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Modeling the Influence of Vegetation Fires on the Global Carbon Cycle

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At present, annual global carbon emissions (gross fluxes) from vegetation fires and other phytomass (plant biomass) burning (e.g., fuel-wood and charcoal burning) are estimated at 4.08 Pg. This compares to global annual carbon emissions from fossil fuel burning of approximately 5 Pg (Andreae and Goldammer 1992; Andreae 1993). Thus, the contribution of vegetation fires to the total global pyrogenic carbon emissions is estimated to amount to approximately 40%. Savanna fires and the deforestation of dry, seasonal, and evergreen tropical forests contribute most to these emissions, whereas forest fires in temperate and boreal regions are of minor importance (Andreae 1993; Crutzen and Andreae 1990; Hao et al. 1990; Houghton et al. 1987; Olson et al. 1983).

While the release of carbon in various forms of radiatively active trace gases contributes to the "greenhouse effect," the formation of black carbon has a contrary effect because it constitutes a carbon sink. Black carbon (synonyms: *soot, elemental carbon*) is the chemically inert and biologically nondegradable fraction of carbon produced by fires. The magnitude of this potential carbon sink is unknown due to a lack of data dealing with the formation and the decomposition rate of black carbon. At present, Kuhlbusch and Crutzen (1995, chapter 16 this volume) assume an annual global formation of 50–270 Tg black carbon originating from vegetation fires.

With the exception of deserts and sparsely vegetated lands, fires are occurring in almost all biomes. However, reliable data on fire occurrence, (e.g., long-term statistics about average areas and phytomass burned per year and vegetation type) exist only in few places. Hence, the existing estimates of global pyrogenic emissions and of the formation of black carbon are not reliable.

In order to determine the pyrogenic carbon fluxes it is also important to know the proportions of phytomass, litter, and soil organic carbon at the total amount of biospheric carbon. How do vegetation fires influence the absolute amount of carbon and the shift of the relative proportions between the pools? In terms

of vegetation science, one of the corresponding questions would be: will tropical savannas expand at the cost of forests?

Other questions are related to climate and particularly to climate anomalies, for example, how are interannual climate anomalies like El Niño-Southern Oscillation (ENSO) event affecting the number and the extent of vegetation fires as well as short-term anomalies of the atmospheric CO₂?

Such internal feedbacks can be handled in global models. Presuming a satisfactory adaptation at present conditions, trend extrapolations and scenarios are feasible in spite of dealing with a complex system characterized by internal feedbacks.

For the successful adaptation of a global fire model to a climate-driven global biospheric carbon cycle model, the following requirements for all grid elements needed to be matched:

- allocation of a biome for each grid element by a global biome model or a global vegetation map;
- information on whether a grid element is agriculturally used, including a clearing scenario for transition stages;
- prediction of the phytomass and its separation in a herbaceous and woody fraction and an above- and belowground fraction respectively; and
- prediction of the litter and its separation in a herbaceous and woody fraction and an above- and belowground fraction respectively.

With the exception of the last item, the High Resolution Biosphere Model (HRBM) fulfills these requirements (Esser et al. 1994).

Methods

Structure of the HRBM

The HRBM has been developed by the systems ecology group of the Institute for Plant Ecology at Giesen University (Germany). It succeeds the Osnabrück Biosphere Model (OBM) developed at the University

of Osnabrück (Esser 1990; 1987; 1986). The HRBM is a model of the terrestrial biosphere calculating the distribution (pools) and the turnover (fluxes) of carbon on a monthly scale for a $0.5 \times 0.5^\circ$ grid (62 483 grid elements) of geographical latitude and longitude. It is driven by mean monthly data for precipitation, temperature, and cloud freeness, and by a soil fertility factor. The climate data are based on annual long-term means providing a constant climate situation (Leemans and Cramer 1991). In addition, a land-use scenario based on data of Richards et al. (1983) and Olson et al. (1983) is included. Grid elements are cleared or afforested following the numerical development of the population until 2050 as predicted by the Food and Agricultural Organization (FAO 1991).

The HRBM is characterized by a modular structure. The modules (or subroutines) deal with separate and different issues from other modules. All modules are adaptable to other carbon cycle models due to defined interfaces between the modules and the main program. Therefore, the HRBM was utilized for the results published in this chapter. For the first fire modeling approach by Mack (1994), the biome model of Prentice et al. (1992) was used, which is also incorporated as a subroutine in the HRBM.

The Module of Vegetation Fires in the HRBM

The fire module provides several fluxes which then can be included in a “generic” carbon cycle model. These fluxes fall into three classes, termed *burning* (*BL*, *burning loss*), *mortality* (*ML*, *mortality loss*), and *black carbon formation* (*CP*, *charcoal production*).

The burning fluxes transport carbon from the phytomass (*PH*) and litter (*L*) compartments to the atmosphere. Mortality fluxes add to the litter production from phytomass. Black carbon formation fluxes transport carbon from phytomass and litter to the black carbon pool.

All of these fluxes are assumed to be proportional to the corresponding source pool that is affected by fires. For instance, the flux “burning of aboveground herbaceous (*ha*) phytomass” is proportional to the amount of carbon in the aboveground herbaceous phytomass compartment: $PHBL_{ha} = \text{const} \times PH_{ha}$.

The calculation of the different proportionality factors is based on four coefficients, *burning probability* (*cburn*), *burning efficiency* (*cbe*), *burning mortality* (*cbmo*), and the *black carbon formation coefficient* (*cbch*).

The *burning probability* (*cburn*) in a given month determines the frequency of fires. Every month, this probability is used together with a random number

generator to decide whether the respective grid element will not be affected by fires, or will be totally burned in this month.

The *burning efficiency* (*cbe*) determines the amount of carbon emitted into the atmosphere by pyrolytic processes. The completeness of combustion is characterized by *cbe*. The *burning mortality* (*cbmo*) determines the amount of phytomass that dies during a fire without being transformed into CO_2 or black carbon. The *black carbon formation coefficient* (*cbch*) determines the amount of carbon converted to black carbon. In general, each coefficient depends on the material (i.e., it is different for herbaceous and woody material, and for phytomass and litter), and on the biome that dominates in the grid element.

Forming Groups of Biomes

Regarding the influence of the biome type on the various coefficients, it is possible to distinguish three major groups: forests (I); shrub formations (II); savannas, grasslands, and deserts (III). Forests are divided into four subgroups for the purpose of calculating mortality coefficients. Table 15.1 shows the biomes of the IIASA-biome model (Prentice et al. 1992) as they are assigned to the three groups.

Determining the Fluxes

Please note that all fluxes and coefficients are calculated for each grid element; those indices are omitted for the sake of readability. The four compartments (herbaceous/woody, above- /belowground) are denoted by the indices *ha*, *hb*, *wa*, *wb*.

All fluxes have a common structure. They contain a logarithmic factor which reflects the time-integrated interpretation of a coefficient, *coeff*, as the fraction of affected-to-total area of the respective grid element. If one takes only a single depleting flux *F* (e.g., burning loss) into account, a pool *P* loses carbon according to

$$\frac{dP}{dt} = -F = +\ln(1 - \text{coeff}) \cdot P$$

Integrated over one month, the resulting carbon amount is

$$P = P_0 \cdot (1 - \text{coeff})$$

This is the fraction that corresponds to the area not affected.

Burning (*PHBL*, *LBL*) Only aboveground pools are directly affected. There are four burning fluxes:

$$PHBL_{ha} = -\ln(1 - cbe_{PH,h}) \cdot PH_{ha}$$

$$PHBL_{wa} = -\ln(1 - cbe_{PH,w}) \cdot PH_{wa}$$

Table 15.1 IIASA-biomes grouped for burning characteristics

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

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.

$$\text{LEL}_{ha} = -\ln(1 - cbef_{L,h}) \cdot L_{ha}$$

$$\text{LEL}_{wa} = -\ln(1 - cbef_{L,w}) \cdot L_{wa}$$

Mortality (PHML) Belowground herbaceous phytomass is not affected. It is assumed that the woody parts from both above- and below-ground die together, therefore they share a common coefficient. There are three mortality fluxes:

$$\text{PHML}_{ha} = -\ln(1 - cbmo_h) \cdot PH_{ha}$$

$$\text{PHML}_{wa} = -\ln(1 - cbmo_w) \cdot PH_{wa}$$

$$\text{PHML}_{wo} = -\ln(1 - cbmo_w) \cdot PH_{wh}$$

Black Carbon Formation (PHCP, LCP) Black carbon formation occurs only above ground. The *black carbon formation coefficient* (*cbch*) is determined by Kuhnsbusch (1994) as that part of the charcoal which is produced by vegetation fires and which is biologically decomposable. *cbch* is calculated separately for herbaceous and woody material.

There are four fluxes:

$$\text{PHCP}_{ha} = -\ln(1 - cbch_{PH,h}) \cdot PH_{ha}$$

$$\text{PHCP}_{wa} = -\ln(1 - cbch_{PH,w}) \cdot PH_{wa}$$

$$\text{LCP}_{ha} = -\ln(1 - cbch_{L,h}) \cdot L_{ha}$$

$$\text{LCP}_{wa} = -\ln(1 - cbch_{L,w}) \cdot L_{wa}$$

Determining the Coefficients

The four coefficients *cburn*, *cbef*, *cbmo*, and *cbch* are calculated using several auxiliary variables, namely the

humidity index (*hi*), the diameter at breast height (*dbh*), the percentage of litter in the total above-ground herbaceous material (*cur*—the “curing factor”), and the dead fine fuel moisture content (*fmc*). The first three are straightforward, but the fuel moisture content itself depends on two other numbers, the current values for temperature (*tf*) and relative humidity (*rhf*) during fires, or a short time before fires.

In forests, burning efficiency, mortality, and black carbon formation of woody phytomass drops with increasing diameter of the trees. The “affected fraction” of the wood, $\lambda(dbh)$, is a function of *dbh* which decreases linearly with increasing diameter. λ lies in the range 0 to 1 and is assumed to be 1 if not stated otherwise.

Auxiliary Variables The humidity index (*hi*) is an applied precipitation (*P_p*) to temperature (*T*) ratio by Gaussen (cit. by Kreeb 1983). It has been widely used by Walter and Lieth (1960) in their climate diagrams to distinguish between humid and arid months.

$$hi = \frac{P_p}{2mm} - \frac{T}{1^\circ C} \quad (15.1)$$

As stated above, *cur* is the fraction of aboveground herbaceous litter in relation to the total aboveground herbaceous plant material [in %].

$$cur = \frac{L_{ha}}{L_{ha} + PH_{ha}} \cdot 100\% \quad (15.2)$$

The diameter at breast height (*dbh*) is used to determine the burning efficiency and the mortality coeffi-

cient in nontropical forests. The equation was empirically derived using the data published by Cannell (1982). dbh depends on the amount of herbaceous and woody phytomass.

$$dbh = 0.856 \cdot 10^{-4} \cdot PH^{0.857} \cdot \exp(-0.904 \cdot 10^{-5} \cdot PH) \quad (15.3)$$

The temperature during fires, t_f , is calculated from the monthly mean temperature:

$$t_f = 0.64 \cdot T + 14.7 \quad (15.4)$$

The relative humidity during fires, rh_f , is calculated from the humidity index hi , except for forest biomes, where an influence was not found. Therefore, rh_f is set to an empirically derived constant value in forests:

$$rh_f = \begin{cases} 0.5 \cdot hi + 40.5 & \text{everywhere, except} \\ 34.4 & \text{in forests} \end{cases} \quad (15.5)$$

Dead Fine Fuel Moisture Content Fine fuel moisture content (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 aboveground herbaceous litter at the total aboveground herbaceous plant material (cur). Different equations are used for different groups of biomes.

Forests (I) Fine fuel moisture content is calculated following parts of the Canadian Forest Fire Weather Index System (CCFWIS) (van Wagner 1987):

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

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 and rh_a are used to correct t_f and rh_f for the influence of radiation. Radiation is derived from the cloud freeness clf , ranging from 0 (complete cloud cover) to 1 (blue sky).

$$t_a = \begin{cases} t_f + 13.9 & \text{if } clf > 0.9 \\ t_f + 10.6 & \text{if } 0.9 \geq clf \geq 0.55 \\ t_f + 6.7 & \text{if } 0.55 > clf \geq 0.1 \\ t_f + 2.8 & \text{otherwise} \end{cases}$$

$$rh_a = \begin{cases} 0.75 \cdot rh_f & \text{if } clf > 0.9 \\ 0.83 \cdot rh_f & \text{if } 0.9 \geq clf \geq 0.55 \\ 0.92 \cdot rh_f & \text{if } 0.55 > clf \geq 0.1 \\ 1.00 \cdot rh_f & \text{otherwise} \end{cases}$$

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 biome *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):

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

Burning Probability Burning probability ($cburn$) is derived from the humidity index. 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 (I), Brown et al. (1991) (fynbos) for shrub formations (II), Braithwaite and Estberg (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: $it < 0^\circ\text{C}$

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) $L_{ha} + L_{wa} < 45 \text{ g} \cdot \text{m}^{-2}$
- (II) $PH_{ha} + PH_{wa} + L_{ha} + L_{wa} < 180 \text{ g} \cdot \text{m}^{-2}$
- (III) $PH_{ha} + PH_{wa} + L_{ha} + L_{wa} < 45 \text{ g} \cdot \text{m}^{-2}$

Otherwise, $cburn$ is determined according to

$$cburn = \begin{cases} 0.0058 \cdot \exp(-0.107 \cdot hi) & \text{for biome group (I)} \\ 0.00083 \cdot \exp(-0.117 \cdot hi) & \text{for biome group (II)} \\ 0.025 \cdot \exp(-0.081 \cdot hi) & \text{for biome group (III)} \end{cases} \quad (15.6)$$

Fuel comprises aboveground phytomass and aboveground 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.

$$cburn_{lw} = \min\{1, \max\{0, 0.214 \cdot \ln(0.023 \cdot L_{wa})\}\}$$

$$cburn_{hi} = \min\{1, \max\{0, 0.229 \cdot \exp(-0.049 \cdot hi)\}\}$$

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

The min/max expressions ensure that the probabilities cannot exceed the limits 0 and 1.

Burning Efficiency and Mortality Coefficient A simple, general formula is provided to calculate burning efficiency ($cbeff$) and mortality coefficient ($cbmo$) for some pools and groups of biomes.

The general burning efficiency has been empirically derived from the dead fine fuel moisture content, fmc . The drier the fuel, the higher is the burning efficiency. Note that $cbeff \geq 0.45$.

$$cbeff = 1.00 - \frac{0.55}{1 + \exp(5.24 - 0.76 \cdot fmc)} \quad (15.7)$$

The mortality coefficient ($cbmo$) is calculated separately for herbaceous and woody material. The belowground woody phytomass pool is the only belowground pool directly affected by fires. It is assumed that the belowground parts die together with the aboveground parts. Therefore, similar values of $cbmo$ for either

proportion of PH are assumed. In contrast, belowground herbaceous phytomass is *not* affected by vegetation fires.

The general mortality coefficient is based on the assumption that *all* carbon reached by fires (the fraction is given by λ) takes one of the three routes: into the air ($cbeff$), into black carbon ($cbch$), and into litter ($cbmo$). Therefore,

$$cbeff + cbch + cbmo = \lambda \quad \text{or} \quad cbmo = \lambda - cbeff - cbch \quad (15.8)$$

Table 15.2 shows the cases to which this general formula and exceptions are applied.

Boreal and Cool Temperate Zones Dominated by Conifers (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 aboveground woody phytomass is burned: $cbeff_{const} = 0.33$.

The equations are based on investigations in *Pseudotsuga menziesii* and *Pinus banksiana* stands (Bergeron and Brisson 1990; Peterson and Arbaugh 1986, 1989). The affected fraction of the wood is given by

$$\lambda(dbh) = \min\{1, \max\{0, -2.68 \cdot dbh + 1.11\}\} \quad (15.9)$$

The burning efficiency decreases from the maximum value (at $dbh < 0.042$) to zero (at $dbh > 0.413$):

$$cbeff_{PH,w} = \lambda \cdot cbeff_{const} \quad (15.10)$$

One third of the affected phytomass is consumed by fire, and another (small) fraction is used to form black carbon. The rest of the affected phytomass dies according to equation (15.8).

Cold Deciduous Forest The equations are based on investigations in *Populus tremuloides* and *Populus tremuloides*/mixed hardwood stands (Alexander and Sando 1989; Quintillo et al. 1989). The affected fraction of the wood is given by

$$\lambda(dbh) = \min\{1, \max\{0, -4.79 \cdot dbh + 0.98\}\} \quad (15.11)$$

leading again to a burning efficiency of

$$cbeff_{PH,w} = \lambda \cdot cbeff_{const} \quad (15.12)$$

which reaches zero at $dbh = 0.204$. The mortality coefficient is determined according to the general rule, equation (15.8).

Burning Efficiency in All Other Forest Biomes The burning material consists mainly of herbaceous and litter material, since ground fires are prevailing (Albini

Table 15.2 Calculation of the coefficients related to burning, depending on biome groups (*gen.* means *general formulas*)

	Biome group I	Biome group II	Biome group III
$cbe_{PH,h}$	depends on dbh^a	1.0 ^b	<i>gen.</i>
$cbe_{PH,w}$	see text	<i>gen.</i>	$\begin{cases} 0.02^c & \text{Tropical dry forest/savanna} \\ \text{gen.} & \text{otherwise} \end{cases}$
$cbe_{L,h}$	<i>gen.</i>	<i>gen.</i>	<i>gen.</i>
$cbe_{L,w}$	<i>gen.</i>	<i>gen.</i>	0.25 ^d
$cbmo_{ha}$	same as 'wa' ^e	0 (no litter) ^f	<i>gen. (all dead)</i> ^g
$cbmo_{wa}$	see text	<i>gen.^h</i>	$\begin{cases} 0^i & \text{Tropical dry forest/savanna} \\ \text{gen.j} & \text{otherwise} \end{cases}$
$cbmo_{hb}$		0 ^k	
$cbmo_{wb}$		same as woody, above ground ^l	

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

$$cbe_{PH,h} = \max(0, -5.93 \cdot dbh + 1.0) \quad (15.17)$$

For temperate deciduous forests, $cbe_{PH,h}$ 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 and 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

$$cbmo_h = \begin{cases} 1 - (cbe_{PH,h} + cbch_{PH,h}) & \text{if } cbmo_w + cbe_{PH,h} + cbch_{PH,h} > 1 \\ cbmo_w & \text{otherwise} \end{cases} \quad (15.18)$$

f. Due to the complete combustion of herbaceous phytomass, $cbmo_h$ is set to 0.

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

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

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

j. Due to lack of data, $cbmo_w$ is assumed to be identical with $cbmo_h$ in shrub formations.

k. It is assumed that the belowground herbaceous phytomass is not affected by fires.

l. Due to lack of data, it is assumed that the belowground parts of a plant die together with the aboveground parts.

1992 for temperate deciduous forests). The amount of burned fine woody material is negligible compared to the largely unaffected stem wood of the trees. Therefore, $cbe_{PH,w}$ is set to zero.

Broad-leaved Evergreen Forest/Warm Mixed Forest (Ic) The equation is based on investigations in *Pinus spec.* stands (Storey and Merkel 1960; Lindenmuth 1960 cit. by Wright 1978).

$$cbmo_w = \begin{cases} 0 & \text{if } dbh > 0.191 \\ -2.56 \cdot dbh + 0.49 & \text{otherwise} \end{cases} \quad (15.13)$$

Tropical Rain and Tropical Seasonal Forests (Id) According to studies by Uhl and Kauffman (1990) at least 50% of the woody phytomass was transformed to litter.

$$cbmo_w = 0.5 \quad (15.14)$$

Black Carbon Formation Coefficient The general black carbon formation coefficient ($cbch$) 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 1994) and is set to 0.02. The formula is valid only for reasonably high values of efficiency.

$$cbch = chmax \cdot (1 - cbe), \quad cbe > 0.1 \quad (15.15)$$

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.

$$cbch = chmax \cdot (0.5 - |cbe - 0.5|), \quad cbe > 0.1 \quad (15.16)$$

Results and Discussion

Global Results

The HRBM enlarged by the fire submodel computes mean annual carbon emissions of $4.14 \text{ Pg} \cdot \text{yr}^{-1}$ produced by vegetation fires (figure 15.1). Andreae (1993) and Olson (1981) estimated this carbon flux at $4.08 \text{ Pg} \cdot \text{yr}^{-1}$ and $4.98 \text{ Pg} \cdot \text{yr}^{-1}$, respectively. (The use of fuel wood of $0.88 \text{ Pg} \cdot \text{yr}^{-1}$ (Andreae 1993) and the burning of agricultural waste of $0.32 \text{ Pg} \cdot \text{yr}^{-1}$ (Andreae 1991) and $1.30 \text{ Pg} \cdot \text{yr}^{-1}$ (Olson 1981) were included in both cases.) The fact that grazing has not been included in the model may explain the high values of the model.

According to the model, $3.13 \text{ Pg} \cdot \text{yr}^{-1}$ carbon of the phytomass is globally transformed to litter, and $0.044 \text{ Pg} \cdot \text{yr}^{-1}$ black carbon is produced. Without including the burning of agricultural waste, the formation of black carbon is estimated by Kuhlbusch (1994) to range between 0.07 and $0.24 \text{ Pg} \cdot \text{yr}^{-1}$. This estimate is based on the same data the model relies on. The rather low model result derives from the model approach assuming a coefficient for the black carbon formation at the lower end of the possible range.

It is important to know whether formation and depletion of black carbon are in an equilibrium or whether natural fires alone or combined with an increasing number of human-caused fires may constitute a significant carbon sink. Houghton (1991) claims that black carbon cannot be accumulated for millions of years, but must be in a steady state. As a consequence, only disturbances of this equilibrium like the growing extent of fires may effect a net flux of black carbon.

The consideration of the impact of vegetation fires on the HRBM leads to a reduction of the total phytomass by 22.9%. At the end of 1980, the carbon content has been reduced from 583.4 Pg to 449.8 Pg . The herbaceous fraction comprises 20.1 Pg compared with 21.6 Pg omitting vegetation fires. The main reason for the difference is a dramatic reduction of the woody phytomass by 57.9% in tropical seasonal and tropical rain forests bordering tropical dry forests or savannas.

The carbon content of the litter pools dropped by 5.5%, the soil organic carbon content decreased by 16.1%. The litter pools comprise 84.4 Pg without fires and 80.1 Pg with fires, whereas the soil organic carbon content changed from 1239.2 Pg to 1039.9 Pg . Between 1860 and 1980, 5.8 Pg black carbon was produced. The total biospheric carbon content differs by 17.4%.

If burning processes are included in the model, the ratio between herbaceous and woody phytomass is affected. After four burns within 10 years, the herba-

ceous phytomass fraction of tropical seasonal forests may rise from 1.5% to 12%. This is similar to herbaceous phytomass fractions of tropical dry forests and savannas. In bush formations, the ratio may change from 8% to 27% after two burns within three years. On the other hand, the present model approach is not suitable for reflecting the decrease of woody phytomass in tropical dry forests and savannas. Annual burning increases the herbaceous phytomass fraction only from 13% to 15% regarding a grid element of the Ivory Coast. It is important to find a way to model aging and mortality of seedlings and saplings due to fire and other disturbance factors.

The present version of the biome model is not structured to react to such changes of the vegetation. Future biome models should be more dynamic. Biomes should be determined not only by climatic parameters but also by natural and anthropogenic disturbance regimes.

The atmospheric CO_2 content of the HRBM rose to 338.6 ppm in 1980 including the fire submodel and up to 342.5 ppm without fire. The consideration of burning processes forced a reduction of the phytomass in the model prerun resulting in a lower net release of carbon on cleared areas after 1860. According to the model, an increase of vegetation fires after 1860 due to climate change causes a rise of atmospheric CO_2 . This is the result of model runs based on a variable instead of a constant climate. Looking at the seasonal cycle of the carbon emissions by vegetation fires, peaks are recorded in July and August (0.43 Pg), January (0.40 Pg), and February (0.38 Pg). Highest carbon sinks are in April (0.26 Pg) and in October (0.23 Pg).

The fire submodel has not yet included agricultural waste burning, effects of grazing, browsing, and trampling, as well as prescribed burning, impacts of fire exclusion, and shifting cultivation. The use of fuel wood is partly considered. Fuel wood not collected by people is considered as fuel available for free-burning fires.

Regional Results

The fire cycles for European and North American countries computed by the fire submodel are shorter than the actually known cycles. The model results were compared with data published annually by the United Nations Economic Commission for Europe (ECE) and the Food and Agriculture Organization of the United Nations (FAO) for both continents (ECE/FAO 1992; 1982). The fire control policies in the industrialized countries as well as landscape fragmentation prevent the spread of large fires. The fire cycle of the model for Germany is 136 times

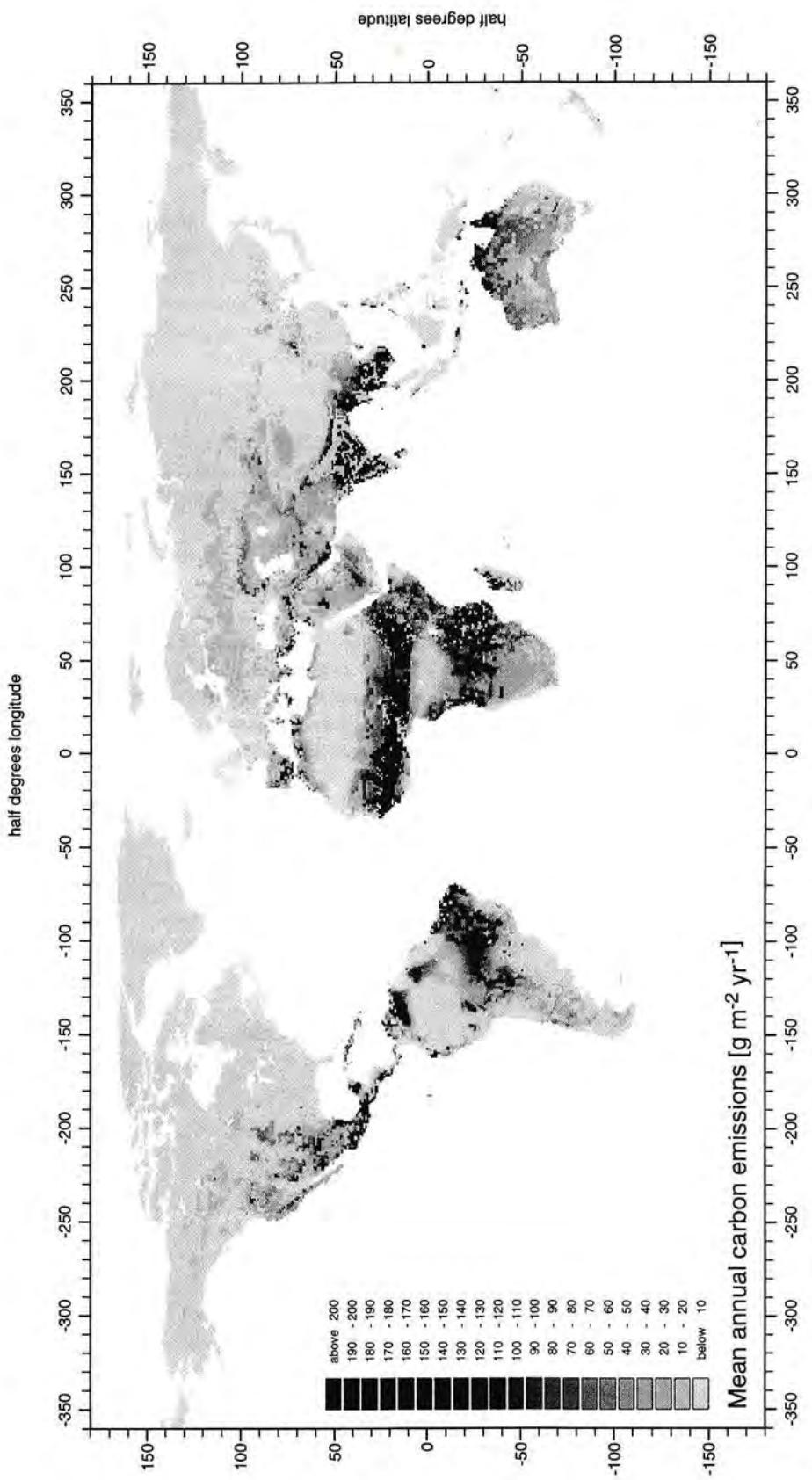


Figure 15.1 Global distribution of mean annual carbon emissions by vegetation fires in the High Resolution Biosphere Model (HRBM)
(Mack 1994)

shorter, for Sweden 63 times, and for the USA 38 times shorter as compared with statistical data from the 1980s. As a conclusion, the model provides more natural fire cycles than fire regimes of densely populated industrial countries. A comparison of known natural fire cycles and modeled fire cycles in Sweden confirms that Zackrisson (1977) determined a natural fire cycle for Sweden of 102 years and Engelmark (1984) of 110 years, respectively. The model computes a fire cycle of 190.1 years exceeding the natural cycle only by a factor of 1.8.

The fire cycles of the Mediterranean countries range from 8.4 to 60.1 years. The southernmost country (Greece) shows the shortest and the northernmost country (France) the longest cycle. These model results match the majority of the available data providing 20 to 50 years for *natural* conditions. The fire cycles calculated by the model for countries with a high proportion of grasslands and savannas are close to most of the available data and estimates ranging between 1 and 5 years (Australia: 1.9 years; Ivory Coast: 3.4 years; India: 2.2 years; Tanzania: 1.8 years; Thailand: 2.5 years).

Model Sensitivity

The coefficients determined in the differential equations of the fire module are based on limited empirical data and many estimates as well as on assumptions by the author. Hence, the coefficients are rather uncertain. Thus, the sensitivity of the model results with regard to changes of the most important coefficients had to be tested by several model runs. The range of uncertainty was estimated referring to the data used. All model runs are characterized by the modification of one coefficient, whereas the others remained unchanged compared with the standard model run.

The doubling of the burning rate caused an increase of the carbon emissions by vegetation fires by 46% to 6.04 Pg. The mortality flux rose by 40% to 4.38 Pg and the black carbon formation by 38% to 0.061 Pg. At the same time, the herbaceous phytomass pools were reduced by 4.2% and the woody phytomass pools by 12.4% to 377.54 Pg carbon. Setting the burning efficiency generally to the maximum of 1 leads to carbon emissions of 7.70 Pg. This amount is 86% higher than the emissions of the standard model run. The herbaceous phytomass grew by 0.3% and the woody phytomass decreased by 5.1%. Another model run implying a general mortality rate of 1 showed an increase of the mortality flux by 116% to 6.78 Pg. This approach additionally caused a reduction of the woody phytomass by 12.2%.

Another model run was characterized by the prevention of the black carbon formation since 1860, the start of the main model run. Compared with the standard model run, the atmospheric CO₂ content rose by 1.1 ppm to 339.7 ppm. The standard model run calculated a loss of 5.8 Pg from the carbon cycle between 1860 and 1980. The atmosphere and the ocean contribute 40% each and the biosphere 20% or 1.16 Pg in 120 years.

Conclusions

Strictly speaking, the fire model does not represent natural fires. Most input data are strongly influenced by human activities.

Savannas and tropical dry forests account for most carbon emissions originating from vegetation fires, while temperate and boreal forests are of minor importance.

The integration of vegetation fires into the HRBM causes a reduction of phytomass stored in the biosphere. This is mainly due to a dramatic decrease of carbon stored in tropical seasonal forests.

This reduction of carbon stored in the biosphere provides less carbon caused by clearing for agricultural purposes resulting in a less accelerated increase of atmospheric CO₂.

Important data are lacking in terms of monthly values concerning fire frequency, burning efficiency, and mortality rate.

Model results regarding the fraction of vegetation fires according to emissions of CO₂ are now available. Therefore, emissions of other trace gases and aerosols can be derived using emission ratios.

The role of black carbon in the global carbon cycle is still uncertain due to a lack of experimental studies.

The effects of an expected climate change and the expected population increase on the change and the shift of biomes are not investigable with static biome models. The development of dynamic biome models including burning effects as a dominant factor in many regions should be focused on. This fire submodel provides basic ideas.

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