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High Resolution Biosphere Model

Documentation

Model Version 3.00.00

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Contents

Chapter 1

Model description

The High Resolution Biosphere Model (HRBM) was developed as an instrument to investigate the carbon balance of the terrestrial biosphere, the impacts of the rising atmospheric CO_2 level and of climatic changes. It therefore had to meet the following demands: (1) include the major carbon fluxes and pools of the terrestrial biosphere; (2) describe the fluxes by means of equations which consider the deterministic relations to the environment; (3) make the equations valid in the entire span of the environmental variables in the terrestrial biosphere; (4) include any important indirect effects which may influence the global carbon budget.

The biospheric carbon pools in the model are balanced by the carbon fluxes which are functions of the vector of driving variables. Figure 1.1 shows the structure of the model. In Table 1.1 the principal model variables and the procedures of their computation are listed. The abbreviations used within the model description are mentioned in Table 1.2. They are in accordance with the variable names used in the program. For the sake of readability pools and fluxes are written in capitals, their compartments (compare to 1.1) are indicated by subscripts. Though most variables are arrays, we refrained from writing the indices. In general, the given equations are applied for each array element separately, except when explicity noted (as in sums over all elements). A complete description of the variables is given at the end of chapter 2.

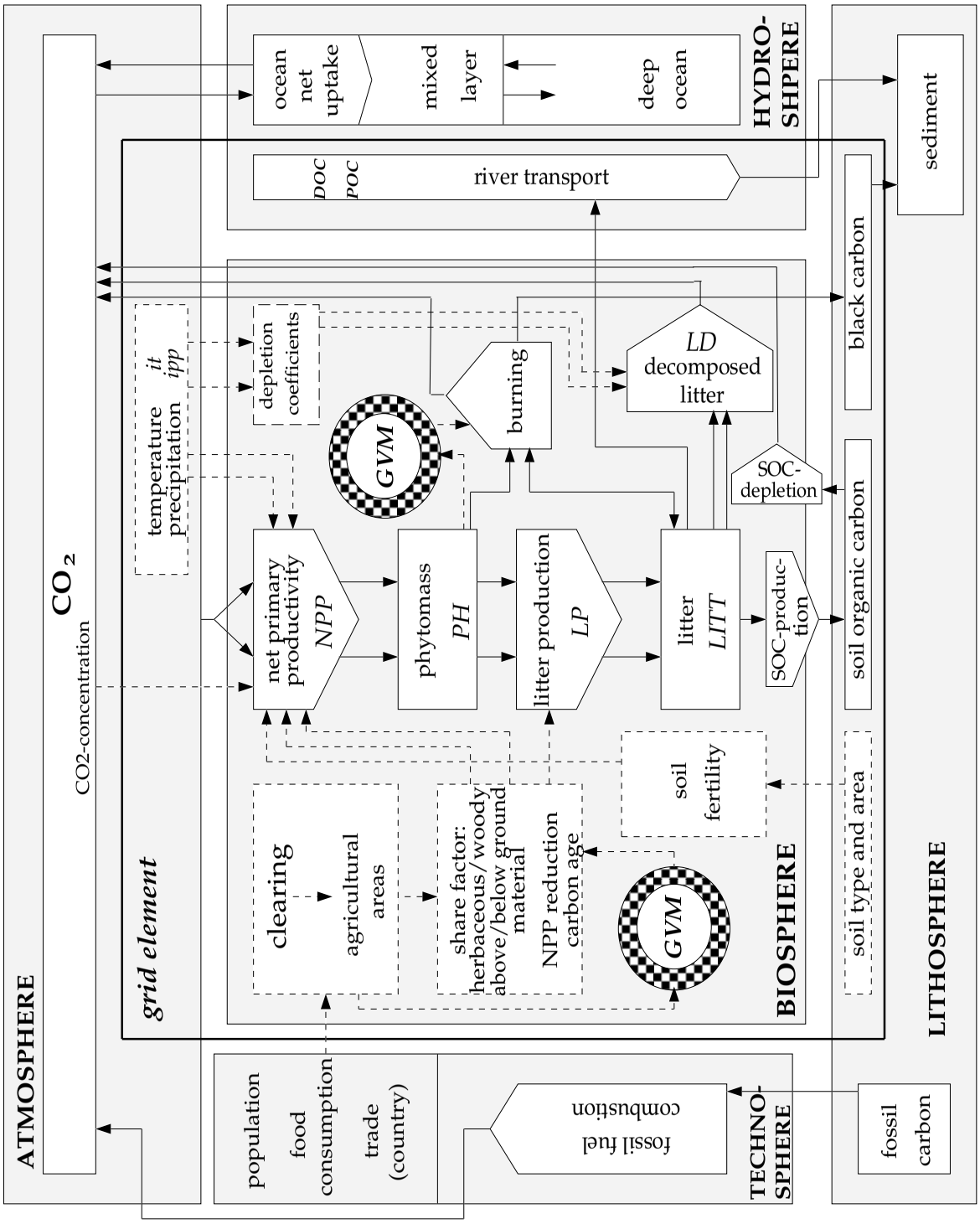


Figure 1.1: Simplified structure of the High Resolution Biosphere Model. The global grid size is 0.5 ° latitude and longitude. Carbon pools are represented by rectangles, carbon fluxes by pentagons, driving forces by dashed rectangles, mass relations by solid arrows, control relations by dashed arrows. *GVM* indicates the exchange with a coupled global vegetation model (Prentice *et al.*, 1992). From Esser (1986), modified.

For the purposes of this model, the surface of the Earth is subdivided into grid elements of 0.5 ° latitude and longitude. Only the landmass is taken into account, leading to a total of 62,483 grid elements. The mass balance of the model pools is carried out by integrating the system of differential equations by a 4th–order Runge–Kutta method. The initial pool values necessary to start the model are computed using a fixed atmospheric CO_2 concentration. The atmosphere then acts as an "unlimited" carbon source to fill the pools. This "pre–run" procedure may need as many as 5,000 model years, a considerable computing time, to stabilize the large soil pools and to prevent model drift in the consecutive model run.

Table 1.1: Principal biospheric variables of the High Resolution Biosphere Model, their computation, and references for further information.

biospheric variable	calculated from	references
net primary productivity	temperature, precipitation, soil fertility, agricultural yield, conversion factors yield $\mapsto$ productivity, land–use areas, CO_2–fertilization	Esser 1991
land–use changes 1860–1990	statistical data on country basis, remote sensing	FAO 1992, Richards *et al.* 1983, Olson *et al.* 1983, Esser 1989
land–use changes after 1990	scenarios considering: agricultural productivity in 1990, population development in each country, natural productivity, soil fertility, spatial distribution of agricultural areas; option: consideration of development of agricultural productivity	Esser *et al.* 1994 , Bulato *et al.* 1990
cleared phytomass	land–use changes, natural phytomass, crop phytomass	Esser 1987
soil fertility	empirical function for the major 37 out of 106 soil units from the Soil Map (FAO 1974 ff.)	Esser 1984, Esser *et al.* 1982
conversion factor yield $\mapsto$ productivity	empirical factor for major field crops	Aselmann, Lieth 1983, Esser 1991
CO_2–fertilization	atmospheric CO_2 concentration, soil fertility	Esser 1991
phytomass	net primary productivity, litter production	Esser 1984, 1987

Table 1.1 continued

biospheric variable	calculated from	references
litter production	mean stand age	Esser 1987
litter pool	litter production minus depletion	Esser, Lieth 1989, Esser *et al.* 1982
litter depletion	depletion coefficient, litter pool	Esser, Lieth 1989, Esser *et al.* 1982
litter depletion coefficient	temperature, precipitation, material depleted	Esser 1991, Esser, Lieth 1989, Esser *et al.* 1982
soil organic carbon production	litter production, lignin content	Esser 1990
soil organic carbon	production minus depletion	Esser 1990
soil organic carbon depletion	temperature, precipitation, soil organic carbon pool	Esser 1990
leaching of dissolved and particulate org. C	precipitation	Esser, Kohlmaier 1991
atmosphere	balanced by: fossil emissions, ocean exchange, net primary production, depletion fluxes of litter and soil organic carbon, burnt phytomass	
ocean	box diffusion ocean, 1 mixed layer, 43 deep sea boxes	Oeschger *et al.* 1975

Table 1.2: List of variables used in this model description in alphabetical order.

symbol	meaning	units
abvgrd	factor for sharing *NPP* into above and below ground compartments	–
aetm	actual evapotranspiration of one month	mm·month^{-1}
age	mean stand age of a vegetation unit	years
ATMBLC	carbon balance on grid element level	g·m^{-2}·month^{-1}
cbch	black carbon (charcoal) formation coefficient	month^{-1}
cbchl	... for litter	month^{-1}
cbchp	... for phytomass	month^{-1}
cbef	burning efficiency	month^{-1}
cbefl	... for litter	month^{-1}
cbefp	... for phytomass	month^{-1}
cbmo	mortality coefficient for vegetation fires	month^{-1}
cbmop	... for phytomass	month^{-1}
cburn	burning probability	–
CHC	black carbon pool	g·m^{-2}
chmax	maximum value of *cbch* coefficient	–
cld	litter decay coefficient	month^{-1}
clf	cloud freeness	–
clp	litter production coefficient	yr^{-1}
co2	CO_2 concentration in the atmosphere	μl·l^{-1} (= ppmv)
co2fak	fertilizing factor of CO_2 on *NPP*	–
csocp	soil organic carbon production coefficient	month^{-1}
csocd	soil organic carbon depletion coefficient	month^{-1}
cur	proportion of above ground herbaceous litter at the total above ground herbaceous plant material	%
dbh	diameter at breast height	m
DFOR	deforestation flux	g·m^{-2}·month^{-1}
DIS	monthly discharge of water	mm·month^{-1}
DOC	dissolved organic C export	g·m^{-2}·month^{-1}
fmc	dead fine fuel moisture content	% dr. w.
fsoil	soil factor of soiltype	–
ha	[index] herbaceous above ground compartment	–
hb	[index] herbaceous below ground compartment	–
herb	factor for sharing herbaceous *NPP*	–
hi	mean monthly humidity index (ipp/2 mm $-it$/1° C)	–

continued on next page

Table 1.2 continued

symbol	meaning	units
ipp	monthly precipitation	$mm \cdot month^{-1}$
ippann	annual sum of precipitation	$mm \cdot yr^{-1}$
it	monthly temperature	°C
itann	mean annual temperature	°C
korri	factor to correct the agriculturally used area	–
LBL	litter burnt to CO_2	$g \cdot m^{-2} \cdot month^{-1}$
LCP	formation of black carbon from litter by fires	$g \cdot m^{-2} \cdot month^{-1}$
LD	litter depletion	$g \cdot m^{-2} \cdot month^{-1}$
LITT	litter pool	$g \cdot m^{-2}$
LP	litter production	$g \cdot m^{-2} \cdot month^{-1}$
NPP	net primary productivity	$g \cdot m^{-2} \cdot month^{-1}$
NPPPP	*NPP* derived from *ippann*	$g \cdot m^{-2} \cdot yr^{-1}$
NPPT	*NPP* derived from *itann*	$g \cdot m^{-2} \cdot yr^{-1}$
part	fraction of annual *NPP* in a given month	
PH	phytomass pool	$g \cdot m^{-2}$
PHBL	phytomass burnt to CO_2	$g \cdot m^{-2} \cdot month^{-1}$
PHCP	formation of black carbon from phytomass by vegetation fires	$g \cdot m^{-2} \cdot month^{-1}$
PHML	mortality from vegetation fires	$g \cdot m^{-2} \cdot month^{-1}$
POC	particulate organic C export	$g \cdot m^{-2} \cdot month^{-1}$
rap	relative agricultural productivity of a country (ratio of annual agricultural NPP to natural NPP)	–
rapg	*rap* of a grid element	–
rh	mean monthly relative humidity	%
rh_a	corrected value for rh_f, depending on radiation	%
rh_f	current relative humidity during, or a short time before, fires	%
share	factor for sharing *NPP* into compartments	–
SOCD	soil organic carbon depletion	$g \cdot m^{-2} \cdot month^{-1}$
SOCP	soil organic carbon production	$g \cdot m^{-2} \cdot month^{-1}$
t_a	corrected value for t_f, depending on radiation	°C
t_f	current temperature during, or a short time before, fires	°C
useann	actual agricultural status	–
usestd	agricultural status in 1980	–

1.1 Differential equations

The change of pools with time is described by balancing time–dependent fluxes. For each pool, the input fluxes occur with positive, the output fluxes with negative prefixes.

The pools phytomass and litter and the respective fluxes are compartmented. The present model version distinguishes the phytomass compartments "herbaceous above ground" (ha; leaves, new shoots, juicy froots, flowers), "woody above ground" (wa; trunks, branches, twigs, woody parts of fruits, bark), "herbaceous below ground" (hb; fine roots, subterraneous soft shoots and tubers), "woody below ground" (wb; main woody roots, below ground trunks). The litter compartments include the dead but incompletely decomposed material produced by litter production from the respective phytomass compartment.

The underlined terms describe fluxes related to vegetation fires.

Phytomass changes of the above and below ground, herbaceous and woody compartments:

$$\frac{d}{dt}PH_{ha} = NPP_{ha} - LP_{ha} - \underline{PHBL_{ha} - PHML_{ha} - PHCP_{ha}} \quad (1.1)$$

$$\frac{d}{dt}PH_{hb} = NPP_{hb} - LP_{hb} \quad (1.2)$$

$$\frac{d}{dt}PH_{wa} = NPP_{wa} - LP_{wa} - DFOR_{wa} - \underline{PHBL_{wa} - PHML_{wa} - PHCP_{wa}} \quad (1.3)$$

$$\frac{d}{dt}PH_{wb} = NPP_{wb} - LP_{wb} - DFOR_{wb} - \underline{PHML_{wb}} \quad (1.4)$$

Litter pool changes of the above and below ground, herbaceous and woody compartments:

$$\frac{d}{dt}LITT_{ha} = LP_{ha} - LD_{ha} - SOCP_{ha} + \underline{PHML_{ha} - LBL_{ha} - LCP_{ha}} \quad (1.5)$$

$$\frac{d}{dt}LITT_{hb} = LP_{hb} - LD_{hb} - SOCP_{hb} \quad (1.6)$$

$$\frac{d}{dt}LITT_{wa} = LP_{wa} + DFOR_{wa} - LD_{wa} - SOCP_{wa} + \underline{PHML_{wa} - LBL_{wa} - LCP_{wa}} \quad (1.7)$$

$$\frac{d}{dt}LITT_{wb} = LP_{wb} + DFOR_{wb} - LD_{wb} - SOCP_{wb} + \underline{PHML_{wb}} \quad (1.8)$$

Change of soil organic carbon:

$$\frac{d}{dt}SOC = \sum_{\mu=h,w} \sum_{\nu=a,b} SOCP_{\mu,\nu} - SOCD \quad (1.9)$$

Change of the pool of black carbon (charcoal) from vegetation fires:

$$\frac{d}{dt}CHC = \underline{\sum_{\mu=h,w} PHCP_{\mu,a} + \sum_{\mu=h,w} LCP_{\mu,a}} \tag{1.10}$$

Carbon balance of a grid element:

$$\frac{d}{dt}ATMBLC = \sum_{\mu=h,w} \sum_{\nu=a,b} (-NPP_{\mu,\nu} + LD_{\mu,\nu}) + SOCD + \underline{\sum_{\mu=h,w} PHBL_{\mu,a} + \sum_{\mu=h,w} LBL_{\mu,a}} \tag{1.11}$$

1.2 Model fluxes

1.2.1 Net primary productivity

The total flux "net primary productivity" (*NPP*) is calculated as an annually integrated two–dimensional array according to equation (1.12).

$$NPP = \min[NPPT, NPPPP] \cdot fsoil \cdot rapg \cdot co2fak \cdot share \cdot part \cdot 0.45 \tag{1.12}$$

The first factor is the phytomass productivity of the potential natural vegetation, provided by the original version of the MIAMI model (Lieth, 1975), as given by equations (1.13) and (1.14).

$$NPPT = 3000/\{1 + \exp[1.315 - 0.119 \cdot itann]\} \tag{1.13}$$

$$NPPPP = 3000 \cdot \{1 - \exp[-0.000664 \cdot ippann]\} \tag{1.14}$$

The result is consecutively modified by several corrective factors, which are discussed in the following.

The influence of the soil found in the respective grid element is represented by the soil factor (*fsoil*). This is an empirical correction factor which relates the productivity measured on a given soil type to the MIAMI productivity. The values of *fsoil* for the major FAO–Unesco soil units (FAO–Unesco 1974 ff.) can be found in table 1.3.

Furthermore, on agriculturally used grid elements the natural NPP is modified by the relative agricultural NPP factor (*rapg*), defined as the ratio between agricultural NPP and natural NPP within one year:

$$rapg = \frac{\sum_{\text{Jan}-\text{Dec}} NPP_{agri}(\text{month})}{\sum_{\text{Jan}-\text{Dec}} NPP_{nat.}(\text{month})} \tag{1.15}$$

Table 1.3: Soil factors *fsoil* of the HRBM which characterize the fertility of the main soil units of the world. Names of soil units according to FAO–Unesco (1974 ff.). The soil factors for soil units not listed in this table were set to 1.0.

soil unit	*fsoil*	soil unit	*fsoil*
Gleyic Acrisol	0.87	Chromic Luvisol	1.04
Humic Acrisol	0.22	Ferric Luvisol	1.65
Orthic Acrisol	0.70	Gleyic Luvisol	2.78
other Acrisol	0.60	Orthic Luvisol	0.85
Dystric Cambisol	0.94	Dystric Histosol	1.39
Eutric Cambisol	1.69	Humic Podzol	0.56
Humic Cambisol	1.58	Orthic Podzol	0.61
Gelic Cambisol	0.76	other Podzols	0.55
Luvic Chernozem	0.99	Calcaric Regosol	1.61
Dystric Podzoluvisol	0.83	Eutric Regosol	1.14
Xanthic Ferralsol	0.88	Gelic Regosol	0.91
Humic Gleysol	0.47	other Regosol	1.20
Gelic Gleysol	0.57	Orthic Solonetz	0.59
other Gleysol	0.50	Vitric Andosol	1.65
Lithosol	0.52	Haplic Xerosol	0.42
Lithosol–Yermosol	1.14	Yermosol	0.30
Fluvisol	0.49	Haplic Yermosol	0.66
Eutric Fluvisol	0.61	Luvic Yermosol	0.23
other Fluvisol	0.55	Takyric Yermosol	0.09
Haplic Kastanozem	1.96	Orthic Solonchak	0.44
Luvic Kastanozem	1.61	Takyric Solonchak	0.03
other Kastanozem	1.80	other Solonchak	0.20
Albic Luvisol	0.34		

The agricultural NPP of one country depends linearly on the yields of the main field crops. The factors relating the productivity of the crops to their yields are given in Table 1.4.

The next factor in equation (1.12), *co2fak*, represents the CO_2 fertilization effect. In the HRBM it is calculated from the actual atmospheric CO_2 concentration and the soil fertility according to equation (1.16).

$$co2fak \quad = \quad a \cdot [1 - \exp\{-r \cdot (co2 - 80)\}] \tag{1.16}$$

where $a = 1 + fsoil/4$ and $r = -\ln(1 - 1/a)/240\,.$

The CO_2 fertilization effect is only applied to natural vegetation. If the grid element is agriculturally used, the factor will be set to 1 assuming supply limited by minerals rather than by CO_2. The existence of such a fertilization effect in nature has been controversial since the beginning of carbon cycle research. In terms of plant physiology

Table 1.4: Factors for the calculation of *NPP* (dry weight) of some agricultural crops from the yields (fresh weight). From Aselmann & Lieth (1983).

crop	factor	crop	factor
wheat	2.15[1]	cotton	5.00
barley	2.12[5]	sugar cane	0.44
oats	3.44[1]	mandioka (cassava)	0.64[4]
rye	2.65[5]	potato	0.54[2]
maize	2.46[1]	batate	0.55[3]
sorghum	3.44[1]	soybeans	2.46[1]
pearl millet	3.44[1]	Phaseolus beans	2.86[1]
paddy rice	2.86[1]	rape	2.81[5]
sugar beets	0.32[6]		

dry matter content in yield:
[1] 86%, [2] 32.5%, [3] 30%, [4] 35%, [5] 87%, [6] 23%

and ecophysiology, the processes are quite clear. The CO_2 concentration acts in three ways:

1. Through a direct effect of the CO_2 partial pressure in the plant cell on the enzyme kinetics of the Ribulose–1,5–bisphosphate–carboxylase/oxygenase. The quantum–efficiency of photosynthesis is influenced directly by this effect.

2. Through an indirect effect on the transpiration of a plant through the stomatal resistance. The elevated external CO_2 level raises the intracellular partial pressure of CO_2. Plants may counteract by raising the stomatal resistance to keep the internal CO_2 partial pressure constant. The reduced transpiration per unit leaf area allows the plant to increase the leaf area or to extend the vegetation period. Since most of the global land areas having mean annual temperatures above 5 °C are limited in water supply (Esser, 1987), this effect may be the most important on a global scale.

3. The lack of minerals limits the fertilization effect. The flux net primary productivity must always be accompanied by adequate fluxes of minerals from the soil, since the ratios carbon/minerals within plant organs are constant within narrow limits (Ingestad & Lund 1986; Ingestad & Ågren 1988). Minor changes of the ratios probably occur in some plant species if grown at very high atmospheric CO_2 concentrations (Overdieck & Forstreuter, 1991).

Equation (1.16) was calibrated by use of physiological data. Physiological and ecophysiological investigations of the fertilization effect have been carried out at many insti-

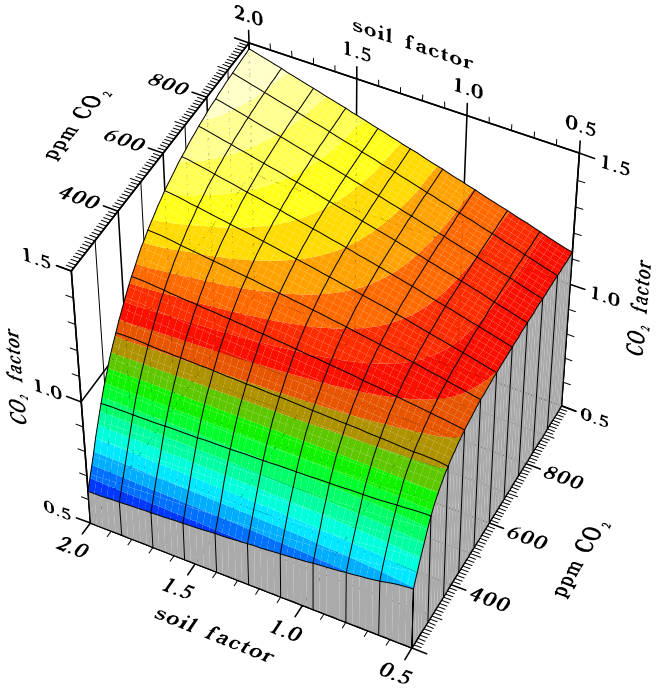


Figure 1.2: Plot of function (1.16), $co2fak = f[CO_2, fsoil]$, to calculate the CO_2 fertilization factor on net primary productivity. The CO_2 compensation concentration for entire plants is assumed to be 80 μl·l^{-1} ($co2fak = 0$, irrespective of $fsoil$). For 320 μl·l^{-1} CO_2 concentration $co2fak = 1.0$, since it was assumed that the data used to calibrate the functions (1.8) and (1.9) were measured mainly during the 1960s when CO_2 was about 320 μl·l^{-1}. The function achieves saturation at 1.125 for $fsoil = 0.5$, at 1.250 for $fsoil = 1.0$, and at 1.375 for $fsoil = 1.5$. For the present atmospheric CO_2 of 355 μl·l^{-1} the function yields the factors 1.034 for $fsoil = 0.5$, 1.052 for $fsoil = 1.0$, and 1.065 for $fsoil = 1.5$.

tutions (see PORTER, 1993), but their value in determining the plant behavior in natural environments is limited. The function proposed here considers soil fertility, but the water interrelations are not considered explicitly. A plot of function (1.16) is found in Figure 1.2.

The annually integrated NPP is distributed over the 12 months, using the cube of the relative actual evapotranspiration as distribution function (equation (1.17)). Partitioning will only take place, if actual evapotranspiration shows greater values than 45 mm·month^{-1}. At present the monthly evapotranspiration is derived from a simple Bucket model (PRENTICE *et al.*, 1992).

$$part = \frac{aetm^3(\text{month})}{\sum\limits_{\text{Jan}-\text{Dec}} aetm^3(\text{month})} \tag{1.17}$$

In consideration of the different compartments, the productivity is partitioned into four separate fluxes: herbaceous and woody, above and below ground productivity (see

equations (1.18)). The sharing factors (*herb* and *abvgrd*), which depend on the vegetation units, are given in table 1.5 for the 17 vegetation formations being used in the model.

$$\begin{aligned} share_{ha} &= herb \cdot abvgrd \\ share_{hb} &= herb \cdot (1 - abvgrd) \\ share_{wa} &= (1 - herb) \cdot abvgrd \\ share_{wb} &= (1 - herb) \cdot (1 - abvgrd) \end{aligned} \tag{1.18}$$

so that

$$share_{ha} + share_{hb} + share_{wa} + share_{wb} = 1\,.$$

The NPP so far calculated gives the amount of dry weight produced. Since fluxes in the HRBM are not expressed in dry weight but in carbon content, the NPP it is multiplied by 0.45, assuming that the carbon content of dry weight of any phytomass compartment is 45%.

1.2.2 Litter production

The annual flux "litter production" (LP) is assumed to be proportional to the respective source pool phytomass:

$$LP = clp \cdot PH \tag{1.19}$$

In order to derive the factors *clp* from the mean stand age of the plant material of the vegetation unit, an equation was used which was originally developed to calculate phytomass from net primary productivity and stand age (Esser, 1984):

$$PH = 0.59181 \cdot NPP \cdot age^{0.79216} \tag{1.20}$$

Reformulated for the herbaceous above ground phytomass compartment and extended by the respective phytomass share factors $share_{ha}$ this equation reads:

$$PH_{ha} = 0.59181 \cdot \frac{NPP_{ha}}{share_{ha}} \cdot {age_h}^{0.79216} \tag{1.21}$$

If we assume mature stands, the mass balance equation for phytomass may be set to zero:

$$\frac{d}{dt}PH = NPP - LP = 0 \tag{1.22}$$

LP is replaced by the term of equation (1.19):

$$NPP - clp \cdot PH = 0 \tag{1.23}$$

Table 1.5: Mean stand ages of woody and herbaceous material (age_w and age_h) and factors for separating herbaceous and above ground NPP (*herb* and *abvgrd*) of the potential natural vegetation for 17 formations (BIOME–model, PRENTICE *et al.*, 1992) and agriculturally used grid elements. Values were derived using data from CANNELL (1982) and our data base DATAVW. From ESSER (1984) and MACK (1994).

formation	mean stand age *woody*, age_w [yr]	mean stand age *herb.*, age_h [yr]	herbaceous factor *herb*	above ground factor *abvgrd*
tropical dry savanna	5	1.0	0.90	0.64
tropical seasonal	150	1.0	0.44	0.91
tropical rain	200	1.2	0.37	0.91
xerophytic wood /scrub	20	1.0	0.40	0.65
hot desert	5	1.0	0.85	0.51
warm grass/shrub	5	1.0	0.90	0.59
broad-leaved evergreen/mixed	130	1.2	0.29	0.83
temperate deciduous	150	1.0	0.38	0.87
cool mixed	100	1.0	0.38	0.84
cold mixed	60	2.0	0.60	0.44
cool conifer	100	1.0	0.34	0.83
cool grass/shrub	10	1.0	0.85	0.33
cool deciduous	100	1.0	0.38	0.49
boreal forest	100	2.0	0.34	0.81
tundra	10	1.0	0.70	0.55
semidesert	15	1.0	0.85	0.41
ice/polar desert	5	1.0	0.90	0.41
agriculture	-	0.6	1.00	0.60

and with (1.21) for the herbaceous above ground phytomass compartment:

$$NPP_{ha} - clp_{ha} \cdot 0.59181 \cdot \frac{NPP_{ha}}{share_{ha}} \cdot {age_h}^{0.79216} = 0 \tag{1.24}$$

Divided by *NPP* and solved for *clp*:

$$clp_{ha} = \frac{share_{ha}}{0.59181 \cdot {age_h}^{0.79216}} \tag{1.25}$$

The partition of the annual LP to the 12 months of the year is done in accordance with the relative decrease of the actual evapotranspiration in the current month. Therefore, the decrease of actual evapotranspiration between two months and the difference between highest and lowest evapotranspiration of one year has to be calulated from the monthly evapotranspiration.

At present, the HRBM recognizes 17 different vegetation types (Biome model, PRENTICE *et al.*, 1992). For the biomes '*temperate deciduous*', '*cool mixed*', '*cold mixed*', '*cold*

deciduous', and '*tundra*', the monthly coefficient of litter production in the herbaceous above ground compartment, clp_{ha}, is set to $(2 \times \ln 2)$. This will reduce the herbaceous phytomass to the half within 14 days.

But litter production *won't start* until the monthly temperature drops to the half of the mean temperature of the warmest month. Then it will persist the following three months, though.

Considering long term adaptation, a 50-years running mean of the temperature of the warmest month is used in this procedure.

According to equation (1.25) the coefficients of the litter production in the woody above ground compartments are determined by:

$$clp_{wa} = \frac{share_{wa}}{0.59181 \cdot {age_w}^{0.79216}} \tag{1.26}$$

Assuming equal partition of annual LP to the months and a roughly constant amount of phytomass, the coefficient is divided by 12. The coefficients determining the litter production fluxes of the herbaceous and woody below ground compartments (clp_{hb} and clp_{wb}) are set to the values of clp_{ha} and clp_{wa}, respectively.

The stand ages for woody and herbaceous material of the 17 vegetation formations are found in Table 1.5.

1.2.3 Litter depletion

It is assumed that the decomposed amount of litter (the flux "litter depletion", LD) is proportional to the litter pool:

$$LD = cld \cdot LITT \tag{1.27}$$

The value of the coefficient cld depends on the composition of the decomposed material, and on the elements of the environmental vector (the HRBM considers temperature and precipitation). cld depends exponentially on the temperature while the relation to precipitation is a maximum function (Esser *et al.*, 1982 and Esser & Lieth, 1989). To calculate cld directly from precipitation and temperature data on a monthly basis, function (1.28) has been developed.

$$\begin{aligned} cld &= \exp\left(p_1 + p_2 \cdot \ln(ipp) - p_3 \cdot ipp^{p_4}\right) \\ &\quad + \exp(p_5) \cdot \tanh(p_6 \cdot ipp) \end{aligned} \tag{1.28}$$

with the parameters

$$
\begin{aligned}
p_1 &= -1.96628 \cdot (it - 5) - 12.39641 \\
p_2 &= 0.002236189 \cdot (it + 55)^2 \\
p_3 &= 4.568434 \cdot \exp(-0.1041649 \cdot (it - 5)) \\
p_4 &= 0.0001132567 \cdot (it + 55)^2 \\
p_5 &= 0.07315304 \cdot (it - 5) - 3.51145 \\
p_6 &= \exp\Big(\frac{15000}{(it + 55)^2} - 6.5\Big)
\end{aligned}
$$

and the restrictions

$$
\begin{aligned}
&\text{If} \quad ipp = 0.0 \quad \text{then} \quad cld = 0.0 \\
&\text{If} \quad it < -30.0 \quad \text{then} \quad cld = \exp(p_5) \cdot \tanh(p_6 \cdot ipp)
\end{aligned}
$$

Function (1.28) was developed using data for above ground herbaceous material (see Esser 1986 for a list of the data used). It is modified for each compartment of litter according to

$$
\begin{aligned}
cld_{ha} &= cld_{hb} = cld \\
cld_{wa} &= cld_{wb} = 0.3\, cld
\end{aligned}
$$

The plot of function (1.28) is given in Figure 1.3.

1.2.4 Soil organic carbon production

It is assumed that the polyphenolic compounds in the litter (lignins) contribute to the soil organic carbon. Thus, soil organic carbon production is part of the flux litter production:

$$SOCP = csocp \cdot LP \tag{1.29}$$

The sharing factors $csocp_h$ and $csocp_w$, which represent the lignin content of the respective material, are set to 0.176 for herbaceous material and 0.48 for woody material. In the HRBM, they do not depend on the grid element or the model year.

1.2.5 Soil organic carbon depletion

It is assumed that lignin compounds have depletion coefficients $csocd$ which amount to 0.8% of the coefficients of fresh herbaceous litter as given by equation (1.28):

$$csocd = 0.008 \cdot cld \tag{1.30}$$

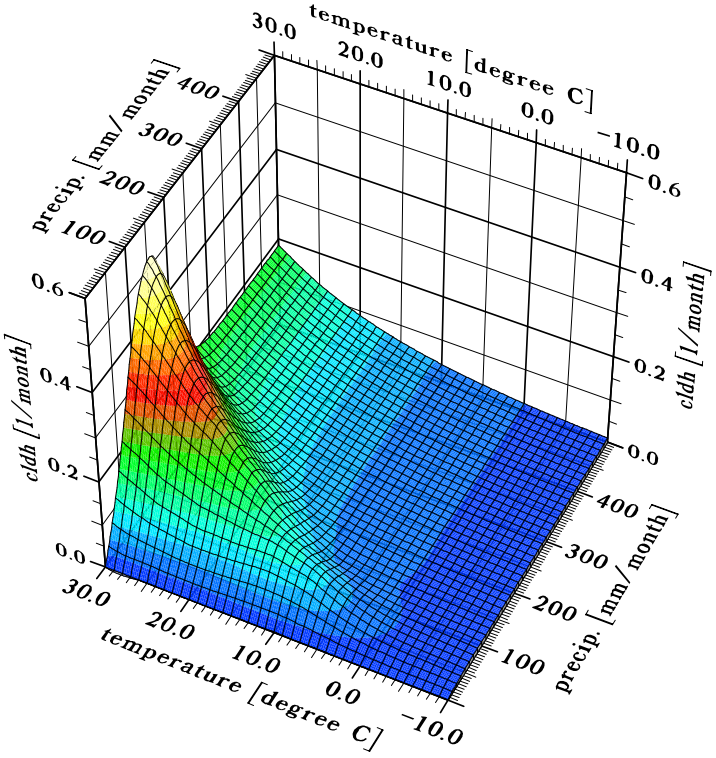


Figure 1.3: Plot of the litter depletion coefficient as a function of monthly precipitation and temperature (eq. 1.28).

Due to unfavourable decomposition conditions prevailing in some soils it is assumed that soil organic carbon depletion is reduced by 80% on Histosols and by 50% on Gelic Gleysols.

1.2.6 Deforestation

The deforestation flux phytomass to litter normally occurs in the model as a consequence of changing stand ages. In addition, a deforestation flux is introduced:

$$DFOR = cdfor \cdot PH \tag{1.31}$$

It is assumed that within one year 50% of the woody phytomass are transferred to litter. Therefore, on agriculturally used grid elements the respective deforestation coefficient *cdfor* for one month is set to 0.06.

$$cdfor \quad = \quad \begin{cases} 0.06 & \text{if grid element is agriculturally used} \\ 0 & \text{otherwise} \end{cases}$$

1.2.7 Leaching of dissolved and particulate organic carbon

Dissolved and particulate organic carbon (DOC and POC) commonly occur as organic carbon freights in each body of fresh water. It has been shown by ESSER & KOHLMAIER (1990), who used data which were acquired by DEGENS *et al.* (1982, 1983, 1985), that the DOC and POC freights of a river mainly depend on its water discharge. In contrast, the correlations of transported DOC and POC with the extent of agriculturally used areas or their change in the watershed of the river were zero or even slightly negative. The authors established two equations to derive DOC and POC from the discharge of water (DIS) through a square meter of the watershed of a river:

$$DOC = 0.0064 \cdot DIS \tag{1.32}$$

$$POC = 0.0022 \cdot DIS \tag{1.33}$$

Since in many regions with high precipitation discharge correlates with precipitation, DIS may be replaced by the mean annual precipitation.

1.2.8 Burning

Determining the fluxes

It is assumed that *burning* ($PHBL$ respective LBL) is proportional to the phytomass respective the litter pool that is affected by fires. The *burning efficiency* ($cbef$) determines the amount of carbon emitted into the atmosphere by pyrolytic processes. $cbef$ characterizes the completeness of combustion.

The *burning probability* ($cburn$) in a given month determines the frequency of fires. Every month, $cburn$ is compared with a number calculated by a random number generator providing uniformly distributed values in the range from 0 to, but not including, 1. If this number exceeds $cburn$, the respective grid element will not be affected by fires, otherwise it is totally burned in the given month.

Only above ground pools are directly affected by fires. Please note that all coefficients are calculated for each grid element; those indices are omitted for the sake of readability. Burning of:

above ground herbaceous phytomass:	$PHBL_{ha}$	$= -\ln(1 - cburn \cdot cbefp_h) \cdot PH_{ha}$
above ground woody phytomass:	$PHBL_{wa}$	$= -\ln(1 - cburn \cdot cbefp_w) \cdot PH_{wa}$
above ground herbaceous litter:	LBL_{ha}	$= -\ln(1 - cburn \cdot cbefl_h) \cdot LITT_{ha}$
above ground woody litter:	LBL_{wa}	$= -\ln(1 - cburn \cdot cbefl_w) \cdot LITT_{wa}$

Forming groups of biomes

According to the different physiognomy of the biomes, which cause differences in the burning probability, the burning efficiency, and the formation of black carbon, the biomes may be classified into three groups: forests; shrub formations; savannas, grasslands, and deserts. The biomes of the IIASA–biome model (PRENTICE *et al.*, 1992) are classified in the following way:

Forests (I)		**Shrub formations (II)**
Taiga Cold mixed forest Cool conifer forest Cool mixed forest	**Ia**	Tundra Broad–leaved evergreen forest/ Warm mixed forest[c] Xerophytic woods/scrub
Cold deciduous forest Temperate deciduous forest	**Ib**	**Savannas, grasslands, and deserts (III)**
Broad–leaved evergreen forest/ Warm mixed forest[a]	**Ic**	Ice/polar desert Cool grass/shrub[d] Hot desert Semidesert Warm grass/shrub
Burning Tropical seasonal forest Tropical rain forest	**Id**	
Cool grass/shrub[b]		Tropical dry forest/savanna **Ie**

[a]only for calculating burning probability and for calculating burning efficiency
[b]only for calculating burning probability
[c]only for calculating dead fine fuel moisture content
[d]only for calculating burning efficiency and for calculating dead fine fuel moisture content

Calculating the coefficients

Burning probability (*cburn*): *cburn* is derived from a humidity index (see section 1.2.8). The less humid a region is, the higher is *cburn*. It is calculated for different groups of biomes.

The equations were empirically derived using data for fire cycles on a monthly time scale from WEIN and MOORE (1979) (transition zone between boreal and cool temperate forest in Nova Scotia (Canada)) for **forests** (biome group I), BROWN *et al.* (1991) (fynbos) for **shrub formations** (II), BRAITHWAITE and ESTBERGS (1985) as well as LAMOTTE *et al.* 1985 (cit. by MENAUT *et al.*, 1991) and MENAUT (pers. comm.) in savannas for **savannas, grasslands, and deserts** (III). The *fire cycle* is defined as the average time span needed to burn an area equal to the entire area of interest (ROMME,

1980). This approach assumes that *cburn* is the reciprocal value of the fire cycle (expressed in months).

Under certain conditions no fire is possible, $cburn = 0$ (see MACK (1994) for a detailed explanation):

if too cold:	$it < 0$ °C
if too humid:	$hi > 50$
if fuel too wet:	$fmc > 25\,\%$ ($35\,\%$ for biome group (III))
if fuel too sparse:	fuel type and minimum amount of above ground plant material depend on the biome group:
	(I) $LITT_{ha} + LITT_{wa} < 45\,\mathrm{g \cdot m^{-2}}$
	(II) $PH_{ha} + PH_{wa} + LITT_{ha} + LITT_{wa} < 180\,\mathrm{g \cdot m^{-2}}$
	(III) $PH_{ha} + PH_{wa} + LITT_{ha} + LITT_{wa} < 45\,\mathrm{g \cdot m^{-2}}$

Otherwise, *cburn* is determined according to

$$cburn = \begin{cases} 0.0058 \cdot \exp(-0.107 \cdot hi) & \text{for biome group (I)} \\ 0.00083 \cdot \exp(-0.117 \cdot hi) & \text{for biome group (II)} \\ 0.025 \cdot \exp(-0.081 \cdot hi) & \text{for biome group (III)} \end{cases}$$

Fuel comprises above ground phytomass and above ground litter pools with exception of the forests, where we assume that only litter contributes to the fuel.

Cleared areas: The burning probability for grid elements that are cleared is calculated by the use of a maximum function based on either humidity index $cburn_{hi}$ or amount of litter $cburn_{lw}$. Similar to the previous equations, fire is believed to occur only if the mean monthly temperature is above 0 °C. In contrast to the previous equations, fire is assumed to be independent from the calculated fuel moisture content since artificial drying is prevailing. Fire is excluded in agriculturally used areas.

$$\begin{aligned} cburn_{lw} &= \min\{1, \max\{0,\ 0.214 \cdot \ln(0.023 \cdot LITT_{wa})\}\} \\ cburn_{hi} &= \min\{1, \max\{0,\ 0.229 \cdot \exp(-0.049 \cdot hi)\}\} \end{aligned}$$

$$cburn = \begin{cases} 0 & \text{if} \quad T \leq 0 \\ \max(cburn_{hi}, cburn_{lw}) & \text{otherwise} \end{cases}$$

This peculiar min/max–construction simply ensures that the *probabilities* cannot exceed the limits 0 and 1.

Burning efficiency in general (*cbef*): A simple, general formula is provided to calculate the burning efficiency for some pools and groups of biomes (see Table 1.8 on page 29).

The general burning efficiency was empirically derived from the dead fine fuel moisture content, *fmc* (see page 24). The drier the fuel, the higher is the burning efficiency. Note that $cbef \geq 0.45$.

$$cbef = 1.00 - \frac{0.55}{1 + \exp(5.24 - 0.76 \cdot fmc)}$$

Burning efficiency of above ground woody phytomass in forests: Regarding the phytomass pools in forests the burning efficiency drops with increasing diameter of the trees. The mean diameter at breast height (*dbh*) can be easily measured and is therefore used in the specific equations for forest types.

Biomes of the boreal and cool temperate zones dominated by conifers (Subgroup Ia): Based on the investigation by HOGAN in a *Picea mariana–Cladonia alpestris* forest close to Schefferville (Canada) (unpubl., cit. by AUCLAIR, 1983), one third of the above ground woody phytomass is burned: $cbef_{const} = 0.33$.

$$cbefp_w = \begin{cases} 0 & \text{if } \; dbh > 0.413 \\ cbef_{const} & \text{if } \; dbh < 0.042 \\ cbef_{const} \cdot cbmop'_w & \text{otherwise} \end{cases}$$

According to the model, $cbef_{const}$ is scaled with the mortality coefficient ($cbmop'_w$) to obtain a dynamic course resulting in a declining burning efficiency with increasing diameter.

Cold deciduous forest: Again, $cbef_{const}$ is scaled with the mortality coefficient ($cbmop'_w$) to obtain a dynamic course of *cbef*.

$$cbefp_w = \begin{cases} 0 & \text{if } dbh > 0.204 \\ cbef_{const} \cdot cbmop'_w & \text{otherwise} \end{cases}$$

All other forest biomes: *cbef* of all other forest biomes is set to 0 due to the fact that the biom *temperate deciduous forest* is affected mainly by ground fires (ALBINI, 1992), and that subtropical trees like *Pinus* and *Eucalyptus* are rather resistant towards frequent fires (see section 1.2.9 on page 26). In addition, it is assumed that most of the woody phytomass in tropical forests dies before crown fires are possible.

$$cbefp_w = 0$$

Table 1.6: Derivation of the coefficients from auxiliary variables.

flux	coefficient in subroutine BRNCLC	auxiliary variable
burning (*PHBL*, *LBL*)	*cburn* *cbef*	*hi*, *fmc* *dbh*, *fmc*
mortality (*PHML*)	*cburn* *cbmo*	*hi*, *fmc* *dbh*, *fmc*
formation of black carbon (*PHCP*, *LCP*)	*cburn* *cbch*	*hi*, *fmc* *dbh*, *fmc*

Table 1.7: Derivation of auxiliary variables from climate data and from the amount of carbon in phytomass and litter pools. The symbol '+' means 'is calculated from', e.g. *dbh* is calculated solely from phytomass.

	cur	*fmc*	*dbh*	*hi*
precipitation		+		+
temperature		+		+
phytomass	+	+	+	
litter	+	+		

Determination of auxiliary variables

Table 1.6 shows the auxiliary variables that are used for the calculation of the coefficients determining the fluxes resulting from the subroutine BRNCLC. Table 1.7 lists concisely the data used to determine the auxiliary variables.

Dead fine fuel moisture content (*fmc*): *fmc* of burned material is calculated from current values for temperature (t_f) and relative humidity (rh_f) during fires or a short time before fires and from the proportion of above ground herbaceous *litter* at the total above ground herbaceous plant material (*cur*). Different equations are used for groups of biomes.

Forests (I): *fmc* is calculated following parts of the CCFWIS (Canadian Forest Fire Weather Index System) (VAN WAGNER, 1987):

$$\begin{aligned} fmc &= 0.942 \cdot rh_f^{0.679} + 11 \cdot \exp((rh_f - 100)/10) \\ &+ 0.18 \cdot (21.1 - t_f) \cdot (1 - \exp(-0.115 \cdot rh_f)) \end{aligned}$$

Shrub formations (II): Here, *fmc* is determined using Burgan's method to calculate fuel moisture content in fynbos (BURGAN, 1987):

$$fmc = \begin{cases} 0.03229 + 0.262577 \cdot rh_a - 0.0010404 \cdot t_a \cdot rh_a & \text{if } rh_a < 10 \\ 1.754402 + 0.160107 \cdot rh_a - 0.026612 \cdot t_a & \text{if } 10 \leq rh_a \leq 50 \\ 21.0606 - rh_a \cdot (0.00063 \cdot t_a + 0.0112) + & \\ +0.005565 \cdot rh_a^2 - 0.483199 \cdot rh_a & \text{otherwise} \end{cases}$$

t_a respectively rh_a correct the corresponding values for temperature and relative humidity during or a short time before fires (t_f and rh_f) for the influence of radiation. The cloud freeness (clf) is the contrary of the cloud cover, or more precisely,

$$\text{cloud freeness} + \text{cloud cover} = 1\,.$$

$$t_a = \begin{cases} t_f + 13.9 & \text{if} \quad clf > 0.9 \\ t_f + 10.6 & \text{if} \quad 0.9 \geq clf \geq 0.55 \\ t_f + 6.7 & \text{if} \quad 0.55 > clf \geq 0.1 \\ t_f + 2.8 & \text{otherwise} \end{cases}, \quad rh_a = \begin{cases} 0.75 \cdot rh_f & \text{if} \quad clf > 0.9 \\ 0.83 \cdot rh_f & \text{if} \quad 0.9 \geq clf \geq 0.55 \\ 0.92 \cdot rh_f & \text{if} \quad 0.55 > clf \geq 0.1 \\ 1.00 \cdot rh_f & \text{otherwise} \end{cases}$$

Savannas, grasslands, and deserts (III): fmc is calculated for grassland and desert biomes using the Australian Grassland Fire Danger Meter (GFDM) 'Mark 5':

$$fmc = \frac{97.7 + 4.06 \cdot rh_f}{t_f + 6.0} - 0.00854 \cdot rh_f + \frac{3000}{cur} - 30.0$$

Regarding the biom *tropical dry forest/savanna* the equation was adapted by leaving out the proportion of above ground herbaceous *litter* at the total above ground herbaceous plant material (cur):

$$fmc = \frac{97.7 + 4.06 \cdot rh_f}{t_f + 6.0} - 0.00854 \cdot rh_f$$

Determination of current values for temperature during or a short time before fires (t_f): t_f is calculated from the monthly mean temperature:

$$t_f = 0.64 \cdot it + 14.7$$

Determination of current values for relative humidity during or a short time before fires (rh_f): rh_f is calculated from the humidity index hi:

$$rh_f = 0.5 \cdot hi + 40.5$$

Concerning forest biomes, an influence of the humidity index as above regarding t_f was not found. Therefore, rh_f is set to an empirically derived constant value:

$$rh_f = 34.4$$

Determination of the humidity index (hi): The applied precipitation to temperature ratio by GAUSSEN (cit. by KREEB, 1983) has been widely used by WALTER and LIETH in their climate diagrams to distinguish between humid and arid months.

$$hi = \frac{ipp}{2\,\mathrm{mm}} - \frac{it}{1^\circ\,\mathrm{C}}$$

Determination of cur: cur is the proportion of above ground herbaceous *litter* at the total above ground herbaceous plant material [in %].

$$cur = \frac{LITT_{ha} \cdot 100}{LITT_{ha} + PH_{ha}}$$

Determination of the diameter at breast height (dbh): dbh is used to determine the burning efficiency and the mortality coefficient in non tropical forests. The equation was empirically derived using the data published by CANNELL (1982). dbh depends on the amount of herbaceous and woody phytomass.

$$dbh = 0.856 \cdot 10^{-4} \cdot PH^{0.857} \cdot \exp(-0.904 \cdot 10^{-5} \cdot PH) \tag{1.34}$$

1.2.9 Mortality

Determining the fluxes

The *mortality* ($PHML$) is assumed to be proportional to the fuel pools affected by fires. The *mortality coefficient* ($cbmo$) is calculated separately for herbaceous and woody material.

Mortality of:

above ground herbaceous phytomass:	$PHML_{ha}$	$= -\ln(1 - cburn \cdot cbmop_h) \cdot PH_{ha}$
above ground woody phytomass:	$PHML_{wa}$	$= -\ln(1 - cburn \cdot cbmop_w) \cdot PH_{wa}$
below ground herbaceous phytomass:	$PHML_{hb}$	$= 0$
below ground woody phytomass:	$PHML_{wb}$	$= -\ln(1 - cburn \cdot cbmop_w) \cdot PH_{wb}$

Calculating the coefficients

See section 1.2.8 and Table 1.6 for the calculation of the burning probability as well as section 1.2.8 and Table 1.7 for the calculation of the auxiliary variables. Table 1.8

summarizes the procedure to calculate the mortality coefficient for the respective pools and groups of biomes.

Mortality coefficient in general ($cbmo$): The below ground woody phytomass pool is the only below ground pool which is directly affected by fires. It is assumed that the below ground parts die together with the above ground parts. Therefore, similar values of $cbmo$ for either proportion of P are assumed. In contrast, herbaceous phytomass is **not** affected by vegetation fires.

The general mortality coefficient is based on the assumption that *all* carbon reached by fires takes one of the three routes: into the air ($cbef$), into black carbon ($cbch$), and into litter ($cbmo$). The equation resulting from this assumption must hold:

$$cbef + cbch + cbmo = 1\,,$$

Table 1.8 shows the cases where this general formula and exceptions are applied.

Mortality coefficients of above ground woody phytomass in forests:

Biomes of the boreal and cool temperate zone dominated by conifers (Subgroup Ia): The equations are based on investigations in *Pseudotsuga menziesii* and *Pinus banksiana* stands (Bergeron & Brisson, 1990; Peterson & Arbaugh, 1986; Peterson & Arbaugh, 1989). It is assumed that one third ($cbef_{const} = 0.33$) of the mortality flux is consumed by fire (see section 1.2.8). Moreover, a small fraction of black carbon is produced ($cbchp_w$; see section 1.2.10). Both proportions are subtracted from $cbmop'_w$ in order to prevent values greater than 1 for the total of burning efficiency, mortality coefficient, and black carbon formation coefficient. This procedure assumes that parts of the dying phytomass determined by $cbmop'_w$ are burned or transformed to black carbon.

$$cbmop'_w = -2.68 \cdot dbh + 1.11$$

$$cbmop_w = \begin{cases} 0 & \text{if } \; dbh > 0.413 \\ 1 - cbef_{const} - cbchp_w & \text{if } \; dbh < 0.042 \\ (1 - cbef_{const} - cbchp_w) \cdot cbmop'_w & \text{otherwise} \end{cases}$$

$$cbef_{const} \;\; = \;\; 0.33$$

Biomes of the boreal and temperate zones dominated by deciduous trees (Subgroup Ib): The equations are based on investigations in *Populus tremuloides* and *Populus tremuloides*/mixed hardwood stands (ALEXANDER & SANDO, 1989; QUINTILLO *et al.*, 1989).

$$cbmop'_w = -4.79 \cdot dbh + 0.98$$

In the biome *cold deciduous forest*, $cbmop_w$ depends — as for conifers — on the burning efficiency and the black carbon formation coefficient.

$$cbmop_w = \begin{cases} 0 & \text{if } \; dbh > 0.204 \\ (1 - cbef_{const} - cbchp_w) \cdot cbmop'_w & \text{otherwise} \end{cases}$$

Broad–leaved evergreen forest/warm mixed forest (Subgroup Ic): The equation is based on investigations in *Pinus spec.* stands (STOREY & MERKEL, 1960; LINDENMUTH 1960, cit. by WRIGHT, 1978).

$$cbmop_w = \begin{cases} 0 & \text{if } \; dbh > 0.191 \\ -2.56 \cdot dbh + 0.49 & \text{otherwise} \end{cases}$$

Tropical rain and tropical seasonal forests (Subgroup Id): According to studies by UHL and KAUFFMAN (1990) at least 50% of the woody phytomass were transformed to litter.

$$cbmop_w = 0.5$$

1.2.10 Black carbon formation

Determining the fluxes

The *black carbon formation* (*PHCP* respective *LCP*) is assumed to be proportional to the phytomass respective the litter pools affected by fires. The *black carbon formation coefficient* (*cbch*) is determined by KUHLBUSCH (1993) as that part of the charcoal which is produced by vegetation fires and which is biologically not decomposable. *cbch* is calculated separately for herbaceous and woody material.

Black carbon formation of:

above ground herbaceous phytomass: $PHCP_{ha} = -\ln(1 - cburn \cdot cbchp_h) \cdot PH_{ha}$

above ground woody phytomass: $PHCP_{wa} = -\ln(1 - cburn \cdot cbchp_w) \cdot PH_{wa}$

above ground herbaceous litter: $LCP_{ha} = -\ln(1 - cburn \cdot cbchl_h) \cdot LITT_{ha}$

above ground woody litter: $LCP_{wa} = -\ln(1 - cburn \cdot cbchl_w) \cdot LITT_{wa}$

Table 1.8: Calculation of the coefficients related to burning, depending on biome groups; (*gen.* means: *general formulae*, see section 1.2.8)

	Biome group I	Biome group II	Biome group III
$cbefp_h$	depends on dbh[a]	1.0[b]	*gen.*
$cbefp_w$	see section 1.2.8	*gen.*	$\begin{cases} 0.02^c & \text{forest subgroup } Ie \\ gen. & \text{otherwise} \end{cases}$
$cbefl_h$	*gen.*	*gen.*	*gen.*
$cbefl_w$	*gen.*	*gen.*	0.25[d]
$cbmop_{ha}$	same as 'wa'[e]	0 (no litter)[f]	*gen.* (all dead)[g]
$cbmop_{wa}$	see section 1.2.9	*gen.*[h]	$\begin{cases} 0^i & \text{forest subgroup } Ie \\ gen.^j & \text{otherwise} \end{cases}$
$cbmop_{hb}$	0[k]		
$cbmop_{wb}$	same as woody, above ground[l]		

[a] Linear relations are assumed due to the available data providing relations between dbh and mortality coefficient:

$$cbefp_h = \max(0, -5.93 \cdot dbh + 1.0)$$

For temperate deciduous forests, $cbefp_h$ is set to 0 (Albini, 1992).

[b] Some investigations prove that the above ground herbaceous phytomass in shrub formations is totally consumed by vegetation fires (Cass *et al.*, 1984; Griffin & Friedel, 1984; van Wilgen, 1982)

[c] This is based on an investigation by Hopkins (1965) in the Okolomeji Forest (Nigeria)

[d] Studies made by Frost (1985) resulted in lower burning efficiencies of woody litter in savannas compared to herbaceous litter. According to these studies, a value of 25 % is estimated.

[e] Due to lack of data, it is assumed that the mortality coefficient of herbaceous phytomass is identical with the mortality coefficient of woody phytomass. However, the restriction holds that the sum of burning efficiency, mortality coefficient, and black carbon formation coefficient may not exceed unity. Therefore, we have

$$cbmop_h = \begin{cases} 1 - (cbefp_h + cbchp_h) & \text{if } cbmop_w + cbefp_h + cbchp_h > 1 \\ cbmop_w & \text{otherwise} \end{cases}$$

[f] Due to the complete combustion of herbaceous phytomass, cbmop_h is set to 0.

[g] This was proved by Bragg (1982) in the prairie (Nebraska).

[h] See also van Wilgen, 1982; Barro & Conrad, 1991; Green, 1981; Griffin & Friedel, 1984; Kilgore, 1973; Minnich, 1983; Rutherford & Westfall, 1986; Vogl & Schorr, 1972; Wright *et al.*, 1979

[i] The trees are adapted to frequent fires and therefore resistant.

[j] Due to lack of data, $cbmop_w$ is assumed to be identical with $cbmop_w$ in shrub formations.

[k] It is assumed that the below ground herbaceous phytomass is not affected by fires.

[l] Due to lack of data, it is assumed that the below ground parts of a plant die together with the above ground parts.

Calculating the coefficients

See section 1.2.8 and Table 1.6 for the calculation of the burning probability and section 1.2.8 and Table 1.7 for the calculation of the auxiliary variables.

Black carbon formation coefficient (*cbch*): The general black carbon formation coefficient increases with lower burning efficiency. A linear interdependence is assumed. *chmax* denotes the maximum black carbon formation coefficient (Comery *et al.*, 1981; Fearnside, 1991; Kuhlbusch, 1993). The formula is valid only for reasonably high values of efficiency.

$$cbch = chmax \cdot (1 - cbef) \ , \quad cbef > 0.1$$

A modified version of this formula is used in forest biomes (subgroups Ia to Ie): Regarding the herbaceous phytomass and the woody phytomass in forests, burning efficiencies less than 0.5 are common. In this case, a proportional relation between burning efficiency and black carbon formation coefficient is assumed to prevent unrealistically high black carbon formation coefficients with very low burning efficiencies. If *cbef* is set to 0, *cbch* will be set to 0.

$$cbch = chmax \cdot (0.5 - |cbef - 0.5|)$$

1.3 Land–use changes and deforestation

Each grid element is considered to be either under agricultural use or covered by natural vegetation. The information is stored in the matrix *useann* which is updated annually. Land use changes are implemented by changing the values of the elements of the matrix (0: natural vegetation, 1: agricultural use). Different methods to calculate *useann* are applied in the periods 1860,..., 1990 and 1991,..., 2050 A. D.

1.3.1 Period 1860 to 1990

From the digitized map of Olson *et al.* (1983), a matrix of agriculturally used grid elements in 1980 has been derived. Based on FAO-data (AGROSTAT-PC Data base, 1992) this matrix has been modified for countries, which agricultural area should be greater than mentioned by Olson. During development of this standard matrix for the year 1980 (*usestd*), clearing probabilities have been considered for each individual grid

element. The total farming area of a country may be computed by adding up the areas of all grid elements of the country for which $usestd = 1$.

The matrix *korri* contains the changes of agriculturally used areas in each country relative to 1980 for the period 1860 to 1990. This matrix is based on data by RICHARDS *et al.* (1983) and FAO (AGROSTAT-PC Data base, 1992). For any model year of that period, the grid elements of a country under use (matrix *useann*) are updated by taking elements of the country into or out of use so that the actual agriculturally used area of the country meets the required area (i.e. area of 1980 $\times$*korri*).

1.3.2 Period 1991 to 2050

Future scenarios of potential land use changes rely on the population development in each country as predicted by the World Bank Population Projections 1989/90 (BULATO *et al.*, 1990). Those predictions, which originally are available for five–year intervals for the period 1955–2050, were interpolated using a polynomial fit (PRESS *et al.*, 1987) to get population figures for each year.

We assume that a certain agricultural production is required per caput of population in each country depending on the state of development of socio–economic features. Here is a first interface to socio–economic models. The agricultural area of the country must provide the production necessary to sustain the population (foreign trade is yet excluded). Accordingly, the matrix *useann* is changed so that, in a given year, the required production is provided for each country. The algorithm follows roughly the following steps:

1. The population of the current year is calculated from the polynomial parameters.

2. The actual agricultural production is computed. To consider only long term effects, a five year running mean is determined.

3. The ratio production per caput is derived.

4. The actual ratio is compared to the required ratio (i.e. the ratio of 1990 corrected eventually for the current year). If the required ratio is not met, *useann* of the country is changed iteratively (one grid element each time). The selection of grid elements to be changed considers soil quality, climatic condition, and agricultural status of surrounding grid elements (see 1.3.3). The maximum number of grid elements which may be taken in use is limited per country by the total number

of grid elements of the country minus the number of grid elements having less production than a given minimum.

The relative agricultural productivity *rapg* is a correction factor which reduces the net primary productivity of a grid element under use depending on the intensity of agricultural practices in the country (see eq. 1.15). This factor may change as a consequence of economic developments. Here is a second interface to socio–economic models. At present, the HRBM module provides possibilities to change *rap* after 1990.

1.3.3 Probability for clearing

Handling the pattern of agricultural areas of the countries, the sequence of clearing and reforestation of grid elements has to be determined. An actual pattern is given by OLSON *et al.* (1983) and has been modified to create a standard pattern for the year 1980. To establish agricultural pattern for every year, the grid elements of one country are ranked according to a "clearing probability" considering

- soil quality,
- climatic conditions, and
- agricultural status of surrounding grid elements.

The soil quality is directy derived from the soilfactor *fsoil*. The annual mean temperature and sum of precipitations are used to calulate the NPP according to the MIAMI model (LIETH, 1975). Due to the fact that clearing often occurs in the neighborhood of agricultural areas, the probability (p) to take one grid element into use depends on the number of cleared grid elements in the surroundings:

$$p = (2^{(mcircl+1)} - 1) \cdot \sum_{icircl=1}^{mcircl} \frac{1}{2^{(icircl-1)}} \cdot \frac{ianz_{icircl}}{icircl \cdot 8} \tag{1.35}$$

icircl: current circle radius around the grid element
ianz: number of agriculturally used grid elements in the current circle

At present all probabilities are normalized and equally weighted. If an increase of agricultural area has to take place, those grid elements with the highest clearing probability will be used. A decrease of agricultural area leads to the transformation of the grid element with the lowest clearing probability.

Chapter 2

Program code

2.1 General conception and structure of the program code

From the programmer's point of view, the primary goal is a flexible and extensible program structure. This is achieved by the following means:

- **modular programming.** Each group of related tasks is handled by a separate subroutine, or module. The interface between the main program and the subroutine consists mainly of common blocks. Several modules can share common blocks among each other and with the main program.

- **variables instead of constants.** Wherever appropriate, variables together with `parameter` statements are used instead of numeric constants for things like file units, array dimensioning and index assignments.
  For example, it's not `pool(1)` but `pool(pphha)`,
  which stands for '**p**ool **ph**ytomass **h**erbaceous **a**bove ground'.

- **simple structures.** The main module is kept as much straightforward as possible.

- **comfortable run-time parameter handling.** It is desirable to be able to change parameters for a model run without re-compiling. This is especially true for output filenames (for means of comparison) and so-called 'switches' which alter the model's behaviour. One set of parameters for a model run is kept together in a special parameter file. Parameter values are accessible via keywords.

- **modular time integration.** The core of the main module is the inner loop that develops the state of the system (described by the contents of the pools) in time.

As time 'ticks' forward, the changes of the pools are given by a set of ordinary differential equations. There are several methods to integrate such equations, but they all have in common that they need the time derivative of the pools at a given time, depending on the actual state. This information is provided by a subroutine, regardless of which method will use it later.

Further general outlines are to keep subroutines readable by having them as short as possible, to comment the code extensively, and to think 'vectors', that is, to recognize data parallelism, avoid recursive array references and to structure the code for automatic vectorization. This alone will inflict the greatest impact on performance and cpu time usage. To watch the progress of a model run, we document subroutine calls with little messages written to Standard Output.

2.1.1 Notation used in this Manual

All variables appearing in the text are written in *italics*. Names of subroutines and block data are CAPITALIZED and names of common–blocks are written in `typewriter` style.

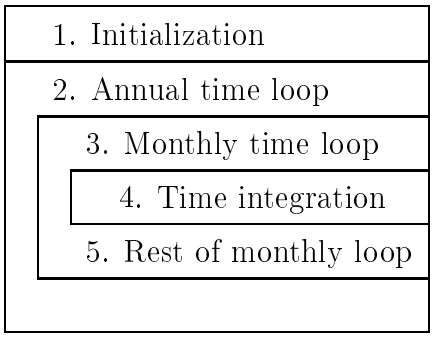
2.1.2 The pre-run

During a model run, we distinguish between the pre-run and the full model run. Subroutine PINIT provides the initial pool values based on long-time means of the driving forces. The pre-run is used to get over initial oscillations and to establish a dynamic balance, a steady state of the system. At the end of a pre-run, we take a 'snapshot' of the pool values, writing them to files. Subsequent model runs can take advantage of these pre-run results and start directly with the full model run. The switch *lpread* ('pre-run read') decides whether to read pre-run results or just to use PINIT in the first month.

2.2 A close look on the main module

In this section, a step-by-step documentation of the main program is presented which can be taken standing alone by itself, but can also be useful while studying the source code. Most of this is recorded in source comments, too.

The main module is divided into five parts: initialization phase, annual time loop, enclosed therein the monthly time loop, again enclosed the time integration over one month, followed by the rest of the monthly time loop consisting mainly of statistics and bookkeeping. These five parts will now be explained according to the sequence in which they appear.



2.2.1 Initialization

The parameter file

After declaring the variables and common blocks, the first thing to do is to initialize the run-time parameters from the parameter file. There are four functions, IPARAM, LPARAM, RPARAM and SPARAM, to be used for integer, logical, real and character string variables (character*50), respectively. All of them take a single argument which is a fixed-length keyword (character*25), e.g.

```
'Time steps per month     '
```

When called, these functions scan the parameter file which is connected to standard input (unit no. 5), looking for an entry of the following form:

```
I Time steps per month      5
```

Each entry begins with a single upper-case character that denotes the type of variable connected with the keyword, in this case 'I' for 'integer'. The second character in the line is ignored. Characters 3 to 27 form the keyword which must match the function argument exactly to be recognized. Again, character 28 is ignored; from characters 29 on up to a maximum line length of 78 follows the value corresponding to the keyword, here the integer value '5'. Since every function call scans the parameter file from beginning to end, the entries don't have to appear in the calling sequence in the main module. The functions will return an error message and stop program execution under two conditions: Either the keyword could not be found or the type declared in the parameter file doesn't match the requested type (depending on which of the four functions was called).

The parameter file contains time limits for the model run, controls the accuracy of the time integration, determines whether a pre-run should be performed or not, allows for flexible future scenarios, and sets the model behaviour 'switches' (whose names begin with 'l' for 'logical') and the filenames for input and output files (filename variables begin with 'F'). A sample parameter file is presented in Fig. 2.1.

```
    I Starting year             1860
    I Ending year               2000
    I Time steps per month      5
    I Output (year)             1960
    I Output (month)            12
    I Pre-run years             300
    L read old pre-run data?    .F.
    L calculate biomes?         .F.
    L scenario rap(2050)fix?    .F.
    R Ann.increase foss.emiss.% 1.0
    R rap in 2050               99.
    R CO2 (ppm)                 360.
    S FILE coordinates          input/coord.05
    S FILE IIASA temperatures   input/tempiiasa.05
    S FILE IIASA precipitation  input/precipiiasa.05
    S FILE IIASA clouds         input/cloudiiasa.05
    S FILE soil factors         input/soilfactors.05
    S FILE rel.agr.productivity input/fyield8090.country
    S FILE usestd OLSEN         input/olson.agri.05
    S FILE korri RICHARDS       input/korrmatrix
    S FILE fossil emissions     input/fossil.year
    S FILE population params.   input/popparam
    S FILE fymult               input/fymult.2050
    S FILE nvi data             input/nvi.05
    S FILE biome data           f80
    S FILE prerun input 1       prerun/f33
    S FILE prerun input 2       prerun/f35
    S FILE prerun output 1      prerun/f34
    S FILE prerun output 2      prerun/f36
    S FILE poolout (f40)        output/f40
```

Figure 2.1: A sample parameter file.

Further initialization

Since the filenames for input data are known by now, we can continue by reading the input files. The subroutine FILRED serves this purpose. The data are read into common blocks for later use.

With the run-time parameter *ews*, a scenario for future CO_2 emission is selected and prepared by the subroutine FOSCEN. *ews* may take the values 1, 2, or 3 corresponding to three different annual increase rates (1.0, 0.5, and 0.1%).

The subroutine ARCALC calculates the area of each grid element.

At the end of initialization, we set limits for the annual loop and some variables used by the time integration method.

2.2.2 The annual time loop

We enter the next section of the source code and open the annual loop. The year starts with the computation of the current climate which is done in the first year of the model run by calling the subroutines BUCKET, and MTEMP.

After that, we take the human influences into account. AGRYIE calculates the agricultural yield for the current year using the future scenario given by the parameter file. One can choose between *a)* extrapolation from the year 1990 on and *b)* levelling to a constant yield factor, the same for all countries, in 2050. AGSUIT ranks the grid elements after their probability for agricultural use. AGRPAT and AGRFUT then set the usage pattern for the past and the future.

2.2.3 The monthly time loop

Embedded within the annual loop lies the monthly loop. If necessary, previous prerun results are read back from the appropriate files at the beginning of the first year.

In the next step, the coefficients in the system of differential equations are calculated by CFFCLC and BRNCLC. One might suggest that these coefficients depend on time and on pool values, and therefore should be determined within the time integration itself. But the time basis of our model is one month. We cannot take sudden changes below the monthly scale into account, because the resolution of available data is too poor.

The net primary production can be obtained from two different approaches, the MONTREAL and the MIAMI model, realized in the subroutines MONTRE and MIAMI. The switch *lmiami* is responsible for this selection.

In order to build global sums of pools and fluxes, special sum variables must be set to zero. Pool values are transferred to the array in which time integration will take place.

2.2.4 Time integration

There are many different methods to integrate a system of coupled differential equations, ranging from Euler's method to refined predictor-corrector methods. In our case, we don't have a too high demand on accuracy, but we need to keep the memory requirements as low as possible, since we currently deal with one system comprising more than a dozen differential equations for tens of thousands of grid elements.

While Euler's method is generally too unreliable because of its lack of symmetry, a Runge-Kutta method of second or fourth order is quite sufficient for our purpose. At

the moment, we do not need the extra expense of adaptive step sizes, but can do with the subdivision of one month in five time steps.

The array *pool(igrid,ipool)* holds the pool values for each grid element (1–62,483) for each pool (1–29). The subroutine DGL provides the time derivative of the pool values, *dt(igrid,ipool)*, based upon such a pool array. The variable *deltat* holds the time interval.

There is a fine distinction between 'real' pools and 'dummy' pools. 'Dummy' pools are used only to sum up fluxes, so that we can say afterwards, we had this much NPP, for instance. This is not necessary while we are still in a pre-run.

2.2.5 The rest of the monthly loop

This part does not much more than bilancing. Global sums of all the pools are computed, and of the fluxes, too, if we are in the full model run. Aside from these monthly sums, there is an annual sum of the NPP, *nppyr*, to build. *nppyr* is set to zero at the beginning of the year and thereafter filled month by month.

Should we happen to be in December of the last pre-run year, the pre-run results are written to files for later use.

The parameter file defines a special 'output' year. In this year, we create an output file for each month for NPP tracking.

Finally, we call the ocean submodel OCEAN, which manages the CO_2 balance between atmosphere and ocean, considering fossil emissions and the biospheric balance *atmsm*.

Outside of the monthly loop, but before closing the annual loop, we call the standard model output routine, POLOUT.

2.3 Flow Chart

In the flow chart presented in Fig. 2.2 all subroutines and block data have been listed. The subroutines mentioned on the right hand side are additionally used during a prerun before 1860, while those on the left hand side are enabled during scenarios upto 2050. The annual and monthly time loops are marked by fat lines. In the present state, the MIAMI or the MONTREAL model can be used to provide the productivity.

Table 2.1: List of pool index names.

HRBM main model

'real' pools		'dummy' pools	
pphha	'phytomass herbaceous above ground'	pnpph	'net primary productivity herb.'
pphhb	'phytomass herbaceous below ground'	pnppw	'net primary productivity woody'
pphwa	'phytomass woody above ground'	plph	'litter production herbaceous'
pphwb	'phytomass woody below ground'	plpw	'litter production woody'
plha	'litter herbaceous above ground'	pldh	'litter depletion herbaceous'
plha	'litter herbaceous below ground'	pldw	'litter depletion woody'
plha	'litter woody above ground'	psocp	'soil organic carbon production'
plha	'litter woody below ground'	psocd	'soil organic carbon depletion'
psoc	'soil organic carbon'	pdfor	'deforestation'
patmo	'atmosphere'		

FIRE submodel

'real' pools		'dummy' pools	
pchc	'black carbon (charcoal)'	pphblh	'phytomass burning loss herbaceous'
		pphblw	'phytomass burning loss woody'
Actually there are more 'real' pools originally belonging to the fire submodel, but they have been integrated into the main HRBM as a subdivision of phytomass and litter pools into above and below ground.		plblh	'litter burning loss herbaceous'
		plblw	'litter burning loss woody'
		pphmlh	'phytomass mortality loss herb.'
		pphmlw	'phytomass mortality loss woody'
		pphcph	'phytomass black carbon product. h.'
		pphcpw	'phytomass black carbon product. w.'
		plcph	'litter black carbon production h.'
		plcpw	'litter black carbon production w.'

2.4 List of integer constants

As mentioned before, we try to avoid using explicit indices, loop bounds etc., but employ variables instead which are 'made constant' by `parameter` statements. These constants can be divided into the following sections:

2.4.1 Pool indices

The names of pool indices begin with a 'p' for 'pool'. Other abbreviations are: 'ph' for 'phytomass', 'l' for 'litter', 'h' for herbaceous, 'w' for 'woody', 'a' for 'above ground', 'b' for 'below ground'. For a complete list, refer to table 2.1.

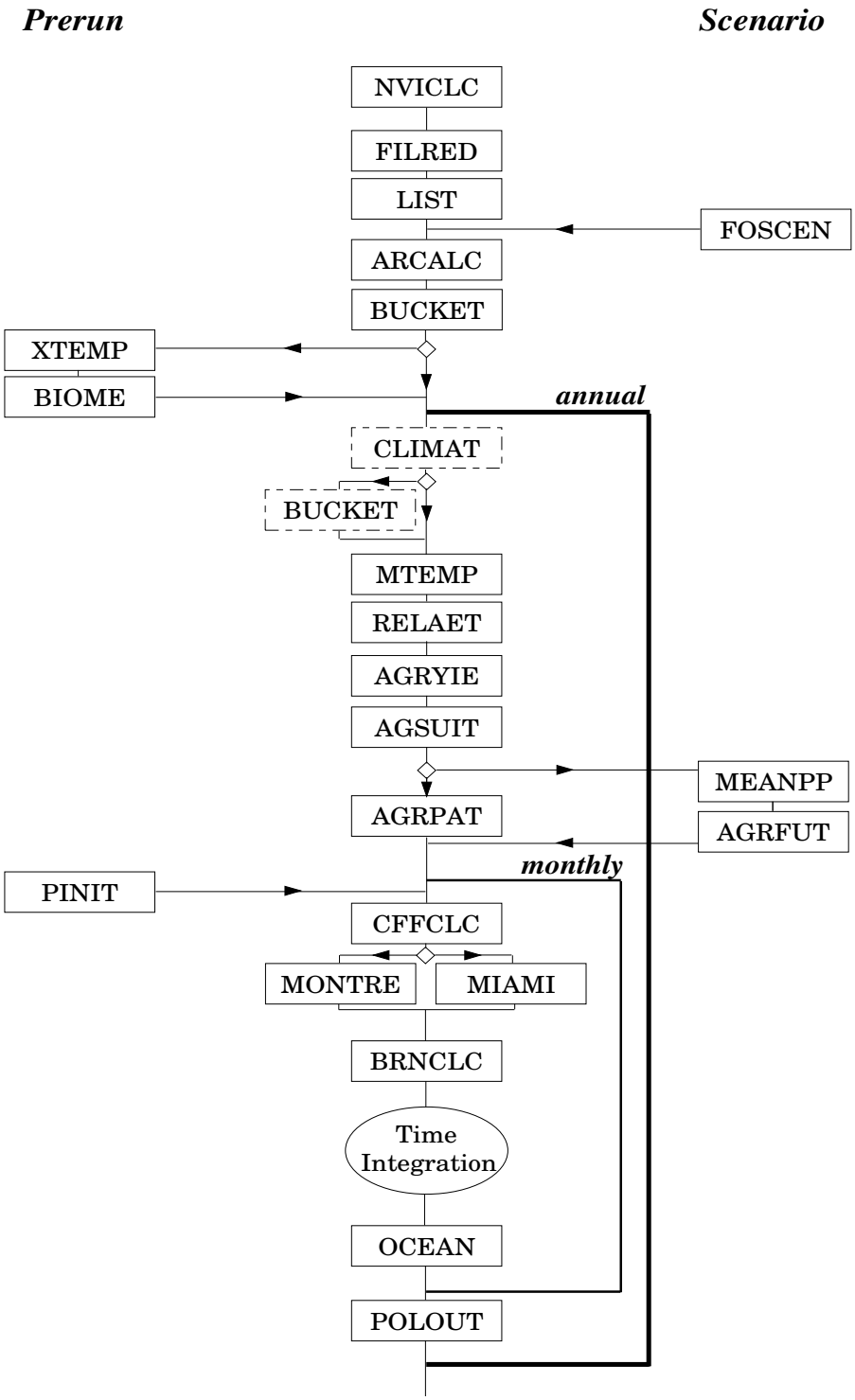


Figure 2.2: Flow chart of the subroutines and block data assignments within the HRBM.

Table 2.2: List of input and output files.

filename	**# of records**	**unit name**	**variables**	**source of data**
input files				
coord.05	62483[a]	ucoord	*lat, lon*	UNI Gießen
tempiiasa.05	62483[a]	utemp	*it, itann*	IIASA
precipiiasa.05	62483[a]	uprecip	*ipp, ippann*	IIASA
soilfactors.05	62483[a]	ufsoil	*fsoil*	UNI Gießen/FAO–Unesco
fyield8090.country	149	urap	*rap80, rap90*	UNI Gießen/FAO
olson.agri.05	62483[a]	uusestd	*usestd*	Olson *et al.* 1983
korrmatrix	894[a]	ukorri	*korri*	Richards *et al.* 1983
fossil.year	135	ufossil	*fossc*	Carbon Information Center
cloudiiasa.05	62483[a]	ucloud	*icloud*	IIASA
popparam	149	uapop	*apop*	Bulato *et al.* 1990
fymult.2050	149	ufymult	*fymult*	UNI Gießen
nvi.05	6×62483[a]	unvi	*gleich, amp, ph*[b]	NOAA
prerun output files				
f34	62483	upreo1	*biomsh, biomsw, littrh, littrw, soiloc*	HRBM, prerun
f36	62483	upreo2	*lfall, ifall, mtwam, aetmdc*	HRBM, prerun
input files from previous prerun output				
f33	62483	uprei1	*biomsh, biomsw, littrh, littrw, soiloc*	HRBM, prerun output
f35	62483	uprei2	*lfall, ifall, mtwam, aetmdc*	HRBM, prerun output
f80	62483	ubiome	*ibiome*	HRBM, prerun output
various other output files				
f40		uout40		HRBM, written by POLOUT
f41 – f52		uout41		HRBM, monthly output
f61 – f72		uout61		HRBM, monthly output

[a] records belonging to different countries are separated by an additional 'header', consisting of the number of the continent, the number of the country and the amount of grid elements of the country.

[b] only used in subroutine NVICLC

2.4.2 Files and unit numbers

The actual spatial resolution of the HRBM of 0.5 ° (55 x 55 km at the equator) leads to 62,483 grid elements. Within the input files, the records containing information about these grid elements are sorted by the 149 countries. A list of files is contained in Table 2.2.

Filenames corresponding to units are stored in variables beginning with 'f' instead of 'u'; the rest of the name is the same. The filenames are set from the parameter file.

2.5 Modules (Subroutines) and Block Data

In this section, the subroutines of the HRBM are listed in alphabetical order. For each subroutine the input and output variables, common blocks and calling information are given, being followed by a short description.

AGRPAT	
input:	*iannum, ianns, area, agrprp, korri, usestd*
output:	*agrsum, useann, useyr*
common:	`agri, agri1, agri2, extent, time`
called:	at the beginning of a model run and once per year betwen 1860 and 1990 from main

Subroutine AGRPAT determines the grid elements of a country used for agricultural purposes in the current model year. AGRPAT is applied to the period 1860 to 1990. The actual pattern of agriculturally used grid elements is assigned to *useann*. This is done by the following steps:

- the total land area and the agriculturally used area in 1980 *agrare* of each country are derived
- the required annual agriculturally used area *agrann* is estimated by multiplying *agrare* with the *korr*–matrix of the current year
- the required agriculturally used area is compared with the actual agriculturally used area
- if the required agriculturally used area is larger than the actual, the grid element with the highest probability for agricultural purposes (*agrprp*) of all grid elements used in 1980 will be transformed to an agriculturally used grid element
- if the required agriculturally used area is smaller than the actual, the agriculturally used grid element with the lowest propability will be transformed to a non–agriculturally used grid element
- these steps will be repeated until the required and actual agricultural area are about the same
- the actual agriculturally used area of all countries in the current model year *agrsum* is written to channel 82

useann is used in subroutine BRNCLC, CFFCLC, MIAMI, MONTRE, MEANPP and PINIT.

AGRFUT	
input:	*iannum, area, nppyrm, apop, rapg, agrprp*
output:	*useann, useyr, agrsum*
common:	`agri, agri1, agri2, agri4, agri7, extent, popula, time`
called:	between 1991 and 2050 once per year from main

The subroutine AGRFUT determines the grid elements of a country used for agricultural purposes in the period 1991 to 2050. Based on the ratio of agicultural NPP to population of each country in 1990, it changes the matrix *useann* so that this ratio stays constant or follows a given trajectory. A grid element is transformed if the required change of the country's agricultual productivity will exceed 60% of the next grid element's productivity to be taken into or out of use. The estimation of agricultural pattern in future is done by the following steps:

- calculation of population figures of the current (*pop*) and the past year (*oldpop*)
- the net primary productivity of all agriculturally used grid elements of each country in the current model year (*nppagr*) is derived. Therefore, the long–term running mean of NPP (*nppyrm*) determined in subroutine MEANPP is used.
- the ratio *nppagr* to *oldpop* in 1990 of each country is determined and assigned to *nppdem*
- the required net primary productivity *nppreq* of each country in the current model year is calculated, taking into account the current population *pop*
- the required net primary productivity *nppreq* is compared with the net primary productivity in 1990 *nppdem*
- if the required net primary productivity is larger than the net primary productivity in 1990, the grid element with the highest propability for agricultural use (*agrprp*) will be transformed to an agriculturally used grid element
- if the required net primary productivity is smaller than the net primary productivity in 1990, the agriculturally used grid element with the lowest propability *agrprp* will be transformed to a non–agriculturally used grid element
- these steps will be repeated until the required and actual net primary productivity are about the same

useann is used in subroutine BRNCLC, CFFCLC, MEANPP, MIAMI, MONTRE and PINIT.

AGRYIE	
input:	*scfut, iannum, rap80, rap90, fymult*
output:	*rap, rapg*
common:	`agri4, agri6, popula, time`
called:	once per year from main

This subroutine provides the relative agricultural net primary productivity for each country and assignes the value (*rap*) to each grid element of the country (*rapg*). The computation of *rap* depends on the current model year (*iannum*).

- If *iannum* is equal to or lower than 1990, *rap* is set to the value of *rap80*.
- If *iannum* is greater than 1990 but equal or lower than 1990, *rap* is determined by linear interpolation between *rap80* and *rap90*.
- For further scenarios, *rap* in 2050 of each country can be modified by a special factor considering individual developments (*fymult*). Alternatively, *rap* in 2050 of all countries can be set to a fixed value (*scfut*). The value *rap* for the current year is computed by linear interpolation between *rap90* and *rap* in 2050.

AGSUIT	
input:	*usestd, useann, lat, lon, itann, ippann, fsoil, iannum*
output:	*agrprp*
common:	`agri, agri1, agri2, coords, forces, time`
called:	once per year from main

In this subroutine, the grid elements are ranked according to a "clearing probability", *agrprp*, which is defined as a product of several individual probabilities. At the present state, these individual probabilities include:

- probability from production potential: the higher the natural productivity, the higher the probability to be taken into use, the productivity is estimated by the MIAMI model (Lieth, 1975).
- probability from soil quality: the higher the soil fertility expression through the soil factor array *fsoil*, the higher the probability to be used for agriculture,
- agricultural status of surrounding grid elements.

ARCALC	
input:	*lat*
output:	*area, areamin*
common:	`coords, extent`
called:	once per model run from main

This subroutine computes the area of each grid element from the latitude of its center point and the grid width. *area* is used in subroutine AGRPAT to calculate the total area and the agriculturally used area of a country and is used in the main program to determine the global sums of pools and fluxes. ARCALC is called once at the beginning of the model run.

BIOME	
input:	*gdd0, gdd5, mtco, mtwa, mi*
output:	*ibiome*
common:	`cloud, forces, temp, veget`
called:	once per model run from main, if a prerun will be performed

Subroutine BIOME determines global vegetation by using climatic limits for different "plant functional types". It derives a biome from the variables *gdd0, gdd5, mtco, mtwa*, and *mi* calculated in subroutines XTEMP and BUCKET, respectively. 17 biomes are distinguished; the biome number of a grid element is written to *ibiome*. BIOME is called at the beginning of the model run, if a prerun will be performed. At the end of a prerun, the array *ibiome* is written to channel 80. Without a prerun, the array *ibiome* is read from channel 80.

Further explanation of the biome model may be found at PRENTICE *et al.*, (1992).

BRNCLC	
input:	*abvgrd, ageh, agew, atmblc, phha, phhb, phwa, phwb, charcl, fsoil, herb, iannum, ianns, ibiome, imonth, icloud, ipp, it, littha, litthb, littwa, littwb, soiloc, useann*
output:	*cphblh, cphblw, clblh, clblw, cphmlh, cphmlw, cphcph, cphcpw, clcph, clcpw*
common:	`agri2, cloud, fircff, forces, init, time, veget`
called:	once per month from main

The integration of vegetation fires into the HRBM required the separation of all phytomass and litter pools in above- and below ground pools due to different effects of fire on above- and below ground plant material. In addition, the formation of black carbon demands a black carbon pool.

For each grid element, a burning probability is calculated from weather data and the state of biospheric above ground pools, considering fuel moisture content. The burning probability determines the frequency of vegetation fires within one grid element. Weather data are estimated from monthly climate data, but in future will be derived from GCMs. In case of a burning event, the amount of material transfered between the various biospheric pools depends on weather data, the state of the biospheric above ground pools, and fuel moisture content.

BUCKET	
input:	*it, ipp, itann, ippann, icloud, lat, lon, ibiome*
output:	*mi, aetm*
common:	`aet, cloud, coords, forces, temp, veget`
called:	once per model run from main, if a prerun will be performed

Subroutine BUCKET provides the ratio of actual and potential evapotranspiration, *mi*, which is used in subroutine BIOME to derive *ibiome* from the climate data. The monthly actual evapotranspiration *aetm* drives the NPP–model in subroutine MIAMI.

CFFCLC	
input:	*aetdsu, aetdm useann, fsoil, soilat, herb, ageh, agew, abvgrd, it, ipp, ippann, itann, ibiome, lfall, ifall, mtco, mtwam, imonth*
output:	*clpha, clpwa, cldha, cldwa, csocph, csocpw, csocd, cdfor, clphb, clpwb, cldhb, cldwb, ifall, lfall*
common:	`aet, agri2, coeff, forces, long, temp, time, veget`
called:	once per month from main

This subroutine provides the coefficients controlling the size of fluxes concerning litter and soil organic carbon.

- *clpha* and *clpwa* are computed as a product of a function of the mean age of the herbaceous or the woody phytomass and the quotient of *aetdm* and *aetdsu*.
  In the biomes number 8, 9, 10, 13 and 15 *clpha* will be set to $(2 \cdot \ln 2)$, if the temperature of the actual month is lower than or equal to the mean temperature of the warmest month divided by 2. The mean temperature of the warmest month is determined with a 50–year running mean.
  Then, *clpha* and *clpwa* are multiplied with the herbaceous factor (respectively herbaceous factor $- 1$). *clphb* and *clpwb* are set to *clpha* and *clpwa*, respectively.

- *cldha* and *cldwa* are functions of annual temperature and precipitation. The coefficients concerning the depletion of the below ground fraction of the litter (*cldhb* and *cldwb*) are assumed to be equal to *cldha* and *cldwa*, respectively.

- *csocd* is assumed to be 1/125 of *cldh*. On Histosols (*soilat* = "O") and on gelic Gleysols (*soilat* = "GX")*csocd* is set to (*cldh* / $125 \cdot 0.2$) and (*cldh* / $125 \cdot 0.5$), respectively. *csocph* and *csocpw* correspond to the mean lignin content of the materials.

- The coefficient *cdfor* influencing the flux from the woody phytomass to litter within agriculturally used grid elements is set to 0.06.

CLIMAT	
common:	`forces, time`
called:	once per year from main, if actual climate data will be used

In this subroutine, the climate data from LEEMANS and CRAMER (1991) which are actually used to drive the model (one set of monthly temperature and precipitation data), are corrected with temperature and precipitation anomalies from interpolated station data. Therefore, actual climate data may be provided for the period 1860 upto 1990.

DGL	
input:	*pool / ptmp*
output:	*dt*
common:	`coeff, fircff, time`
called:	in the time integration routine

Subroutine DGL provides the time derivative of the pools for each grid element, based on the initial condition *pool / ptmp*. This is a direct translation of the mathematical fact that ordinary differential equations may be written as

$$\frac{d}{dt}P = f(P,t)$$

DGL simply calculates the left hand side of this equation, leaving the result in the array *dt*. In this case there is no explicit dependence on time t.

FILRED	
common:	`agri1, agri4, agri6, cloud, coords, forces, fossil, popula`
called:	once per model run from main

In this subroutine, driving forces of the model are read from files.

- The korrmatrix (*korri*) is read from channel 25.
- The land–use reduction factors *rap80* and *rap90* are read from channel 22.
- The polynomial parameters *apop* are read from channel 28.
- The multiplicators to modify *rap* in future (*fymult*) are read from channel 29.
- The coordinates of each grid element *lat* and *lon* are read from channel 18.
- Monthly temperature data *it* and annual means *itann* are read from channel 19.
- Monthly precipitation data *ipp* and annual sums *ippann* are read from channel 20.
- Soil factors *fsoil* and the soiltypes *soilat* are read from channel 21.

- Monthly "cloud freeness" values *icloud* are read from channel 27.
- The pattern of agriculturally used grid elements in 1980 (*usestd*) is read from channel 24. All grid elements with a *usestd*–value above 1 are actually not used for agriculture in the model (*usestd* = 0).
- The fossil emissions for the period 1860 to 1986 *fossc* are read from channel 26.

FOSCEN	
input:	*ews*
output:	*fossc*
common:	`fossil`
called:	once per model run form main

This subroutine determines the values of fossil emissions *fossc* in the period 1987 to 2050. The annual increase of fossil emissions relative to 1986 may be set to 1.0%, 0.5%, or 0.1% by the value of *ews* (1, 2 or 3 respectively). *ews* is one of the "high–level" control–parameters read at the beginning of the model run from channel 5.

LIST	
output:	*abvgrd, ageh, agew, herb*
common:	`forces`

In this block data assignment, the biome related arrays *herb, ageh, agew*, and *abvgrd* are defined.

MEANPP	
input:	*rapg, iannum, nppyr, useann*
output:	*nppyrm*
common:	`agri2, agri4, agri5, agri7, time`
called:	once per year from main

The subroutine MEANPP calulates for every grid element a long-term running mean of potential agricultural NPP. Therefore, to compute a 10–year running mean for example, *nppyrm* of the last year multiplied by 0.9 and *nppyr* of the current year multiplied by 0.1 are added up.

MIAMI	
input:	*aetm, useann, useyr, fsoil, rapg, herb, ageh, agew, abvgrd, it, ipp, ippann, itann, ibiome, co2, imonth*
output:	*nppha, nppwa, npphb, nppwb*
common:	`aet, agri2, agri4, coeff, forces, time, veget`
called:	once per month from main

This subroutine provides the coefficients controlling the productivities.

- The NPP is calculated by the MIAMI model (LIETH, 1975) and modified with the soil factor *fsoil*.
- The computed value is multiplied by *co2fak* which is a function of *fsoil* and the atmospheric CO_2 concentration.
- If the grid element is agriculturally used, the NPP will be modified by the factor *rapg* (relative agricultural productivity).
- This value is multiplied by the cube of actual evapotranspiration of the current month ($aetm^3$) and divided by the annual sum of $aetm^3$. Thus, the annual NPP is distributed to each month.
- The monthly NPP is split into *nppha*, *nppwa*, *nppwb*, and *npphb* by multiplying it with *herb* (or 1 – *herb*), the herbaceous factor and *abvgrd* (or 1 – *abvgrd*), the above ground factor defined for each biome.

MONTRE	
input:	*aetm, aetsum, useann, fsoil, rapg, herb, ageh, agew, abvgrd, ibiome, co2, imonth*
output:	*nppha, nppwa, npphb, nppwb*
common:	`aet, agri2, agri4, coeff, forces, time, veget`
called:	once per month from main

This subroutine provides the coefficients controlling the productivities.

- The NPP is calculated by the MONTREAL model (LIETH & ESSER, 1981) and multiplied with the soil factor *fsoil*.
- The computed value is multiplied by *co2fak*, which is a function of *fsoil* and the atmospheric CO_2 concentration.
- If the grid element is agriculturally used, the NPP will be modified by the factor *rapg* (relative agricultural productivity).
- This value is multiplied by the cube of actual evapotranspiration of the current month ($aetm^3$) and divided by the annual sum of $aetm^3$. Thus, the annual NPP is distributed to each month.
- The monthly NPP is split into *nppha*, *nppwa*, *nppwb*, and *npphb* by multiplying it with *herb* (or 1 – *herb*), the herbaceous factor and *abvgrd* (or 1 – *abvgrd*), the above ground factor defined for each biome.

MTEMP	
input:	*it, iannum*
output:	*mtwam, mtwa, mtco*
common:	`forces, long, temp, time`
called:	once per year from main

The subroutine MTEMP calulates for every grid element a long-term running mean of the temperature of the warmest months. Therefore, to compute a 50–year running mean, *mtwam* of the last year multiplied by 49/50 and *mtwa* of the current year multiplied by 1/50 are added up. Besides, MTEMP returnes coldest and warmest month's temperature.

NVICLC	
input:	*mean, amp, ph,* which are read from channel 77 in this subroutine
output:	*nvisum, difsum, nvifrc, nvidif*
common:	`nvidat`
called:	once per model run from main

The parameters of the fourier analysis *mean, amp*, and *ph* are used to reconstruct the original nvi-values for the frequencies 1, 1/2, 1/3, 1/4, 1/5, and 1/6 year. There are three alternative ways of computing the nvi which can be chosen by the switch *nvisel*. The three altenative nvi-values are called *snvi, ndvi*, and *gemi*. The selected nvi-values are normalized to acquire values ranging from 0 to 1 stored in *nvifrc*. *nvisum* is the annual sum of *nvifrc*. *nvidif* is calculated as the difference between the nvi of the current month and the nvi of the last month. *difsum* is the annul sum of these differences. The variables of `nvidat` are provided to partition the anually calculated fluxes NPP and litter production according to diagnostic data.

OCEAN	
input:	*fossc, atmsm, co2, fossc*
output:	*co2, mixsm, deepsm*
common:	`time, oceres, biobil, fossil`
called:	once per month from main

This ocean/atmosphere balance subroutine consists of a simple box diffusion model containing 43 ocean layers (one mixed layer and 42 deep sea layers) and the atmospheric pool coupled to the mixed layer. OCEAN is called at the end of the monthly loop and uses a forth order Runge–Kutta method for the integration of the equations. Subroutine OCEAN considers the fossil emmisions *fossc* of the current model year. The new calculated CO_2 concentration of the atmosphere is returned as output together with accumulated changes in mixed layer and deep sea, *deepsm* and *mixsm*. The ocean model is the ocean part of the box diffusion model published by OESCHGER *et al.* (1975).

PINIT	
input:	*fsoil, rapg, herb, ageh, agew, abvgrd, it, ipp, ippann, itann, useann, ibiome*
output:	*phha, phwa, littha, littwa, soiloc, phhb, phwb, litthb, littwb, charcl, atmblc*
common:	`forces, agri2, agri4, veget, init`
called:	once per model run from main, if a prerun will be performed

This routine computes the initial values for the pools *biomsh, biomsw, littrh, littrw*, and *soiloc* in the case of a prerun. Here, the variables have the same names as the coefficients of the common–block `coeff`. They are not arrays, but single variables and thus not identical with the variables of the common–block `coeff`. The coefficients are calculated in a similar way as in CFFCLC, but without seasonal qualities. At last, the pools are derived from the coefficients assuming that pool changes are zero (steady state).

POLOUT	
common:	`biobil, fluxout, init, outvar, oceres, time`
called:	once per year from main

Subroutine POLOUT provides the output of the model. The monthly values of pools and fluxes are transformed to gigatons and written to channel 40 together with the CO_2 concentration (*co2mon*). The annual values of *deepsm* and *mixsm* are also transformed to gigatons and written to standard output together with *co2mon* and *atmsm*.

RELAET	
input:	*aetm, iannum*
output:	*aetsum, aetdsu, aetdm, aetmdc*
common:	`aet, time`
called:	once per year from main

Subroutine RELAET computes the annual sum of actual evapotranspiration (aet) *aetsum* and the difference between highest and lowest aet of the current year *aetdsu*. Furthermore, if there is a decrease in aet between the last and the current month, the difference will be determined, and saved in variable *aetdm*. The actual evapotranspiration in December of the current year is given by *aetdc*.

XTEMP	
input:	*it, itann, ipp, ippann*
output:	*gdd0, gdd5, mtco, mtwa*
common:	`cloud, forces, temp, veget`
called:	once per model run from main, if a prerun will be performed

Subroutine XTEMP estimates the temperature sum (growing degree days) from monthly temperature values and returns coldest and warmest month's temperature. *gdd0, gdd5, mtco*, and *mtwa* are used in subroutine BIOME to derive *ibiome* from the climate data.

2.6 COMMON–Blocks and their variables

In this section the common blocks are listed with the variables they contain, the subroutine(s) from which they are initialized, and the subroutines which use them.

aet

var's: *aetsum, aetm, aetdsu, aetdm, aetmdc*
init by: BUCKET, RELAET
used by: CFFCLC, MIAMI, MONTRE

agri

var's: *agrprp*
init by: AGSUIT
used by: AGRFUT, AGRPAT

agri1

var's: *inumbr, korri, usestd*
init by: FILRED
used by: AGRFUT, AGRPAT

agri2

var's: *useann, useyr*
init by: AGRPAT, AGRFUT
used by: BRNCLC, CFFCLC, MEANPP, MIAMI, MONTRE, PINIT

agri4

var's: *rap, rapg*
init by: AGRYIE
used by: AGRFUT, AGRYIE, CFFCLC, FILRED, MEANPP, MIAMI, MONTRE, PINIT

agri5

var's: *nppyr*
init by: main
used by: MEANPP

agri6

var's: *rap80, rap90, land*
init by: FILRED
used by: AGRYIE

agri7

var's: *nppyrm*
init by: MEANPP
used by: AGRFUT

biobil

var's: *atmsm*
init by: main
used by: OCEAN, POLOUT

cloud

var's: *icloud*
init by: FILRED
used by: BIOME, BUCKET, BRNCLC, XTEMP

coeff

var's: *cldha, cldhb, cldwa, cldwb, clpha, clphb, clpwa, clpwb, cdfor, csocd, csocph, csocpw, nppha, npphb, nppwa, nppwb*
init by: CFFCLC, MIAMI, MONTRE
used by: DGL

coords

var's: *lat, lon*
init by: FILRED
used by: ARCALC, BUCKET

extent

var's: *area, aremin*
init by: ARCALC
used by: main, AGRPAT, AGRFUT

fircff

var's: *cphblh, cphblw, clblh, clblw, cphmlh, cphmlw, cphcph, cphcpw, clcph, clcpw*
init by: BRNCLC
used by: DGL

fluxout

var's: *npphsm, nppwsm, lphsm, lpwsm, ldhsm, ldwsm, socpsm, socdsm, rodsm, bibhsm, bibwsm, libhsm, libwsm, bmohsm, bmowsm, bichsm, bicwsm, lichsm, licwsm*
init by: main
used by: POLOUT

forces

var's: *ageh, agew, abvgrd, fsoil, soilat, herb, ipp, ippann, it, itann*
init by: FILRED, LIST
used by: AGSUIT, BIOME, BRNCLC, BUCKET, CFFCLC, MIAMI, MONTRE, PINIT, XTEMP

fossil

var's: *fossc*
init by: FILRED, FOSCEN
used by: OCEAN

init

var's: *phha, phhb, phwa, phwb, littha, litthb, littwa, littwb, charcl, atmblc, soiloc*
init by: PINIT, main
used by: BRNCLC, POLOUT

long

var's: *mtwam, lfall, ifall*
init by: MTEMP, CFFCLC or main
used by: CFFCLC

nvidat

var's: *difsum, nvidif, nvifrc, nvisum*
init by: NVICLC
used by: MIAMI, CFFCLC; (at present not used)

oceres

var's: *deepsm, mixsm*
init by: OCEAN
used by: POLOUT

outvar

var's: *phhasm, phhbsm, phwasm, phwbsm, lhasm, lhbsm, lwasm, lwbsm, socsm, charsm*
init by: main
used by: POLOUT

popula

var's: *apop, fymult*
init by: FILRED
used by: AGRFUT, AGRYIE

temp

var's: *gdd0, gdd5, mi, mtco, mtcw*
init by: BUCKET, MTEMP, XTEMP
used by: BIOME, CFFCLC

time

var's: *iannum, ianns, imonth*
init by: main
used by: AGRFUT, AGRPAT, AGRYIE, BRNCLC, CFFCLC, MEANPP, MIAMI, MONTRE, MTEMP, OCEAN, POLOUT, RELAET

veget		
	var's:	*ibiome*
	init by:	BIOME
	used by:	main, BRNCLC, BUCKET, CFFCLC, MIAMI, MONTRE, PINIT, XTEMP

2.7 Global variables

This section contains a complete list of "global" variables; global in the sense of being shared between several modules. For each global variable, its common block, type (real, integer, or character), dimension (if it is an array), and meaning are given.

variable(dim.)	common	type	meaning
abvgrd(17)	`forces`	R	above ground proportion of net primary productivity
aetdm(mgrid,12)	`aet`	R	difference of actual evapotranspiration between last and current month, if aet decreases [mm]
aetdsm(mgrid)	`aet`	R	difference between highest and lowest actual evapotranspiration of a year[mm]
aetm(mgrid,12)	`aet`	R	monthly actual evapotranspiration [mm]
aetmdc(mgrid)	`aet`	R	actual evapotranspiration in December of the last year [mm]
aetsum(mgrid)	`aet`	R	annual sum of actual evapotranspiration [mm]
ageh(17)	`forces`	R	mean age of herbaceous parts of each biome
agew(17)	`forces`	R	mean age of woody parts of each biome
agrprp(mgrid)	`agri`	R	probability of each grid element to be used for agricultural purposes
apop(mcount)	`popula`	R	parameters for polynomials to calculate the population of each country in the period 1991–2050
area(mgrid)	`extent`	R	area of each grid element [m^2]
aremin	`extent`	R	smallest area of all grid elements [m^2]
atmblc(mgrid)	`init`	R	pool atmospheric balance [g m^{-2}]
atmsm(12)	`biobil`	R	pool global sum of carbon in atmosphere of each month [g C]
bibhsm(12)	`fluxout`	R	global sum of burning emissions of aboveground herbaceous phytomass [g C $month^{-1}$]
bibwsm(12)	`fluxout`	R	global sum of burning emissions of aboveground woody phytomass [g C $month^{-1}$]
bichsm(12)	`fluxout`	R	global sum of black carbon formation of aboveground herbaceous phytomass [g C $month^{-1}$]
bicwsm(12)	`fluxout`	R	global sum of black carbon formation of aboveground woody phytomass [g C $month^{-1}$]
bmohsm(12)	`fluxout`	R	global sum of burning litter production of aboveground herbaceous phytomass [g C $month^{-1}$]
bmowsm(12)	`fluxout`	R	global sum of burning litter production of above- and belowground woody phytomass [g C $month^{-1}$]
cdfor(mgrid)	`coeff`	R	deforestation coefficient [$month^{-1}$]
charcl(mgrid)	`init`	R	pool black carbon [g m^{-2}]
charsm(12)	`outvar`	R	global sum of black carbon [g C]
clblh(mgrid)	`fircff`	R	litter burning coefficient: aboveground, herbaceous [$month^{-1}$]
clblw(mgrid)	`fircff`	R	litter burning coefficient: aboveground, woody [$month^{-1}$]

variable	common	type	meaning
clcph(mgrid)	`fircff`	`R`	litter black carbon formation coefficient: aboveground, herbaceous [month^{-1}]
clcpw(mgrid)	`fircff`	`R`	litter black carbon formation coefficient: aboveground, woody [month^{-1}]
cldha(mgrid)	`coeff`	`R`	litter depletion coefficient: aboveground, herbaceous [month^{-1}]
cldhb(mgrid)	`coeff`	`R`	litter depletion coefficient: belowground, herbaceous [month^{-1}]
cldwa(mgrid)	`coeff`	`R`	litter depletion coefficient: aboveground, woody [month^{-1}]
cldwb(mgrid)	`coeff`	`R`	litter depletion coefficient: belowground, woody [month^{-1}]
clpha(mgrid)	`coeff`	`R`	litter production coefficient: aboveground, herbaceous [month^{-1}]
clphb(mgrid)	`coeff`	`R`	litter production coefficient: belowground, herbaceous [month^{-1}]
clpwa(mgrid)	`coeff`	`R`	litter production coefficient: aboveground, woody [month^{-1}]
clpwb(mgrid)	`coeff`	`R`	litter production coefficient: belowground, woody [month^{-1}]
cphblh(mgrid)	`fircff`	`R`	phytomass burning coefficient: aboveground, herbaceous [month^{-1}]
cphblw(mgrid)	`fircff`	`R`	phytomass burning coefficient: aboveground, woody [month^{-1}]
cphcph(mgrid)	`fircff`	`R`	phytomass black carbon formation coefficient: aboveground, herbaceous [month^{-1}]
cphcpw(mgrid)	`fircff`	`R`	phytomass black carbon formation coefficient: aboveground, woody [month^{-1}]
cphmlh(mgrid)	`fircff`	`R`	phytomass mortality coefficient: aboveground, herbaceous [month^{-1}]
cphmlw(mgrid)	`fircff`	`R`	phytomass mortality coefficient: aboveground and belowground, woody [month^{-1}]
csocd(mgrid)	`coeff`	`R`	soil organic carbon depletion coefficient [month^{-1}]
csocph(mgrid)	`coeff`	`R`	soil organic carbon production coefficient: herbaceous [month^{-1}]
csocpw(mgrid)	`coeff`	`R`	soil organic carbon production coefficient: woody [month^{-1}]
deepsm	`oceres`	`R`	accumulated changes in deep sea of ocean model
difsum(mgrid)	`nvidat`	`R`	annual sum of nvidif
fossc(1860:2050)	`fossil`	`R`	fossil emissions of the years 1860 through 2050
fsoil(mgrid)	`forces`	`R`	soil fertility factor
fymult(mcount)	`popula`	`R`	multiplicator to modify rap in future
gdd0(mgrid)	`temp`	`R`	growing degree days on a zero degree basis

variable	common	type	meaning
gdd5(mgrid)	`temp`	R	growing degree days on a five degree basis
herb(17)	`forces`	R	herbaceous factor of each biome
ianns	`time`	I	year of start of model run [AD]
iannum	`time`	I	current model year [AD]
ibiome(mgrid)	`veget`	I	current biome
icloud(mgrid)	`cloud`	I	cloud freeness
ifall(mgrid)	`long`	I	number of months of litter production
imonth	`time`	I	current month: 1,..,12
inumbr(mcount)	`agri1`	I	number of grid elements of each country
ipp(mgrid,12)	`forces`	I	monthly precipitation [mm]
ippann(mgrid)	`forces`	I	annual sum of precipitation [mm]
it(mgrid,12)	`forces`	I	mean monthly temperature [Celsius]
itann(mgrid)	`forces`	I	mean anuual temperature [Celsius]
korri (mcount, 1860:1990)	`agri1`	I	correction matrix to calculate the agriculturally used area in each country for the current year of the period 1860–1990
land(mgrid)	`agri6`	I	number of the country the grid element belongs to
lat(mgrid)	`coords`	R	latitude of each grid element
ldhsm(12)	`fluxout`	R	global sum of litter depletion herbaceous [g C month^{-1}]
ldwsm(12)	`fluxout`	R	global sum of litter depletion woody [g C month^{-1}]
lfall(mgrid)	`long`	I	status of litter production
libhsm(12)	`fluxout`	R	global sum of burning emissions of above ground litter herbaceous [g C month^{-1}]
libwsm(12)	`fluxout`	R	global sum of burning emissions of above ground litter woody [g C month^{-1}]
lichsm(12)	`fluxout`	R	global sum of black carbon formation of above ground litter herbaceous [g C month^{-1}]

variable	common	type	meaning
licwsm(12)	`fluxout`	R	global sum of black carbon formation of above ground litter woody [g C month^{-1}]
lhasm(12)	`outvar`	R	pool global sum of above ground litter herbaceous of each month [g C]
lhbsm(12)	`outvar`	R	pool global sum of below ground litter herbaceous of each month [g C]
lwasm(12)	`outvar`	R	pool global sum of above ground litter woody of each month [g C]
lwbsm(12)	`outvar`	R	pool global sum of below ground litter woody of each month [g C]
littha(mgrid)	`init`	R	pool above ground litter herbaceous [g m^{-2}]
litthb(mgrid)	`init`	R	pool below ground litter herbaceous [g m^{-2}]
littwb(mgrid)	`init`	R	pool above ground litter woody [g m^{-2}]
littwb(mgrid)	`init`	R	pool below ground litter woody [g m^{-2}]
lphsm(12)	`fluxout`	R	global sum of litter production herbaceous [g C month^{-1}]
lpwsm(12)	`fluxout`	R	global sum of litter production woody [g C month^{-1}]
lon(mgrid)	`coords`	R	longitude of grid element
mi(mgrid)	`temp`	R	ratio of potential to actual evapotranspiration
mixsm	`oceres`	R	accumulated changes in mixed layer of ocean model
mtco(mgrid)	`temp`	R	mean temperature of coldest month [Celsius]
mtwa(mgrid)	`temp`	R	mean temperature of warmest month [Celsius]
mtwam(mgrid)	`long`	R	running mean of mean temperatures of warmest months [Celsius]
nppha(mgrid)	`coeff`	R	net primary production coefficient: above ground, herbaceous [g m^{-2}month^{-1}]
npphb(mgrid)	`coeff`	R	net primary production coefficient: below ground, herbaceous [g m^{-2}month^{-1}]
npphsm(12)	`fluxout`	R	global sum of herbaceous net primary production [g C month^{-1}]
nppwa(mgrid)	`coeff`	R	net primary production coefficient: above ground, woody [g m^{-2}month^{-1}]
nppwb(mgrid)	`coeff`	R	net primary production coefficient: below ground, woody [g m^{-2}month^{-1}]
nppwsm(12)	`fluxout`	R	global sum of woody net primary production [g C month^{-1}]
nppyr(mgrid)	`agri5`	R	annual sum of woody and herbaceous net primary production [g m^{-2}]
nvidif(mgrid)	`nvidat`	R	difference: vegetation index of current minus vegetation index of last month

variable	common	type	meaning
nvifrc(mgrid)	`nvidat`	`R`	current vegetation index minus minimum vegetation index divided by total range of vegetation index
nvisum(mgrid)	`nvidat`	`R`	annual sum of nvifrc
phha(mgrid)	`init`	`R`	pool above ground phytomass herbaceous [g m^{-2}]
phhasm(12)	`outvar`	`R`	pool global sum of above ground phytomass herbaceous of each month [g C]
phhb(mgrid)	`init`	`R`	pool below ground phytomass herbaceous [g m^{-2}]
phhbsm(12)	`outvar`	`R`	pool global sum of below ground phytomass herbaceous of each month [g C]
phwa(mgrid)	`init`	`R`	pool above ground phytomass woody [g m^{-2}]
phwasm(12)	`outvar`	`R`	pool global sum of above ground phytomass woody of each month [g C]
phwb(mgrid)	`init`	`R`	pool below ground phytomass woody [g m^{-2}]
phwbsm(12)	`outvar`	`R`	pool global sum of below ground phytomass woody of each month [g C]
rap80(mcount)	`agri6`	`R`	relative agricultural net primary productivity in 1980
rap90(mcount)	`agri6`	`R`	relative agricultural net primary productivity in 1990
rap(mcount)	`agri4`	`R`	relative agricultural net primary productivity
rapg(mgrid)	`agri4`	`R`	relative agricultural net primary productivity
rodsm(12)	`fluxout`	`R`	global sum of deforestation [g C $month^{-1}$]
socdsm(12)	`fluxout`	`R`	global sum of soil organic carbon depletion [g C $month^{-1}$]
soilat(mgrid)	`forces`	`C`	soiltype
socpsm(12)	`fluxout`	`R`	global sum of soil organic carbon production [g C $month^{-1}$]
socsm(12)	`outvar`	`R`	pool global sum of soil organic carbon [g C]
soiloc(mgrid)	`init`	`R`	pool soil organic carbon [g m^{-2}]
useann(mgrid)	`agri2`	`I`	agricultural pattern of the current model year
usestd(mgrid)	`agri1`	`I`	agricultural pattern in 1980
useyr(mgrid)	`agri2`	`I`	number of years of the current agricultural state

2.8 References

Publications related to the HRBM:

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