) - 2.0 \cdot (1981 - i)/121.$

Gradient + 10%

$Pp(m, i) =$
$Pp(m, 1981) - 0.1 \cdot Pp(m, 1981) \cdot (1981 - i)/121.$

As reference values for 1981, the standard climatic data set described in Subsection 2.1 was used. Table 9 gives the global results for the 5 scenarios in comparison to the reference results extracted from Table 2. The global integrals of the biospheric sink function (Table 9, column 10)

$$\Delta \sum_{m=1}^{2433} \Delta P(m) + \Delta L(m),$$

generally vary stronger than observed in model

Table 9. *Effects of climatic gradients in the period 1860–1981 on major fluxes and pools of biosphere, atmosphere, and ocean, in comparison to results of the reference model run with constant climate (see Subsection 3.1 and Table 2)*

Climate gradient (1)	*NPP* 1860 (2)	*LD* 1860 (3)	*NPP* 1981 (4)	*LD* 1981 (5)	Clearings 1860–1981 (6)	Increase of phytomass (7)	Net change of phytomass (8)	Change of litter (9)	Δ sink (10)	Ocean (11)	Atmosphere (12)	CO_2 in 1860 p.p.m. (13)	Mean increase 1958–1981 p.p.m./a (14)
Reference (*T*, *Pp* const.)	43.1	43.1	48.6	48.0	−137.0	119.5	−17.5	15.0	0.0	64.0	105.2	290	1.1
1 ($T+2°C$)	42.4	42.4	48.6	47.9	−136.1	133.1	−3.0	11.5	11.0	58.7	99.4	293	1.0
2 ($Pp+10\%$)	41.5	41.5	48.6	47.8	−135.2	139.7	4.5	12.3	19.3	54.7	95.1	295	1.0
3 ($Pp+250$ mm)	45.8	45.0	58.4	57.5	−152.3	182.0	29.7	7.9	40.1	44.4	84.6	301	1.0
4 ($Pp-250$ mm)	49.8	49.8	48.4	48.2	−141.5	77.3	−64.2	21.7	−40.0	82.6	126.5	279	1.1
5 ($T+2°C$, $Pp+10\%$)	40.9	40.9	48.7	47.9	−134.7	151.4	16.7	9.4	28.6	50.4	90.2	298	1.0

The terms in brackets (column 1) indicate the change of either climatic variable in the total period. For further explanations see heading for Table 8.

runs where altered climatic levels were used (Table 8). The highest deviations occur in scenarios 3 and 4 with precipitation gradients. The effect of the combined *T* and *Pp* gradient used for scenario 5 is slightly lower than the sum of individual effects in scenarios 1 and 2. The effect of the temperature gradient of scenario 1 alone is low since, as was demonstrated in Fig. 1, most of the grid elements are limited by precipitation.

The changes of the biospheric sink function are at the cost of atmosphere and ocean. The ocean supplies between 46.5% and 48.9% of the carbon additionally stored by the biosphere. Although the cleared areas are identical in the 5 scenarios, the emissions from clearings also depend on the phytomasses per unit area which develop differently in the scenarios (Table 9, column 6).

The increase of phytomasses from 1860 to 1981 (column 7) is due to combined effects of CO_2 fertilization and the climatic gradient. The value given by the reference run, 119.5 Gt C, is due to the CO_2 fertilization alone. The model does not calculate the influences of both effects separately, but it can be concluded that effects of fertilization deviate from the reference value in the scenarios 1–5, since *NPP* and atmospheric CO_2 develop differently.

In the Figs. 7–9 the regional values for the change of the biospheric sink function are plotted for the scenarios 1, 2, and 5. Figs. 7–9 are directly comparable with Figs. 5 and 6. The sink capacity of phytomass and litter is increased by a positive temperature gradient in those regions, where temperature is the limiting factor for *NPP*. If the decomposition too is limited by temperature, an opposite effect is produced in the litter pool. The sink change for an individual grid element is the balance of both effects.

Large positive effects occur in mountainous areas as well as in subpolar and especially boreal regions. In lowlands of the tropics positive values are limited to regions where precipitation is in excess, i.e., the upper Amazon basin. Negative values occur in regions limited by precipitation. The model equation (11) for the calculation of *NPP* does not reduce the *NPP* in those regions in case of increasing temperature. The effect is rather due to the CO_2 fertilization which is reduced in scenario 1 in comparison to the reference, because the atmospheric CO_2 increases 3 p.p.m. less. This is especially obvious if Fig. 7 is compared with Fig. 5.

The constant level of $T+2°C$ influences the atmosphere insignificantly and negative values for the change of sink capacity are then highly reduced.

A precipitation gradient causes opposite changes in many regions (Fig. 8). The effects, however, are not completely complementary, since the fluxes contributing are nonlinear functions of climate and CO_2 concentration. The combined positive gradient of temperature and precipitation used in scenario 5 causes positive changes of the sink capacity in all parts of the world where a considerable biological activity exists (Fig. 9). In desert areas with low biological activity the changes are insignificant. Changes even might become slightly negative in those

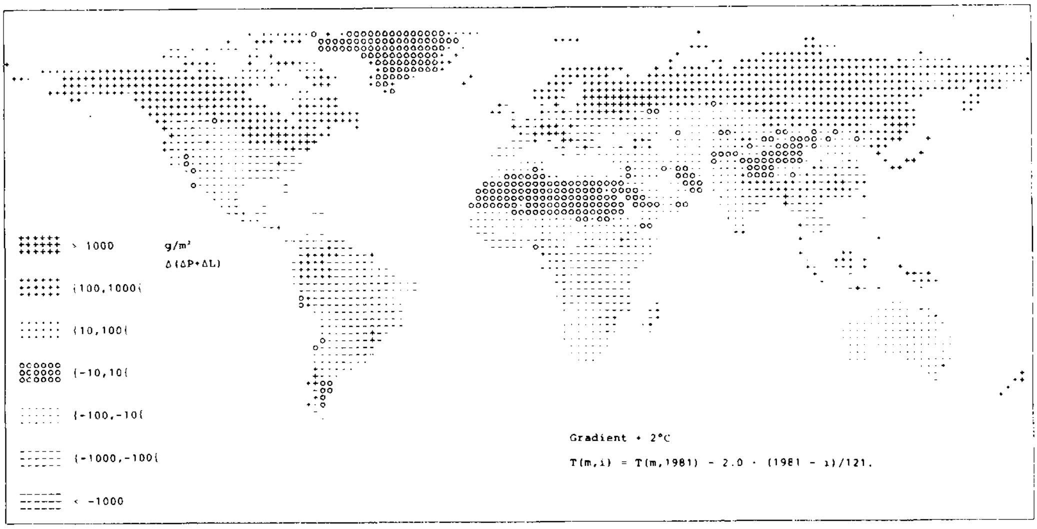

Fig. 7. Response of the regional biospheric sink capacity to a temperature gradient ($T + 2$°C, scenario 1 in Table 9) in the period 1860–1981. Further explanations in the legend to Fig. 5.

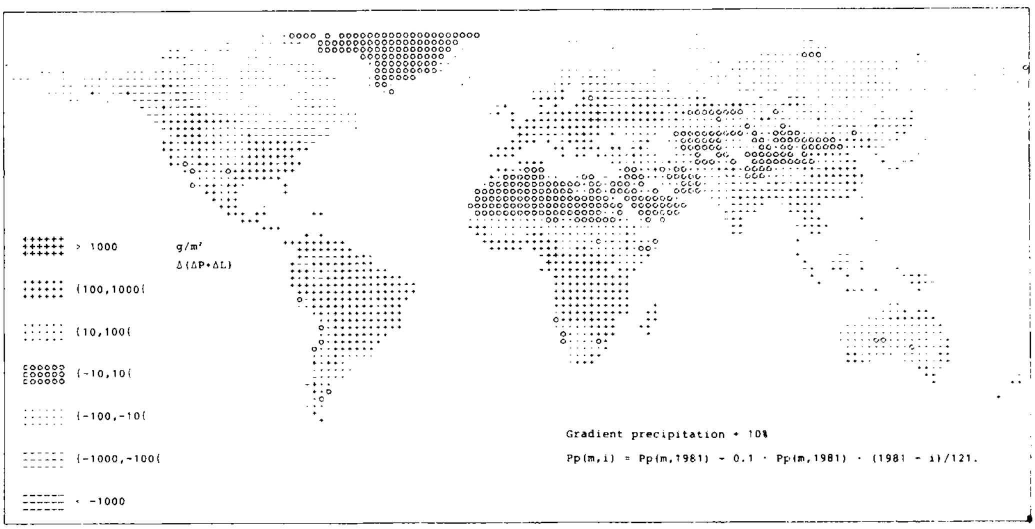

Fig. 8. Response of the regional biospheric sink capacity to a precipitation gradient (+10%, scenario 2 in Table 9). Further explanations in the legend to Fig. 5.

regions, since the fertilization effect is low due to the 8 p.p.m. lower increase in atmospheric CO_2.

4. Conclusions

The OBM, like other models, includes uncertainties which originate from the restricted knowledge of the functioning of natural systems and from the limited availability of adequate field data to calibrate the relations. Internal parameters of vegetation are assumed to be invariable while the environmental vector changes. This assumption is implied as long as functions calibrated with data measured along a geographic climate-gradient ((12), (13), (19)–(24)) are applied

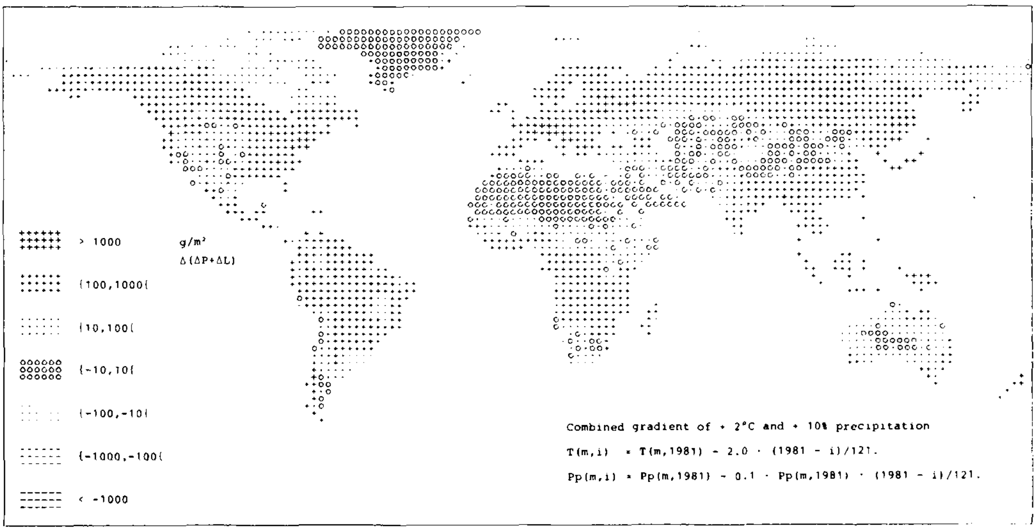

Fig. 9. Response of the regional biospheric sink capacity to a combined temperature and precipitation gradient ($T + 2$°C, $Pp + 10$%, scenario 5 in Table 9). Further explanations in the legend to Fig. 5.

to changes of climate in time. This may be tenable, lacking other solutions, as long as changes are small. The OBM is a "quantified working hypothesis" and subject to future improvements.

The following conclusions can be drawn from the results reported in this paper:

- —The atmospheric starting value of 290 p.p.m. for 1860 calculated by the OBM is close to the present value from ice cores of 287 ± 3 p.p.m. (Oeschger, 1986). The CO_2 increase since 1958 is similar to the Mauna Loa value (Bacastow and Keeling, 1981), but the year to year deviations are not reproduced.
- —At the end of the period 1860–1981, the carbon pool of the biosphere became more or less balanced. The emissions from clearings were compensated by the CO_2 fertilization effects. Before 1970 the biosphere was a small net source, after 1970 it temporarily became a small sink, since emissions from clearings prevailed over the CO_2 fertilization effects.
- —If one does not consider the CO_2 fertilization, the results for atmosphere and ocean deviate largely from what should be expected according to measurements.
- —The implementation of river transport described in Subsection 2.3 is not very reasonable if the results in Subsection 3.3 are considered and the fertilizing effect of CO_2 is as large as assumed in eq. (15). It is the question whether *DOC* and *POC* really depend on land use and the compounds transported reach a final sink quantitatively. A regionalized submodel for *DOC* and *POC* has to be developed to overcome these problems.
- —The effects of altered levels of either temperature or precipitation are much smaller than the effects of gradients of the same span. Thus failures in the climatic data sets of the model are most probably insignificant in respect to the biospheric results. In contrast, climatic fluctuations in the period 1860–1981 are to be expected to influence the biospheric carbon balance and the atmospheric CO_2 concentration thoroughly.
- —The influence of precipitation changes is higher than the influence of temperature changes. Although only global gradients were investigated, it is evident that regional changes may be even more effective if they occur in regions, where the variable under consideration is the limiting component. This underlines the importance of reliable regional data sets, especially of precipitation patterns, for the period modelled. Year to year climatic variations may be partly responsible for the annual fluctuations of the seasonally corrected Mauna Loa records.

Altogether the land use changes as well as the CO_2 fertilization effects roughly amount to 4/5 of the fossil source, while effects of potential climatic fluctuations since 1860 may not exceed 1/5 of that amount.

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