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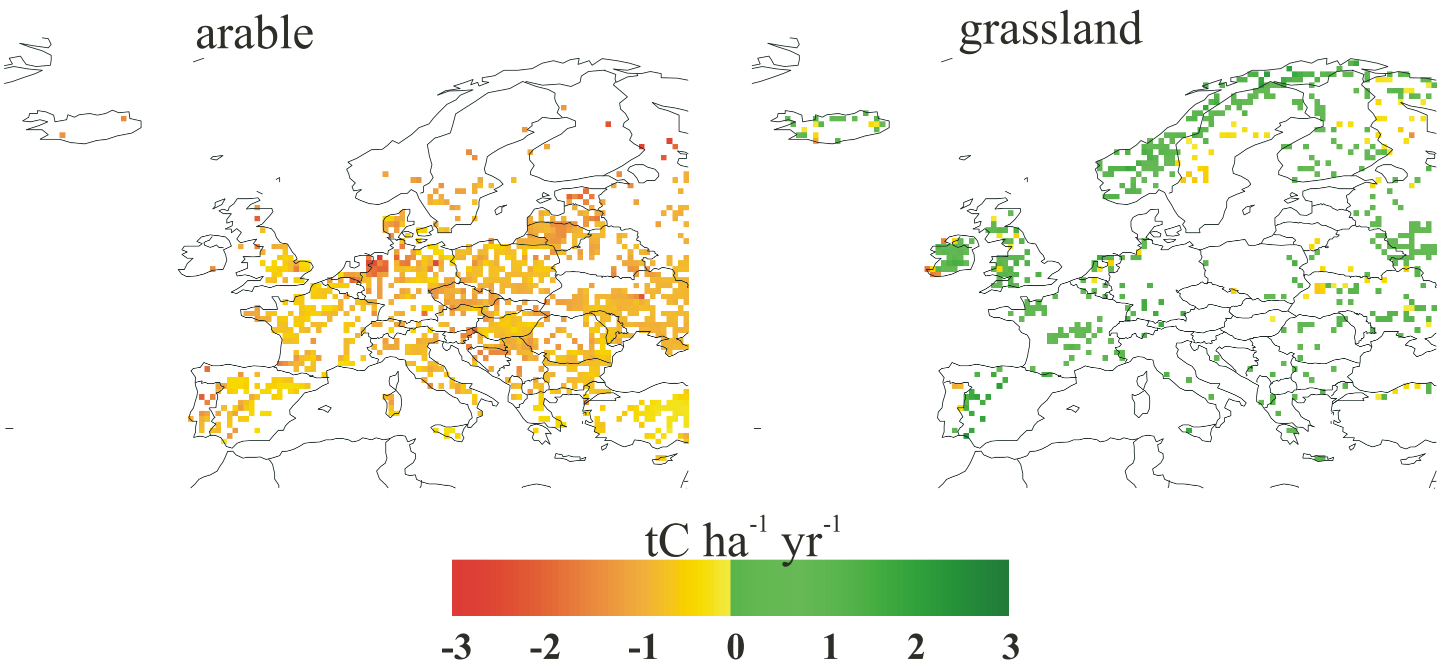

Report 36

WAGENINGEN UR

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1. Introduction

Article 3.4 of the Kyoto Protocol (UNFCCC) has generated broad interest in the possibilities of using agricultural land for carbon dioxide mitigation. Quantification of the net carbon sequestration potential by different land-use options plays an important role in the discussions on the implementation of the article. In agricultural land, the great majority of carbon is stored in the soil. Using statistical relationships between agricultural land-management practices and changes in soil organic carbon, Smith *et al.* (2000*a*) conclude that there is considerable potential for carbon dioxide mitigation by total European agriculture. A substantial spatial component in the net sequestration potential may be expected, however, because of regional differences in soil, climate, land cover, and crop yields. To support the development of climate policies, regional estimates of the carbon mitigation potential of land-management strategies may be helpful.

The CESAR model (Carbon Emission and Sequestration by AgRicultural land use) was developed to simulate changes in the carbon content of plant production systems. The model includes the effects of crop (species, yields, and rotations), climate (temperature, rainfall, and evapotranspiration) and soil (carbon content and water retention capacity) on the carbon budget of agricultural land. In this report we present regional estimates of net carbon sequestration by different land-management practices in Europe, calculated by the CESAR model linked to spatially explicit data on a 0.5 × 0.5° grid. Apart from land-management practices, we also calculated the effects of indirect human-induced developments, viz. the rising atmospheric CO_2 concentration and the rising temperature owing to climate change.

The CESAR model, as described in this report, focuses on carbon stocks and fluxes in soil organic matter. The model calculates carbon input into the soil from plant residues, and carbon output from the soil by decomposition of the accumulated organic matter in the soil. In specific situations, it may be useful to estimate carbon stocks and carbon fluxes in the more transient carbon pools in plant production systems, viz. standing biomass, crop residues with a short residence time, and harvested biomass. Equations to calculate these stocks and fluxes are given in Appendix I.

2. General description of CESAR

In the CESAR model, four carbon pools are distinguished:
- carbon in living biomass,
- carbon in harvested dry matter,
- carbon in crop residues in the soil,
- carbon in soil organic matter (humus).

The carbon pools in both crop residues and soil organic matter are supplied by remains of the crop in the field after harvest. The two pools are distinguished by their age. Materials younger than one year are called crop residues, material older than one year is called soil organic matter or humus. The distinction is rather arbitrary, but it is useful from the point of view of data availability. It has been used by many authors before (e.g. Kortleven, 1963; Kolenbrander, 1974; De Haan, 1977).

On a time scale of years, the carbon dynamics of the crop-soil system are quantitatively dominated by fluxes of carbon in the soil organic matter pool. Therefore, in this chapter, only the calculation of annual changes in soil organic carbon by CESAR will be described. A detailed description of the complete model dealing with all four classes of carbon in agricultural areas is given in Appendix I. Variables and parameters used in this chapter are summarized in Table 1.

Even though the soil organic matter pool is treated as one pool by the model, it is far from homogeneous. In sections 3.1.1 and 3.2.1, it will be explained how CESAR deals with the heterogeneity of the soil organic matter pool without distinguishing classes of soil organic matter, and the consequences of the approach will be discussed. The reason for taking a simple approach was that CESAR was developed to evaluate carbon emission and sequestration on a regional scale, where input data are limited or have to be averaged. In specific situations, e.g. in field experiments where detailed information is available on the input of organic matter to the soil, models that trace the decomposition of separate carbon pools in soil organic matter may give a more accurate description of the carbon dynamics in the soil (Jenkinson & Rayner, 1977; Janssen, 1984; Parton *et al.*, 1987; Van der Linden *et al.*, 1987; Verberne *et al.*, 1990). Most of these models, however, contain parameters that were estimated from observations.

The annual carbon flux with respect to soil organic matter, F_{Cs}, was calculated by subtracting the annual decomposition rate from the annual supply rate,

$$F_{Cs} = f_s\, h_c \left(\frac{B_{hh}}{HI} - B_{hh} \right) - r_{sa}\, C_s \tag{1}$$

for arable fields,

$$F_{Cs} = f_s\, h_c \left(\frac{B_{hhtot}}{HI} - B_{hhtot} \right) - r_{sa}\, C_s \tag{2}$$

for hay-fields, and

$$F_{Cs} = f_s \left[h_c \left(\frac{B_{hhtot}}{HI} - B_{hhtot} \right) + h_{faec}\, f_{faec}\, B_{hhtot} \right] - r_{sa}\, C_s \tag{3}$$

for meadows. In the calculation of the annual supply rate, f_s is the carbon fraction in soil organic matter, h_c is the humification coefficient of crop residues, *HI* is the harvest index related to total (above- and below-ground) dry matter, and B_{hh} and B_{hhtot} denote the harvested biomass per year. It should be noted that the definition of the harvest index used in this study differs from the most commonly used definition (see section 3.2.3). B_{hh} and B_{hhtot} are input to the model from statistical databases (e.g. FAO, Eurostat). In the model, the amounts of biomass and organic matter are expressed as dry matter. Yield data in statistical databases that relate to fresh matter are re-calculated into dry matter with help of the moisture content of the harvested biomass, m_h. In meadows there is recycling of carbon in harvested biomass via faeces, calculated with help of h_{faec}, the humification coefficient of faeces, and f_{faec}, feaces biomass as a fraction of total grazed biomass per year, B_{hhtot}. In the calculation of the annual decomposition rate, r_{sa} is the annual relative rate of decrease in soil organic matter, and C_s is the amount of carbon in soil organic matter.

Table 1. Summary of variables and parameters used in the calculation of carbon fluxes from soil organic matter in CESAR. Subscript o.m. denotes organic dry matter, subscript C denotes carbon, subscript f.m. denotes fresh matter.

Symbol	Variable or parameter	Dimension
B_{hh}	harvested biomass	$t_{o.m.}$ ha^{-1} y^{-1}
B_{hhtot}	total amount of harvested biomass during the year	$t_{o.m.}$ ha^{-1} y^{-1}
C_s	carbon in soil organic matter	t_C ha^{-1}
d	Julian day number	d
d_r	rooted depth	m
E_a	actual evapotranspiration	mm d^{-1}
e_m	soil moisture response function	dimensionless
E_p	potential evapotranspiration	mm d^{-1}
e_s	saturation water vapour pressure at Ta	kPa
e_T	soil temperature response function	dimensionless
F_{Cs}	annual flux of carbon to soil organic matter	t_C ha^{-1} y^{-1}
f_{faec}	faeces biomass as fraction the total grazed biomass per year	dimensionless
f_s	fraction carbon in soil organic matter	t_C $t_{o.m.}^{-1}$
h_c	humification coefficient of crop residues	dimensionless
h_{faec}	humification coefficient of faeces	dimensionless
HI	harvest index (related to total, above- and below-ground biomass)	dimensionless
K	global radiation	J m^{-2} d^{-1}
m_h	moisture content of harvested product	kg_{H2O} $kg^{-1}_{f.m.}$
P	precipitation	mm d^{-1}
Q_{10}	factor change in decomposition rate with a 10 °C change in temperature	dimensionless
r_s	relative rate of decrease in soil organic matter	d^{-1}
r_{sa}	annual relative rate of decrease in soil organic matter	y^{-1}
r_{sref}	reference relative rate of decrease in soil organic matter	d^{-1}
s	slope of the saturation water vapour temperature curve at T_a	kPa °C^{-1}
T_a	air temperature	°C
T_{ref}	reference temperature	°C
T_s	soil temperature	°C
γ	psychometric constant	kPa °C^{-1}
λ	latent heat of vaporization of water	J kg^{-1}
θ	soil moisture content	m^3 m^{-3}
θ_{cr}	critical soil moisture content	m^3 m^{-3}
θ_{fc}	soil moisture content at field capacity	m^3 m^{-3}
θ_{wp}	soil moisture content at wilting point	m^3 m^{-3}

In CESAR, the decomposition rate of soil organic matter is dependent on soil temperature and soil moisture content. Simulation is largely done according to Johnsson *et al.* (1987). The relative rate of decrease in soil organic matter per day, r_s, is calculated as

$$r_s = r_{sref} \cdot e_T \cdot e_m, \tag{4}$$

where r_{sref} is r_s at the reference temperature T_{ref} and optimal soil moisture content, and e_T and e_m are response functions for soil temperature T_s and soil moisture θ, respectively. Temperature response function e_T equals

$$e_T = Q_{10}^{\left(\frac{T_s - T_{ref}}{10}\right)}, \tag{5}$$

where Q_{10} is the factor change in decomposition rate with a 10 °C change in temperature. Soil moisture response function e_m equals

$$e_m = 1 \qquad \text{when } \theta > \theta_{cr} \tag{6}$$

$$e_m = \frac{\theta - \theta_{wp}}{\theta_{cr} - \theta_{wp}} \qquad \text{when } \theta_{wp} < \theta \leq \theta_{cr} \tag{7}$$

where θ_{cr} is the critical soil moisture content, above which decomposition is not hampered by moisture stress, and θ_{wp} is the soil moisture content at wilting point. Critical soil moisture content is calculated as

$$\theta_{cr} = \frac{\theta_{wp} + \theta_{fc}}{2} \tag{8}$$

where θ_{fc} is the soil moisture content at field capacity. Note that owing to the soil moisture module used in CESAR, the soil moisture content does not decrease below θ_{wp}. The soil moisture content in the rooted soil layer θ is simulated by a simple soil water balance model of the ‘tipping bucket’ type. The water balance processes are precipitation, evapotranspiration from soil surface and crop canopy, and drainage. Potential evapotranspiration, E_p, is calculated by the Makkink equation (De Bruin, 1987),

$$E_p = 0.65 \frac{s}{s + \gamma} \frac{K}{\lambda}, \tag{9}$$

where s is the slope of the saturation water vapour temperature curve at the prevailing air temperatu-reT_a, γ is the psychometric constant, K is global radiation, and λ is the latent heat of vaporization of water. Slope s is calculated as

$$s = \frac{4158.6\, e_s}{(239 + T_a)^2}\,, \tag{10}$$

where e_s, the saturation water vapour pressure at T_a, is calculated as

$$e_s = 0.611 \exp\left(\frac{17.4\, T_a}{239 + T_a}\right). \tag{11}$$

Actual evapotranspiration, E_a, is reduced in comparison with potential evapotranspiration when soil moisture content decreases, according to

$$E_a = e_m\, E_p. \tag{12}$$

Precipitation, P, is added to the actual soil water content in the rooted zone, and water loss by evapotranspiration is subtracted.

$$\theta_{d+1} = \theta_d + (0.001/d_r)\,(P - E_a), \tag{13}$$

where d_r is the rooted depth, factor 0.001 is introduced for unit conversion, and precipitation and evapotranspiration are multiplied by the time-step of 1 day used in the simulation. Water can be stored until field capacity has been reached. Any excess water over field capacity is lost by drainage.
The annual relative rate of decrease in soil organic matter, r_{sa}, is calculated as

$$r_{sa} = 1 - \prod_{d=0}^{365} (1 - r_s)\,. \tag{14}$$

3. Crop parameters

3.1 Parameter values

Values and literature references of the crop parameters used in the model are given in Table 2. Values of crop-specific model parameters are given for seven arable crops (wheat, potato, sugar beet, peas, rapeseed, flax and cabbage) and perennial rye-grass (*Lolium perenne*). Wheat parameters refer to the average between spring wheat and winter wheat. The ratio between grain yield and straw yield in wheat (Table 2) was used to estimate the amount of straw removed from the field. The fraction fibre in harvested dry matter of flax (Table 2) was used to calculate total harvested dry matter, since flax yields are rendered as fibre and tow yields in the FAO database.

Table 2. Crop parameters and physical parameters input into CESAR.

Symbol	Parameter	Value and dimension	Reference
Crop parameters input into the model			
General			
d_r	rooted depth	0.3 m	[1]
f_s	fraction carbon in soil organic matter	0.58 t_C $t_{o.m.}^{-1}$	[2]
Q_{10}	factor change in decomposition rate with a 10 °C change in temperature	2	[3]
r_{sref}	reference relative rate of decrease in soil organic matter	0.000092 d^{-1}	[4]
T_{ref}	reference temperature	10 °C	
Crop-specific			
Wheat (cereals)			
Straw harvested			
h_c	humification coefficient of crop residues	0.31	[5]
HI	harvest index (related to total, above- and below-ground biomass)	0.67	[5]
m_h	moisture content of harvested product	0.16 kg_{H2O} $kg^{-1}_{f.m.}$	[6]
	straw yield relative to grain yield	0.46	[5]
Straw not harvested			
h_c	humification coefficient of crop residues	0.31	[5]
HI	harvest index (related to total, above- and below-ground biomass)	0.46	[5]
m_h	moisture content of harvested product	0.16 kg_{H2O} $kg^{-1}_{f.m.}$	[6]
Potato (roots and tubers)			
h_c	humification coefficient of crop residues	0.22	[5]
HI	harvest index (related to total, above- and below-ground biomass)	0.69	[5]
m_h	moisture content of harvested product	0.79 kg_{H2O} $kg^{-1}_{f.m.}$	[7]
h_c	humification coefficient of crop residues	0.21	[5]
HI	harvest index (related to total, above- and below-ground biomass)	0.69	[5]

Table 2. Continued.

Symbol	Parameter	Value and dimension	Reference
Sugar beet			
h_c	humification coefficient of crop residues	0.21	[5]
HI	harvest index (related to total, above- and below-ground biomass)	0.69	[5]
m_h	moisture content of harvested product	0.76 kg_{H2O} $kg^{-1}_{f.m.}$	[8]
Peas (pulses)			
h_c	humification coefficient of crop residues	0.24	[5]
HI	harvest index (related to total, above- and below-ground biomass)	0.69	[5]
m_h	moisture content of harvested product	0.125 kg_{H2O} $kg^{-1}_{f.m.}$	[9]
Rapeseed (oilcrops)			
h_c	humification coefficient of crop residues	0.33	[5]
HI	harvest index (related to total, above- and below-ground biomass)	0.52	[5]
m_h	moisture content of harvested product	0.18 kg_{H2O} $kg^{-1}_{f.m.}$	[10]
Flax (fibre crops)			
h_c	humification coefficient of crop residues	0.33	[5]
HI	harvest index (related to total, above- and below-ground biomass)	0.92	[5]
	dry fibre yield as a fraction of harvested dry matter	0.2	[11]
Cabbage (vegetables and melons)			
h_c	humification coefficient of crop residues	0.23	[5]
HI	harvest index (related to total, above- and below-ground biomass)	0.42	[5]
m_h	moisture content of harvested product	0.9 kg_{H2O} $kg^{-1}_{f.m.}$	[12]
Perennial rye-grass (grassland)			
f_{faec}	faeces biomass as a fraction of the total grazed biomass per year	0.255	[13]
h_{faec}	humification coefficient of faeces	0.44	[14]
h_c	humification coefficient of crop residues	0.33	[5]
HI	harvest index (related to total, above- and below-ground biomass)	0.444	[13]
Physical parameters input to the model			
γ	psychometric constant	0.067 kPa °C^{-1}	
λ	latent heat of vaporization of water	2.4 10^6 J kg^{-1}	

References

[1] Estimate

[2] Wolf & Janssen (1991)

[3] Kätterer *et al.* (1998)

[4] Derived from daily weather data for Wageningen (1961-1990) with the assumption that the average annual relative rate of decrease in the Netherlands is 2.9% (see section 3.1.1)

[5] Derived from Consulentschap in Algemene Dienst voor Bodemaangelegenheden in de Landbouw (1980)

[6] Landbouw Economisch Instituut (2000)
[7] R. Postma (pers. comm.)
[8] Derived from Elliot & Weston (1993)
[9] Vogel (1996), Proefstation voor de Akker- en Weidebouw (1967)
[10] FAO (1999)
[11] Dempsey (1975)
[12] Vogel (1996)
[13] Derived from Whitehead (1986)
[14] Average for sand and clay given by De Haan (1977)

3.1.1 Decomposition rate of soil organic matter

Kortleven (1963) analyzed the results of a field experiment in which soil organic matter was measured during 22 years of fallow. Assuming a constant decomposition rate of soil organic matter during the experiment, he estimated the annual decomposition rate of soil organic matter at 0.02 y^{-1}. As a rule of thumb, the value of 0.02 y^{-1} is often used for the decomposition rate of soil organic matter in the Netherlands. Van Dijk (1982) and Janssen (1984, 1986) pointed out that Kortleven's assumption of a constant decomposition rate in time is incorrect since the decomposition rate of soil organic matter decreases as the material ages. In the case of fallow, where there is no annual supply of fresh organic matter to the soil, the average age of the soil organic matter that is present increases from year to year, and the decomposition rate decreases. This effect may be described by the equation proposed by Yang (1996),

$$Y_t = Y_0 \, e^{-R\, t^{(1-S)}} , \tag{15}$$

where Y_t and Y_0 are the amounts of organic matter at time t and time 0, respectively, R is the initial relative mineralization rate, and S is the speed of aging of organic matter. Eq. (15) was used to describe the results of three experiments in Northwest Europe in which organic matter in a fallow field was measured over time (Fig. 1) (Netherlands, Kortleven, 1963; England, Jenkinson, 1977; Denmark, Dam Kofoed, 1982). Figure 1 shows that the description given by eq. (15) is more appropriate than that based on a constant decomposition rate. The reference decomposition rate of soil organic matter in CESAR, r_{sref}, is derived from the decomposition of organic matter estimated by eq. (15) for the second year of the experiments rendered in Figure 1. In CESAR, organic material in the soil older than one year is considered soil organic matter. In the second year of the experiments, therefore, all age classes of soil organic matter are present, without the measured decomposition rate being affected by the presence of easily decomposable crop residues, which remain in the soil shorter than one year. The value in the second year was considered most apt for use of the model in non-fallow conditions, where there is an annual supply of biomass to soil organic matter, and all age classes of soil organic matter are present. The annual decomposition rates were 0.032 y^{-1} for the Netherlands, 0.030 y^{-1} for England, and 0.024 y^{-1} for Denmark. Since we lack exact weather data during the experiments we took the average value of the three experiments, 0.029 y^{-1}, and assumed it to relate to the average weather conditions in the Netherlands. Using daily weather data from the meteorological station 'Haarweg' in Wageningen, and assuming a soil with a water holding capacity of 60 mm in the rooted layer, we calculated the daily decomposition rate, r_{sref}, from the annual decomposition rate at 0.000092 d^{-1} (Table 2).

3.2 Uncertainties in parameters

3.2.1 Reference rate of decomposition of soil organic matter

The reference rate of decomposition of soil organic matter, r_{sref}, was derived from three long-term fallow experiments. The lack of weather data from these experiments led to a fairly rough estimate. Yet, the annual value compares well to a value of 0.026 y^{-1} at a reference temperature of 9 °C derived from a series of experiments analyzed by Yang (1996).

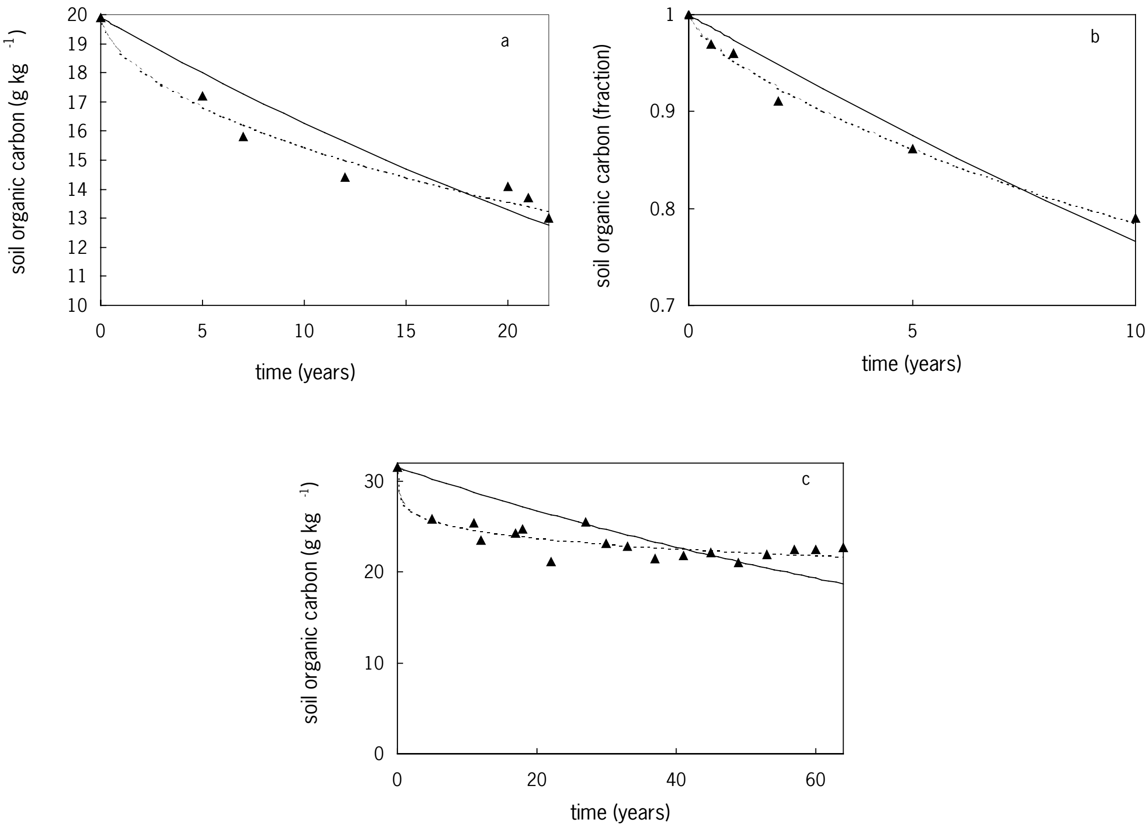

Figure 1. Decrease in the amount of soil organic matter in fallow agricultural fields (▲ measured; — fitted by eq.(9), according to Yang, 1996; ---- fitted by an exponential curve according to Kortleven, 1963). (a) Netherlands (data from Kortleven, 1963), (b) England (data from Jenkinson, 1977), (c) Denmark (data from Dam Kofoed, 1982).

During the process of plant litter decomposition, decomposition rates decrease from 0.001 d^{-1} in fresh litter to 0.00001 d^{-1} or less in more decomposed material (Berg, 1998). The decrease in decomposability is due to the fact that the easily decomposable fractions are lost first, to chemical changes in the substrate, and to the succession in micro-organisms that decompose the material. This also implies that the effect of environmental factors, e.g. nitrogen supply, changes during the decomposition process (Berg, 1998). Since no discrete stages can be distinguished during the decomposition process, a continuous range of decomposition rates can be found in the literature, mostly depending on the starting material and the time span over which measurements were made. The decomposition rate of soil organic matter used in this study compares reasonably well to estimates from studies in which a similar definition of soil organic matter was used, viz. 0.025 – 0.04 y^{-1} for grassland and arable land in a global study

(Goudriaan & Ketner, 1984), and 0.02 y^{-1} for agricultural lands and forest in the Netherlands (Wolf & Janssen, 1991). The decomposition of organic matter being dependent on its source and its age implies that it is dependent on the history of the field. The value in CESAR may be regarded as a reasonable average when the field is subjected to similar agricultural practice for a number of years, so that there is a balance between soil organic matter composition and supply of fresh material. If the present supply of organic material differs significantly from that in the past, the model tends to overestimate the resulting rate of change in soil organic matter, both in a situation where soil organic matter decreases and increases. If the supply of fresh organic material ceases or strongly declines, recently formed soil organic matter will be underrepresented in the pool of soil organic matter, and the decomposition rate of the soil organic matter pool as a whole will be overestimated by the model. If the supply of fresh organic material strongly increases, recently formed soil organic matter will be overrepresented in the soil organic matter pool, and the decomposition rate of the soil organic matter pool as a whole will be underestimated by the model.

3.2.2 Humification coefficients

Humification coefficients were adopted from Consulentschap in Algemene Dienst voor Bodemaangelegenheden in de Landbouw (1980). They were based on studies by the Institute for Soil Fertility in the Netherlands (e.g. Kolenbrander, 1974; De Haan, 1977). The values compare well to values originating from studies using ^{14}C-labelled compounds (e.g. Jenkinson, 1977; Sauerbeck & Gonzalez, 1977). When comparing humification coefficients, it is important to note that values relating to dry organic matter are lower than values relating to the amount of carbon in the organic matter (see Wolf & Janssen, 1991).

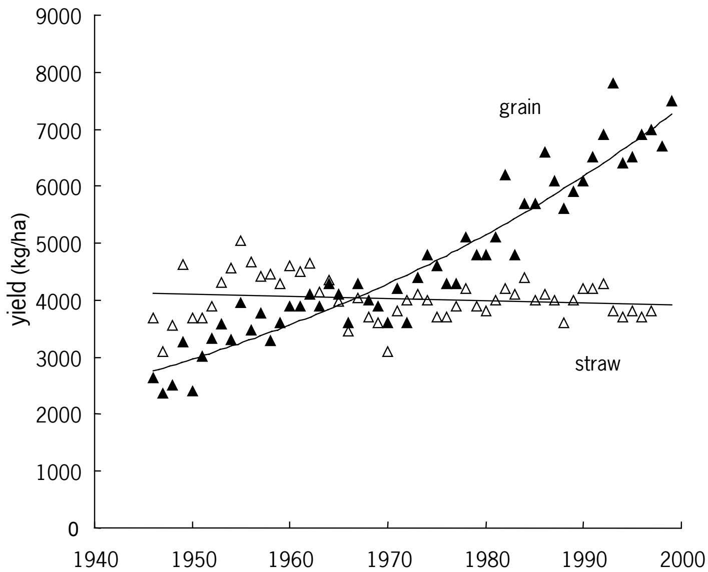

Figure. 2. Statistical trends in grain and straw yields of spring wheat in the Netherlands in the period 1946-1997. Data provided by Landbouw-Economisch Instituut.

3.2.3 Harvest indices

The harvest indices (*HI*) used in this study relate harvested product to total crop biomass production during the growing season. They are derived from data presented by Consulentschap in Algemene Dienst voor Bodemaangelegenheden in de Landbouw (1980). They should not be compared to the most commonly used values, which relate harvested product to standing biomass at the moment of harvest. In this study, the harvest index is treated as a crop constant. Probably, however, the harvest index differs both in time and in space. Analysis of grain and straw yields of cereals in the Netherlands revealed that grain yield has more than tripled since the World War II, while straw yield remained at almost the same level (Fig. 2). This implies that the harvest index has decreased in this period. One should be cautious, therefore, to derive a time trend in the amount of crop residues from a time trend in the amount of harvested product. Besides, it is not obvious whether the harvest index used in this study, which was derived from data in Dutch agriculture, is the best estimate for countries with lower crop production levels, where crop varieties with lower harvest indices may be used. Furthermore, when crop management is sub-optimal the amount of harvested product may be reduced more than the amount of non-harvested crop residues. The availability of relevant data might lead to a regional diversification of harvest indices used in CESAR.

3.2.4 Q_{10}

On the basis of a review of the literature, Kätterer *et al.* (1998) reported Q_{10} values between 1.35 and 2.88 for the effect of temperature on the decomposition of organic matter. They consider a Q_{10} of 2 adequate to describe the temperature dependence of decomposition in the range from 5 to 35 °C. This value has been used in CESAR. Johnsson *et al.* (1987) use a Q_{10} of 3. They explain the relatively high value by temperatures around 0 °C during long periods in their study. In (strong) contrast, however, a Q_{10} of 4 in the temperature range 10-20 °C can be concluded from Van der Linden *et al.* (1987).

3.2.5 Effect of soil moisture

The effect of soil moisture in CESAR is based on Johnsson *et al.* (1987). The assumptions in CESAR are that the high water content for which the soil moisture response function e_m is optimal, equals field capacity, and the low water content for which e_m is optimal, is intermediate between field capacity and wilting point. These assumptions agree well with the data provided by Johnsson *et al.* (1987). In the model by Van der Linden *et al.* (1987), the decomposition rate is reduced above pF 2.5, but decreases more slowly than in CESAR until it is zero at pF 5. In the model by Harpaz (1975), e_m is a step function that is 1 when the soil moisture content is higher than one third of its waterholding capacity, and 0 when it is lower.

4. Application of the model: carbon stocks and fluxes in European agriculture

The CESAR model was used to calculate carbon stocks and fluxes in European agricultural areas. Results were rendered on a 0.5 x 0.5 ° grid.

4.1 Site-specific parameters and input variables

4.1.1 Weather variables

Monthly average values of global radiation, precipitation and air temperature between 1961 and 1990 were provided by the Climatic Research Unit in Norwich, UK (IPCC DDC). Daily values of K and T_a calculated by linear interpolation of the monthly values that were assigned to the date half-way each month were used in the calculations. Soil temperature T_s was equalled to T_a. Daily precipitation was derived from both the average total precipitation per month and the average number of days with precipitation per month. Daily precipitation data were generated by a random generator assuming a gamma distribution of the amount of precipitation over the days with precipitation (Geng *et al.*, 1986). Parameters characterizing the gamma distribution were adopted from De Ruijter (1990). To decrease the influence of random deviations, the generation of the rainfall distribution, consecutive simulation of soil moisture and the site-specific decomposition rate of soil organic matter was repeated ten times, and the results were averaged.

4.1.2 Soil physical parameters and initial soil carbon content

Soil parameters θ_{fc} and θ_{wp}, and the initial carbon content of the soil were taken from the IGPB-DIS (Global Soil Data Task, 2000) soil data base. Critical soil moisture content θ_{cr} was calculated by eq. (34). A soil depth of 30 cm was used, since the great majority of changes in soil organic carbon will occur in the top 30 cm of the soil (Smith *et al.*, 2000*b*).

4.1.3 Crop and yield parameters

FAO provides data on the productivity and cropped areas of arable crops in Europe (FAO). The majority of arable crops are classified into eight categories: cereals, roots and tubers, pulses, treenuts, oil-crops, fibre crops, vegetables, fruit. This study covers data on six out of the eight categories, and on sugar beet, not included in any of the categories. Crop categories treenuts and fruit, which mainly consist of woody species, are not considered in this study.

The parameters for each category were derived from a major crop species within that category (Table 3). Parameters of the seven crops that represent the seven crop categories are given in Table 2. FAO data on arable crops relate to the fresh yield of the harvested product. In this study data relating to 1998 were used, the most recent available data. Country-specific grass dry matter yields were taken from experimental fields in the FAO Sub-network for Lowland Grassland in the period 1982-1986 (for a description of the background of the network see Bouman *et al.*, 1996).

Table 3. Overview of the crop categories that are included in the study, and the crops that represent the categories in the calculations.

Category	Representative crop
Cereals	spring and winter wheat
Roots and tubers	potato
Sugar beet	sugar beet
Pulses	peas
Oilcrops	rapeseed
Fibre crops	flax
Vegetables	cabbage

Grassland yields relate to fertilized, non-irrigated fields sown with either *Lolium perenne* or *Phleum pratense*. Grassland dry matter yields for Russia and Ukraine were taken from the grassland database provided by Oakridge National Laboratory (ORNL). Table 4 shows the yield data that were taken from the databases, and the derivation of yield data for countries from which no data were available. The crop parameters used for grassland were taken from *Lolium perenne*.

Table 4. Grassland production ($t_{o.m.}$ ha^{-1} y^{-1}) data used in the European study.

Country	Yield	Country	Yield approached by that in
Belgium	11.0	Albania	Yugoslavia
Finland	9.7	Austria	Switzerland
France	9.7	Belarus	Kursk, Russia
Germany	13.4	Bosnia and Herzegovina	Yugoslavia
Iceland	6.0	Bulgaria	Greece and Romania (averaged)
Ireland	11.7	Croatia	Yugoslavia
Italy	10.7	Czech Republic	Ukraine
Netherlands	12.0	Denmark	Kiel, Germany
Norway	10.9	Estonia	St Petersburg, Russia
Portugal	3.8	Greece	Portugal
Romania	9.0	Hungary	Ukraine
Russia	6.4	Latvia	St Petersburg, Russia
Spain	12.1	Lithuania	St Petersburg, Russia
Sweden	6.4	Luxemburg	Belgium
Switzerland	12.2	Macedonia	Yugoslavia
United Kingdom	11.1	Republic of Moldavia	Rumania
Ukraine	4.6	Poland	Kursk, Russia, and
Yugoslavia	7.6		Braunschweig, Germany (averaged)
		Federal Republic of Yugoslavia	Yugoslavia
		Slovakia	Ukraine
		Slovenia	Yugoslavia
		Turkey	Portugal

The calculations for Europe were made for each grid cell of 0.5 by 0.5 ° (approx. 50 by 50 km). Grid cells were classified as arable and grassland areas according to the predominant land use given by the Pan-European Land Use and Land Cover Monitoring database (PELCOM). The initial values of the soil carbon content taken from the IGPB-DIS database were assumed to relate to the year 2000. The results are presented as the annual change in soil carbon per hectare in the commitment period 2008-2012, both for arable fields and for grassland. The results for arable crops were calculated as the weighted average for the arable crop categories occurring in the grid cell. Weighting was done according to the areas cropped with the different crop categories in the grid cell. The results for grassland were calculated as the average of the values for hay-fields and meadows.

4.2 Uncertainties in input data

The effect of variation in soil carbon content on carbon fluxes to or from the soil was explored by carrying out simulations for the mean value of the carbon content reported by the IGBP-DIS database, for the mean value plus standard deviation, and for the mean value minus standard deviation. Figure 3 shows the three initial soil carbon levels for which calculations were made.

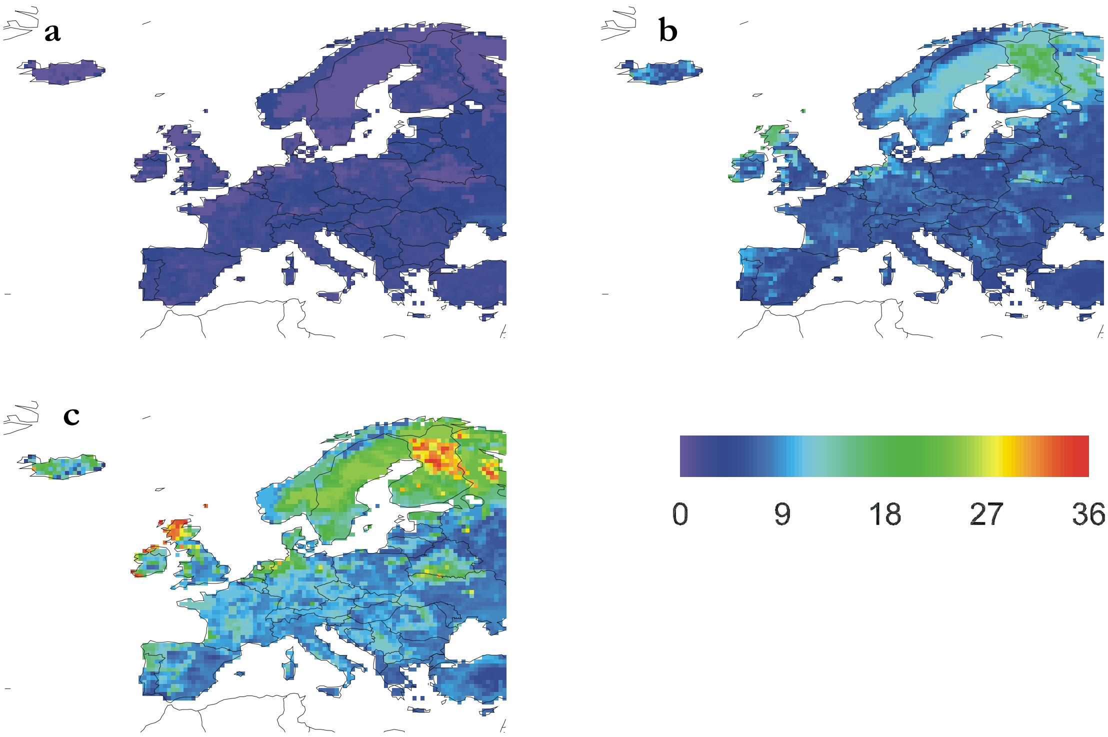

Figure. 3. *Carbon contents in soil organic matter (kg m*$^{-2}$*) reported by IGPB-DIS: (a) mean value minus standard deviation, (b) mean value, (c) mean value plus standard deviation.*

FAO arable production data contain several limitations or uncertainties. Area and production data on cereals relate to crops harvested for dry grain only. Cereal crops harvested for hay or harvested green for food, feed or silage, or used for grazing, are therefore excluded. Data on pulses show production of crops harvested for dry grain only, whether used for food or feed. Data on vegetables relate to vegetable crops grown mainly for human consumption. In general, the estimates refer to crops grown for sale, thus excluding crops cultivated in family gardens mainly for household consumption. Vegetable production from gardens not included in current statistical surveys constitutes quite an important part of the estimated total production in certain countries, for example, about 40% in Austria, France and Germany, and almost 20% in Italy.
The most recent yield data, relating to 1998, were used. This implies that in some cases the yields may be less representative, viz in those cases where a crop had an exceptionally high or low yield in 1998.

In contrast to weather and soil data, which differ from one grid cell to another, data on crop production and cropping areas are not available on the scale of one grid cell. Therefore, average data per country were used. This may in particular in large countries lead to a considerable smoothing away of regional differences between yields and relative areas of different crops.

In contrast to FAO production data on arable crops, which concern total production per country, available grassland production data are fragmentary. They are not available for all European countries, and relate to only one or a few sites per country. Besides, the production data were recorded in experimental fields, that may not always be representative for agricultural grass production areas. The data for Russia and Ukraine may partly refer to semi-natural grassland.

4.3 Results and discussion

Annual relative decomposition rates, r_{sa}, calculated by CESAR are given in Figure 4. Decomposition of soil organic matter is hampered by low temperatures (e.g. Northern Europe) or by dry summers (e.g. Spain, Turkey, and Eastern Europe). The simulated carbon fluxes in the commitment period 2008-2012 are shown in Figure 5, which show that arable fields are carbon sources, whereas the majority of grasslands are carbon sinks. Carbon fluxes from arable soils tend to be highest in the western part of the Iberian peninsula, in North-Germany and in Eastern Europe. Most areas where net losses of carbon from grassland occur are situated in North-East Europe. On a hectare basis, average carbon loss in arable fields exceeds average carbon gain in grassland. Since the areas of arable land and grassland in Europe are roughly equal, this implies that European agricultural soils as a whole are a carbon source. There are considerable differences between regions, however. Regional differences result from the interaction between crop, soil and climate. In general, low crop yields, high soil carbon contents and high soil organic matter decomposition rates enhance the loss of carbon from agricultural soils. High decomposition rates particularly occur in regions where high temperatures in summer coincide with moist conditions (Fig. 4). Soil carbon contents tend to be higher in Northern Europe (Fig. 3), and crop yields tend to be higher in Western Europe.

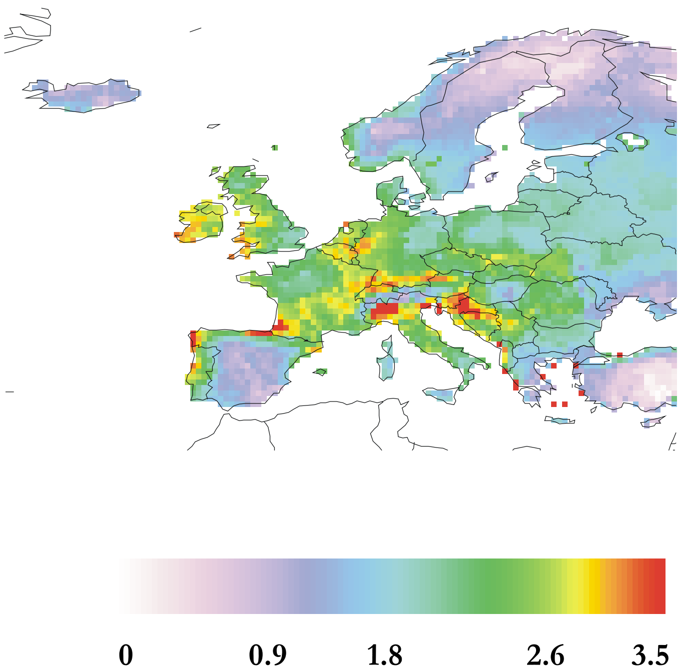

Figure 4. Annual relative decomposition rates (% y^{-1}) calculated by CESAR.

The variation in the initial soil carbon content considerably affects the carbon flux to or from agricultural soils. Using the mean value of the soil carbon content minus its standard deviation, arable soils in a large part of Western Europe are net sinks of carbon (Fig. 5a). Using the mean value of the soil carbon content plus its standard deviation, grassland soils are carbon sources in the larger part of Europe (Fig. 5f).

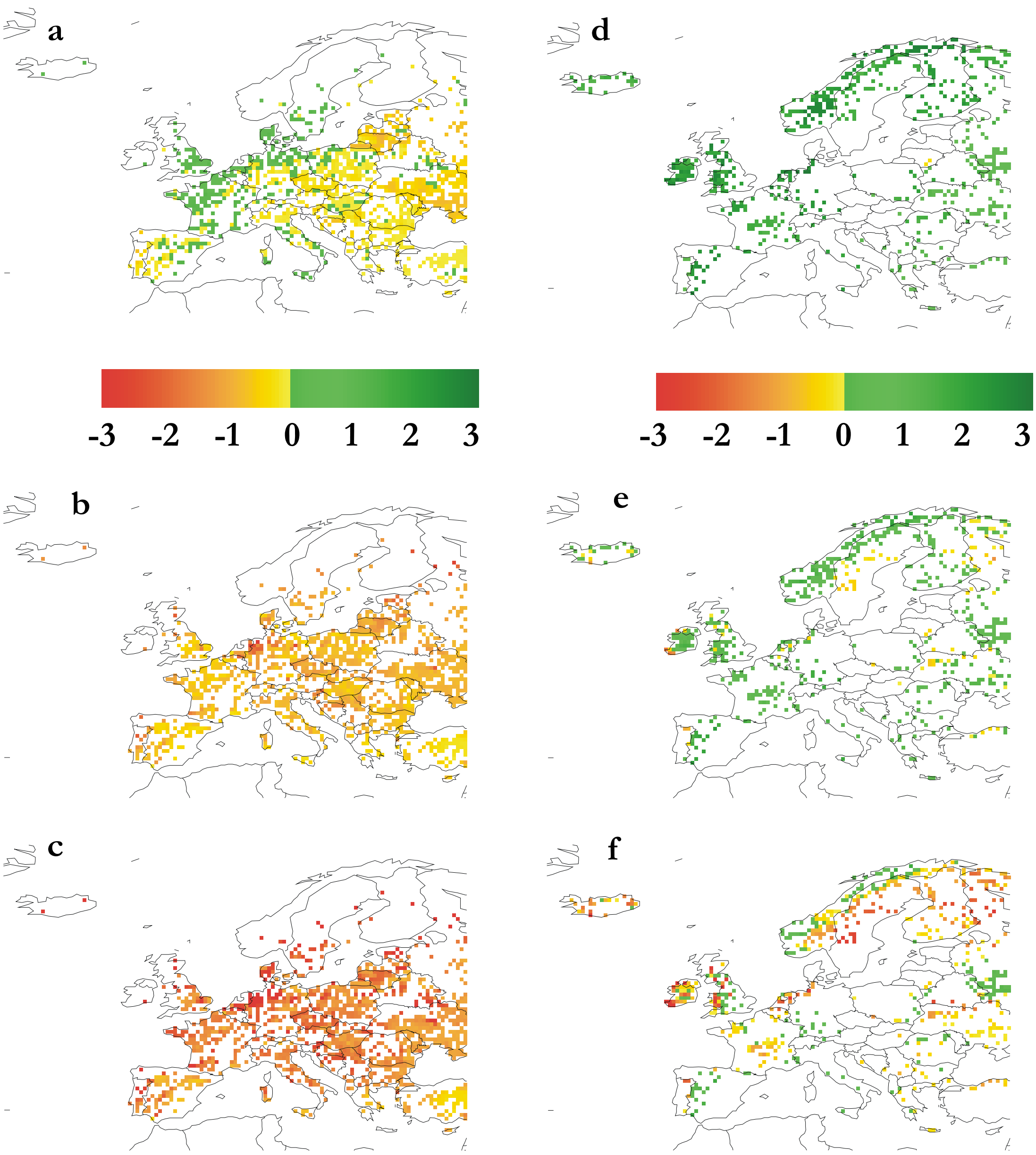

Figure 5. *Simulated carbon fluxes in soil organic matter in Europe (t_C ha^{-1} y^{-1}) in the commitment period 2008-2012 (business-as-usual scenario); (a – c) arable fields, (d – f) grassland. Simulations were made using the mean soil organic carbon content reported by IGBP-DIS as the initial situation in 2000 (b and e), mean organic carbon content minus standard deviation (a and d), and mean organic carbon content plus standard deviation (c and f).*

The data in Figure 5 represent average values for the grid cell. The values for carbon stocks and fluxes in grid cells in which arable farming is the dominant land use were calculated as the average of different crop categories, which are in turn represented by one crop. The values for carbon stocks and fluxes in grid cells in which grassland is the dominant land cover were calculated as the average of hay-fields and meadows. This implies that carbon stocks and fluxes for a specific location within a grid cell can vary in a broad range of values around the average values given in Figure 5.

5. Application of the model: natural, direct and indirect human-induced trends

Natural, direct and indirect human-induced factors may all affect the emissions and removals of greenhouse gases from terrestrial ecosystems. Distinguishing between these effects is a significant issue in the design of accounting systems. The IPCC Special Report on land use, land-use change and forestry claims that '*it may be very difficult, if not impossible, to distinguish with present scientific tools that portion of the observed stock change that is directly human-induced from that portion that is caused by indirect and natural factors*' (IPCC, 2000). For agricultural areas, however, models like CESAR may be used to tackle this problem. CESAR allows evaluation of the separate contribution of:

Direct human-induced effects, caused by e.g:
- application of farm-yard manure,
- green manuring,
- leaving behind crop residues in the field,
- reduced tillage,
- change of land cover.

Indirect human-induced effects, caused by e.g.:
- increasing agricultural production by crop breeding and improved crop management,
- rising atmospheric CO_2 concentration due to human-induced emissions,
- rising temperature owing to climate change.

Natural effects, caused by e.g.:
- interannual variation in weather conditions.

5.1 Evaluated measures and trends

In this application of CESAR, only the carbon stock in soil organic matter was considered, which is by far the most important carbon stock in agricultural areas. The input of carbon into the soil consists of crop residues (non-harvested crop biomass) and extra additions of organic matter (e.g. through farm-yard manure). The output of carbon from the soil depends on soil temperature and moisture content, and on the tillage method. The effects of the following trends or measures were evaluated for arable fields in Europe:
- *Application of farm-yard manure*. Farmyard manure was applied at an annual rate of 35 t ha^{-1}. The organic matter content of farm-yard manure was 14% (Janssen, 1992), and the humification coefficient was estimated at 0.50 (Kolenbrander, 1974).
- *Leaving behind cereal straw in the field*. In cereals, the straw that is usually harvested for several purposes may be left in the field to increase the amount of soil organic matter. The average effect on the amount of soil organic matter depends on straw yields but also on the proportion of cereals in the crop rotation.
- *Reduced tillage*. Soil tillage stimulates the decomposition of soil organic matter, mainly because of aeration of the soil. Reducing soil disturbance by shallow tillage or no tillage, therefore, decreases the decomposition rate of soil organic matter. From data presented by Smith *et al.* (2000*a*) it was assumed that reduced tillage lowers the decomposition rate of soil organic matter by 25%.
- *Change of land cover*. The conversion of arable fields to grassland was evaluated in the model simulations.
- *Rising CO_2 concentration in the atmosphere*. The amount of total crop biomass increases with increasing CO_2 concentration. The annual increase was estimated at 0.2% (Goudriaan & Unsworth, 1990).

It was assumed that the increase also applies to the amount of crop residues. It was also assumed that the decomposition of organic matter in the soil is not affected by the elevated CO_2 concentration in the atmosphere (Sadowsky & Schortemeyer, 1997; Van Ginkel *et al.*, 1997).

- *Rising temperature owing to climate change.* The effect of rising temperatures on the decomposition of soil organic matter was calculated using a climate scenario in which the temperature rises by 3 °C in the 21st century. The possible effect of temperature on other factors (e.g. yield) was not included.
- In the simulations, the measures were assumed to start in 2000. The sources of weather data, crop yield data and soil data are described in Chapter 4. The annual net effect in the commitment period 2008-2012 was calculated according to IPCC (2000) (for an example, see Fig. 6). The results of model calculations in which the above-mentioned measures and trends were evaluated for arable fields in Europe are shown in Figure 7.

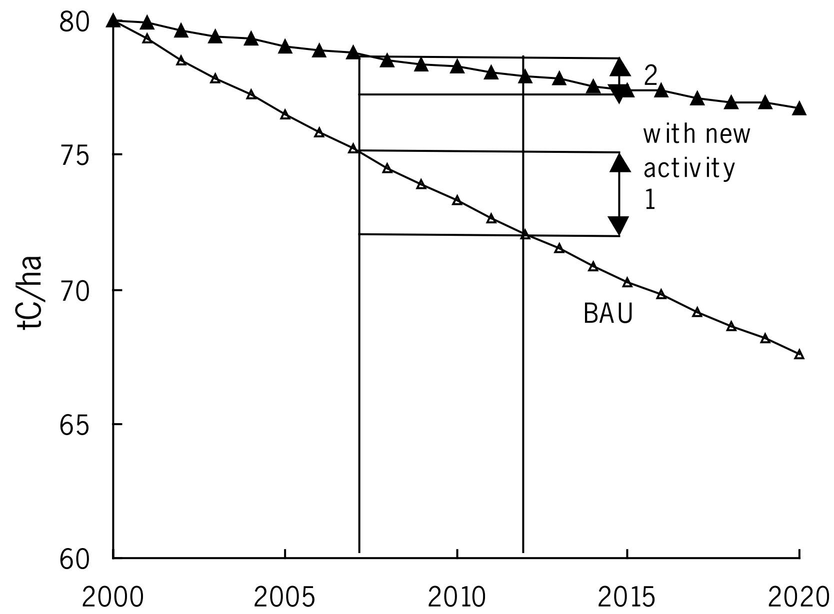

Figure 6. Calculation of net carbon sequestration by an agricultural activity starting in 2000. The calculated business-as-usual (BAU) scenario is taken as baseline (Δ—Δ). The activity results in a slower decrease of the carbon stock compared to business-as-usual (▲—▲). The net effect of the new activity is calculated as the difference between the change in carbon stock between 2008 and 2012 with the new activity (arrow 2) and the change in carbon stock between 2008 and 2012 under business-as-usual (arrow 1). Note that both changes are negative, but result in a positive, i.e. net carbon sequestering effect of the activity.

Apart from the effects of carbon dioxide abatement measures, the effect of interannual variation in weather and growth conditions on the effectiveness of measures was evaluated. In the analysis, leaving behind straw in the field was used as an example. Weather conditions affect the decomposition of soil organic matter, and growth conditions affect the amount of crop residues that are produced. Farmers have limited or no influence on the interannual variation in these factors. Nevertheless, the effectiveness of leaving behind straw in the field is dependent on weather and growth conditions. Here, it will be analyzed to what extent a 5-year duration of the commitment period stabilizes the effect of year-to-year variation in weather and growth conditions. The calculations were made for spring wheat in the Netherlands in the period 1954-1997. Calculations were based on daily weather data from the meteorological station 'Haarweg' in Wageningen, and yearly straw production data provided by Landbouw-Economisch Instituut.

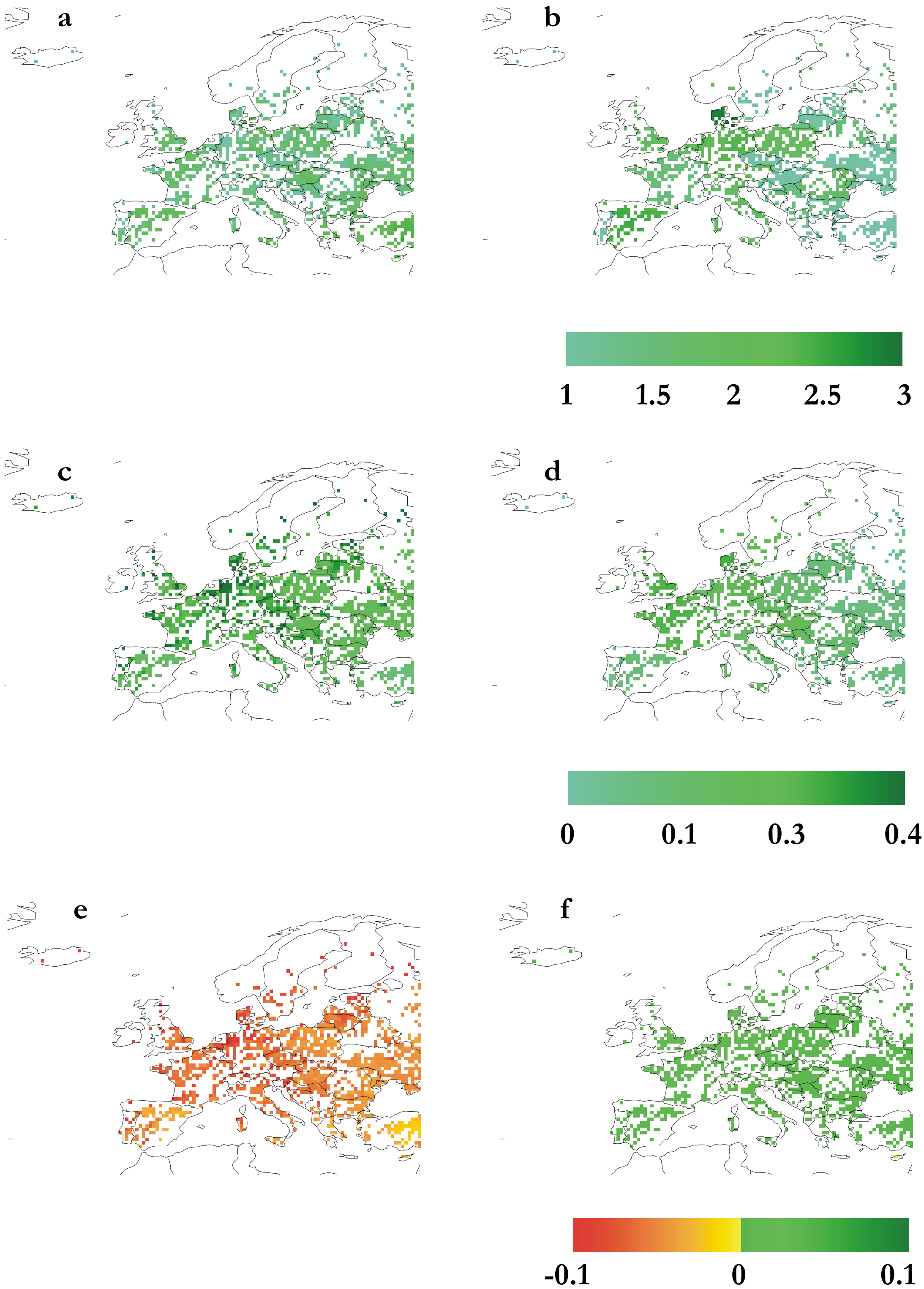

Figure 7. *Estimated average annual net effect on the carbon content of soil organic matter in arable fields in the commitment period 2008-2012 (t_C ha^{-1} y^{-1}): (a) application of farm-yard manure, (b) conversion into grassland, (c) reduced tillage, (d) leaving behind cereal straw, (e) rising temperature, (f) rising atmospheric CO_2 concentration. Note that to be able to discern spatial differences, different colour scales were used in different maps.*

5.2 Results and discussion

The question whether agricultural areas are net sinks or net sources of carbon (section 4.4) is of minor importance for the assessment of the effects of carbon dioxide mitigation options, since a measure may reach its effect by enhancement of a sink as well as by reduction of a source. All land use options for arable land evaluated in this study reduce atmospheric CO_2 concentrations compared to business as usual, but only the application of farm-yard manure and the conversion into grassland may turn arable land into net carbon sinks. The highest sequestration rates through the application of farm-yard manure were calculated for South-West and South-East Europe (e.g. Spain and Turkey), where low soil carbon contents occur together with a dry summer season, which reduces the decomposition of soil organic matter. Conversion of arable land into grassland and leaving behind cereal straw exerted the greatest effect in Western Europe, where grassland and cereal yields are highest. The effect of reduced tillage was highest where relatively high soil carbon contents occur simultaneously with relatively high decomposition rates, which occurs for example in the Netherlands and in North-Germany. The effect of a temperature increase interacts with the distribution of rainfall over the year. In countries where soil moisture allows decomposition all year long (e.g. in North-Western Europe) increased temperature has the greatest effect.

The figures rendered in the maps cannot be calculated directly into totals per region, country or for Europe as a whole. When calculating totals, the area where it is feasible to carry out a specific measure should be taken into account. For example, application of farm-yard manure is restricted by the amount of manure produced, and conversion of arable land to grassland is restricted to the area of surplus arable land. Finding these data will be an important step forward in assessing regional differentiation in the efficacy of carbon dioxide abatement options in European agriculture. European totals based on estimates of the average gain of measures and the average proportion of agricultural areas that may be subjected to the measures were calculated by Smith *et al.* (2000*a*).

The relative effects of the different measures in this study agree well with Smith *et al.* (2000*a*, *b*). Only the effects of applying farm-yard manure calculated in this study differ considerably from the effects of applying animal manure as calculated by Smith *et al.* (2000*a*, *b*). This may be caused by a difference in characteristics of the materials. Farm-yard manure, which partly consists of straw, is likely to be more resistant to decomposition than pure animal manure. In our study, conversion into grassland is the most effective carbon mitigation option, which endorses the main conclusion by Smith *et al.* (2000*a*, *b*) implying that putting surplus arable land into long-term alternative climate change abatement is the most effective land use option in agriculture.

Compared to the business-as-usual scenarios (section 4.4), the *changes* in carbon fluxes owing to the different measures or climate change effects evaluated in this study were considerably less sensitive to the initial soil carbon content. The reason for this is that they are the resultant of the difference between two carbon fluxes calculated with the same initial value of soil carbon content. This favorably affects the robustness of the estimates and the quantification of regional differences.

Figure 8 illustrates the effect of leaving behind and incorporating straw residues, presented as the annual flux of carbon to the field (t_C ha^{-1} y^{-1}). Figure 8a shows the effect of incorporating straw per se. Figure 8b shows the carbon flux from the field under business as usual, which implies the harvesting of straw. Figure 8c shows the annual net effect of ploughing-down straw, i.e. the difference between Figures 8a and 8b. Figure 8d shows the annual net effect of ploughing-down straw, averaged over 'commitment periods' of 5 years. Even when averaged over a period of 5 years, natural interannual variation in prevailing conditions and crop yields may cause substantial variation in the effect of the measure. This raises the question whether it may be more appropriate to reward an activity aimed at the increase of carbon rather than to reward its actual effect on the carbon stock in the field, since the latter may partly depend on the conditions during the commitment period that cannot be influenced by farmers.

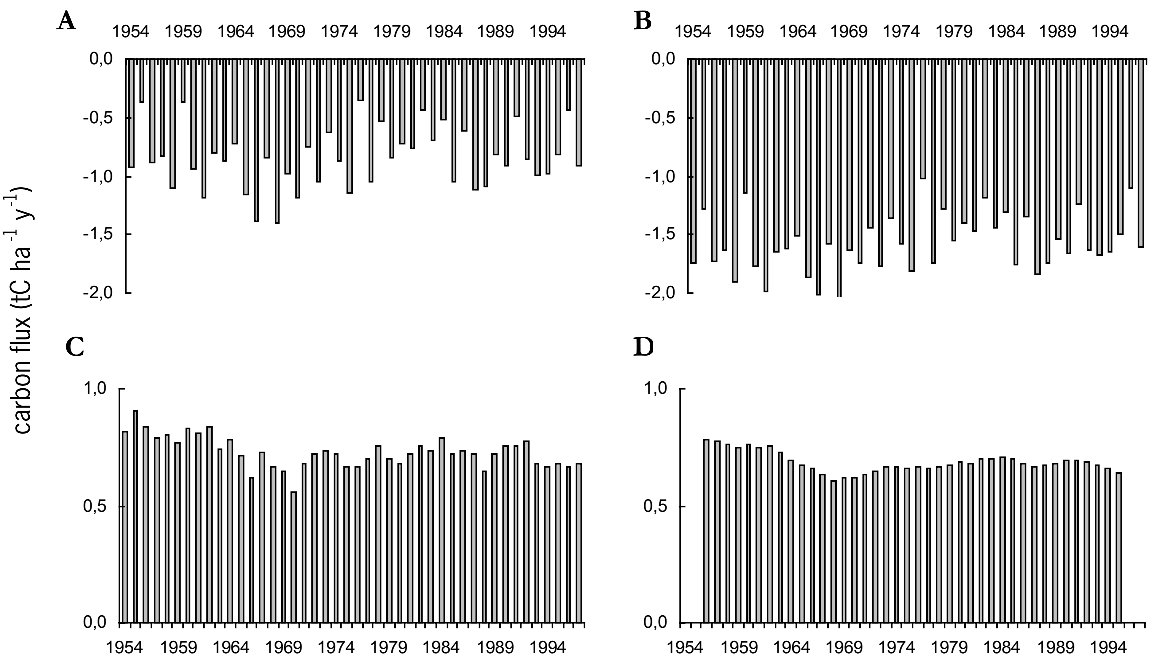

Figure 8. *Annual flux of carbon to arable fields cropped with spring wheat (t_C ha^{-1} y^{-1}), as a result of leaving behind straw residues: (a) carbon flux per se when incorporating straw, (b) carbon flux per se under business as usual, which implies the harvesting of straw, (c) annual net effect of leaving behind straw, i.e. the difference between Figs 8a and 8b, (d) annual net effect of leaving behind straw, averaged over 'commitment periods' of 5 years.*

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Appendix I. Detailed description of CESAR

Variables and parameters used in Appendix I are summarized in Table I-1. Parameter values are given in Table I-2.

I.1 Carbon dynamics

I.1.1 Arable fields

I.1.1.1 Carbon in living biomass (C_l)

The growth rate of total (i.e. above- and below-ground) crop biomass during the growing season, G, is assumed to be constant between the day of canopy closure, d_{cc}, and the day of harvest, d_h,

$$G = \frac{B_{hh} / HI}{d_h - d_{cc}}, \qquad (I.1)$$

where B_{hh} is the harvested biomass at harvest, and HI is the harvest index related to total (above- and below-ground) dry matter. It should be noted that the definition of the harvest index used in this study differs from the most commonly used definition (see section 3.2.3). B_{hh} is input to the model from statistical databases (e.g. FAO, Eurostat). In the model, the amounts of biomass and organic matter are expressed as dry matter. Since yield data in statistical databases generally relate to fresh matter, they should be re-calculated into dry matter with help of the moisture content of the harvested biomass, m_h. In arable crops, start and end of the growing season may be calculated using an algorithm developed for Europe by Daniël van Kraalingen (pers. comm.),

$$d_{cc} = 75 - 45\,(60 - L)/26, \qquad (I.2)$$

and

$$d_h = 240 - 75\,(60 - L)/26, \qquad (I.3)$$

where L is the latitude in degrees.

The carbon content of living crop biomass, C_l, is calculated by multiplying the amount of living biomass, B_l, by the fraction carbon in living dry matter, f_l,

$$C_l = f_l\, B_l. \qquad (I.4)$$

At harvest, total living crop biomass, B_{lh}, is calculated by

$$B_{lh} = \sum_{d_{cc}}^{d_h} G \, . \tag{I.5}$$

Note that B_{lh} is also equal to B_{hh}/HI. At harvest, total living crop biomass decreases to zero, and dry matter in living biomass is distributed over two carbon stocks: harvested biomass (B_{hh}) and crop residues (B_{rh}).

I.1.1.2 Carbon in harvested dry matter (C_h)

It is assumed that during its life-time, l_h, the harvested biomass B_h decreases linearly from B_{hh} at harvest to zero,

$$B_h = B_{hh} - (d - d_h)\frac{B_{hh}}{l_h} \, . \tag{I.6}$$

The carbon content of harvested biomass, C_h, is calculated as

$$C_h = f_h \, B_h, \tag{I.7}$$

where f_h is the fraction of carbon in harvested biomass.
When the life-time of the harvested product is longer than one year, the amount of harvested biomass is the sum of the amounts of biomass originating from different harvests. In that case, the carbon content of harvested biomass, C_h, is calculated as

$$C_h = f_h \, \Sigma B_h. \tag{I.8}$$

I.1.1.3 Carbon in crop residues (C_r)

The amount of crop residues at harvest, B_{rh}, equals

$$B_{rh} = B_{lh} - B_{hh}. \tag{I.9}$$

B_{rsh} is the amount of slowly decomposing crop residues at harvest, equaling

$$B_{rsh} = h_c \, B_{rh}, \tag{I.10}$$

where h_c is the humification coefficient of the crop residues. The humification coefficient indicates the fraction of crop residues whose life-time exceeds one year. Therefore, the amount of slowly decom-

posing crop residues, B_{rs}, does not decrease during the year after harvest, and equals its initial value B_{rsh}. In accordance with Kortleven (1963), it is assumed that the humification process of this pool of crop residues is completed within one year. In the model, the organic matter that undergoes humification is added to the pool of soil organic matter one year after harvest.
B_{rfh} is the amount of decomposing crop residues at harvest, amounting to

$$B_{rfh} = (1-h_c)\, B_{rh}. \tag{I.11}$$

The residence time of the fast decomposing crop residues is less than one year. The pool of fast decomposing crop residues, B_{rf}, is depleted at rate D_{rf},

$$D_{rf} = r_{rf}\, B_{rf} \tag{I.12}$$

where r_{rf} is the relative rate of decrease in fast decomposing crop residues.
The carbon content of crop residues is calculated by

$$C_r = f_s\, B_{rs} + f_{rf}\, B_{rf}, \tag{I.13}$$

where C_r is the carbon content of crop residues, f_s is the fraction of carbon in slowly decomposing crop residues, which equals that in soil organic matter, and f_{rf} is the fraction of carbon in the fast decomposing soil organic matter, equaling

$$f_{rf} = \frac{f_1 - h_c\, f_s}{1 - h_c}\,. \tag{I.14}$$

I.1.1.4 Carbon in soil organic matter (C_s)

One year after harvest, the slowly decomposing crop residues have undergone humification, and are added to soil organic matter, B_s. The pool of soil organic matter is depleted by decomposition. The rate of decrease in B_s is given by D_s,

$$D_s = r_s\, B_s \tag{I.15}$$

where r_s is the relative soil organic matter decrease rate.
The carbon content of soil organic matter, C_s, is calculated as

$$C_s = f_s\, B_s. \tag{I.16}$$

I.1.2 Grassland

I.1.2.1 Hay-fields

I.1.2.1.1 Carbon in living biomass (C_l)

The growth rate of total (i.e. above- and below-ground) crop biomass, G, is assumed to be constant during the growing season,

$$G = \frac{\left(\frac{B_{\text{hhtot}}}{HI}\right)}{d_e - d_s}, \tag{I.17}$$

where B_{hhtot} is the annual total of harvested biomass, HI is the harvest index related to total (above- and below-ground) dry matter, d_e is the last day and d_s is the first day of the growing season. B_{hhtot} is input into the model from statistical databases. According to Bouman *et al.* (1996), the growing season in grassland may be calculated as the period of the year when the 10-day average of the daily temperature exceeds 6 °C. Crop growth is partitioned between harvestable biomass (B_{ha}), stubble (B_{st}) and roots (B_{ro}). The growth rate of harvestable biomass, G_{ha}, is calculated by

$$G_{\text{ha}} = HI\ G. \tag{I.18}$$

Growth rates of stubble and roots, G_{st} and G_{ro}, are calculated as

$$G_{\text{st}} = f_{\text{st}}\ G \tag{I.19}$$
$$G_{\text{ro}} = f_{\text{ro}}\ G \tag{I.20}$$

where f_{st} and f_{ro} are the fractions growth partitioned to stubble and roots, respectively (note that HI, f_{st} and f_{ro} add up to 1). Stubble and roots have turnover rates, r_{st} and r_{ro}, and the mortality rates of stubble and roots, D_{st} and D_{ro}, amount to

$$D_{\text{st}} = r_{\text{st}}\ B_{\text{st}} \tag{I.21}$$
$$D_{\text{ro}} = r_{\text{ro}}\ B_{\text{ro}}. \tag{I.22}$$

Living crop biomass, B_l, is calculated as

$$B_l = B_{\text{ha}} + B_{\text{st}} + B_{\text{ro}}. \tag{I.23}$$

The carbon content of the living crop biomass, C_l, is calculated by eq. (I.4).

In contrast to arable crops, there usually are several harvest dates during the growing season. At the harvest dates, the present amount of B_{ha}, B_{hh}, is removed from the field. Mortality of biomass that is not harvested (stubble and roots) occurs throughout the year, whereas in annual arable crops mortality of non-harvested biomass is concentrated at the moment of crop harvest. The carbon stocks in crop residues and soil organic matter are supplied through the mortality of stubble and roots.

I.1.2.1.2 Carbon in harvested dry matter (C_h)

The amount of harvested biomass, B_h, is calculated by eq. (I.6), and the carbon content of harvested biomass, C_h, by Eq. (I.8).

I.1.2.1.3 Carbon in crop residues (C_r)

The increase rate of biomass in crop residues, I_r, amounts to

$$I_r = D_{st} + D_{ro}. \qquad \text{(I.24)}$$

The increase rate of biomass in slowly decomposing crop residues, I_{rs}, amounts to

$$I_{rs} = h_c \, I_r \qquad \text{(I.25)}$$

where h_c is the humification coefficient of dead stubble and roots. The biomass remains in this pool for one year in which it undergoes humification and after which it is added to soil organic matter. The amount of biomass does not decrease during this year.
The increase rate of fast decomposing crop residues, I_{rf}, amounts to

$$I_{rf} = (1-h_c) \, I_r \qquad \text{(I.26)}$$

I_{rf} adds to the pool of fast decomposing crop residues, B_{rf}. B_{rf} is depleted at rate D_{rf}, given by eq. (I.12). The carbon content of crop residues, C_r, is given by eqs. (I.13) and (I.14).

1.2.1.4 Carbon in soil organic matter (C_s)

The soil organic matter pool, B_s, is supplied by humification of slowly decomposable crop residues, and is depleted by decomposition. The rate of decrease in B_s is given by eq. (I.15) and the carbon content of the soil organic matter, C_s, is calculated by eq. (I.16).

I.1.2.2 Meadows

Modelling of carbon in meadows is identical to that in hay-fields, with a few exceptions. In meadows, there is a continuous harvesting of biomass by grazing livestock. In the model it is assumed that, while there is a continuous flow of carbon through harvestable and harvested biomass, the carbon stocks of harvestable and harvested biomass are negligible. Besides, there is a recycling of carbon from grazed grass through the excretion of faeces at the pasture. The excretion of faeces leads to an additional input of biomass into the pool of ‘crop residues’.

I.1.2.2.1 Carbon in living dry matter (C_l)

Living crop biomass, B_l, is calculated as

$$B_l = B_{st} + B_{ro}. \tag{I.27}$$

I.1.2.2.2 Carbon in harvested dry matter (C_h)

Carbon in harvested dry matter is approximately zero.

I.1.2.2.3 Carbon in crop residues

The increase rate of biomass in crop residues, I_r, amounts to

$$I_r = D_{st} + D_{ro} + f_{faec}\, B_{hhtot}/365 \tag{I.28}$$

where f_{faec} is the faeces biomass as a fraction of total grazed biomass per year, B_{hhtot}. For practical reasons, faeces are considered as crop residues.
The increase rate of biomass in slowly decomposing crop residues, I_{rs}, amounts to

$$I_{rs} = h_c\,(D_{st} + D_{ro}) + h_{faec}\, f_{faec}\, B_{hhtot}/365 \tag{I.29}$$

where h_{faec} is the humification coefficient of faeces.
The increase rate of fast decomposing crop residues, I_{rf}, amounts to

$$I_{rf} = (1-h_c)\,(D_{st} + D_{ro}) + (1-h_{faec})\, f_{faec}\, B_{hhtot}/365. \tag{I.30}$$

I.1.2.2.4 Carbon in soil organic matter

Calculation of carbon in soil organic matter in meadows is identical to that in hay-fields.

I.2 Effects of environmental factors

I.2.1 Carbon in living biomass

The effects of environmental conditions are implicitly incorporated in B_{hh} or B_{hhtot}, which are taken from statistical databases and are subject to differences between years and locations. As yet, the turnover rates of grassland stubble and roots are taken constant.

I.2.2 Carbon in harvested dry matter

The consumption of harvested biomass is assumed to be independent of environmental factors.

I.2.3 Carbon in crop residues and in soil organic matter

In CESAR, the decomposition rates of soil organic matter and fast decomposing crop residues are dependent on soil temperature and soil moisture content. Simulation is largely done according to Johnsson *et al.* (1987). The relative rates of decrease in soil organic matter and fast decomposing organic matter are calculated as

$$r_{\mathrm{rf}} = r_{\mathrm{rfref}} \cdot \mathrm{e}_T \cdot \mathrm{e}_{\mathrm{m}}, \tag{I.31}$$

and

$$r_{\mathrm{s}} = r_{\mathrm{sref}} \cdot \mathrm{e}_T \cdot \mathrm{e}_{\mathrm{m}}, \tag{I.32}$$

where r_{rfref} and r_{sref} are r_{rf} and r_{s}, respectively, at the reference temperature T_{ref} and optimal soil moisture content, and e_T and e_{m} are response functions for soil temperature T_{s} and soil moisture θ, respectively. The temperature response function e_T equals

$$\mathrm{e}_T = Q_{10}^{\left(\frac{T_{\mathrm{s}}-T_{\mathrm{ref}}}{10}\right)}, \tag{I.33}$$

where Q_{10} is the factor change in decomposition rate with a 10 °C change in temperature. The soil moisture response function e_{m} equals

$$\mathrm{e}_{\mathrm{m}} = 1 \qquad \text{when } \theta > \theta_{\mathrm{cr}} \tag{I.34}$$

$$\mathrm{e}_{\mathrm{m}} = \frac{\theta - \theta_{\mathrm{wp}}}{\theta_{\mathrm{cr}} - \theta_{\mathrm{wp}}} \qquad \text{when } \theta_{\mathrm{wp}} < \theta < \theta_{\mathrm{cr}} \tag{I.35}$$

where θ_{cr} is the critical soil moisture content, above which decomposition is not hampered by moisture stress, and θ_{wp} is the soil moisture content at wilting point. The critical soil moisture content is calculated as

$$\theta_{\mathrm{cr}} = \frac{\theta_{\mathrm{wp}} + \theta_{\mathrm{fc}}}{2} \tag{I.36}$$

where θ_{fc} is the soil moisture content at field capacity.

I.3 Annual average carbon stocks

CESAR is a dynamic simulation model, which calculates stocks and fluxes with a time step of one day. For some applications of the model annual average carbon stocks may be desired. Therefore, analytical expressions were derived to calculate annual averages of carbon stocks. In those cases where the carbon pool remains present from one year to another (soil organic carbon, and possibly carbon in the harvested product), the expressions were derived for the situation in which the net fluxes of carbon from year to year are zero, i.e. for steady-state conditions.

I.3.1 Arable fields

I.3.1.1 Carbon in living biomass (C_{la})

The average carbon pool in living biomass, C_{la}, is calculated by averaging carbon present in living biomass during the growing season over the whole year,

$$C_{la} = \frac{f_l \; 0.5\,(d_h - d_{cc})(B_{hh}\,/\,HI)}{365}\,. \tag{I.37}$$

I.3.1.2 Carbon in harvested dry matter (C_{ha})

The average carbon pool in harvested biomass, C_{ha}, is calculated by averaging carbon present in the harvested product (which may originate from several growing seasons when its life-time is longer than one year) over the whole year,

$$C_{ha} = f_h \frac{0.5\, l_h \; B_{hh}}{365}\,. \tag{I.38}$$

If l_h is greater than one year, the average value of B_{hh} over years should be used.

I.3.1.3 Carbon in crop residues (C_{ra})

The average carbon pool in slowly decomposing crop residues is equal to

$$C_{rsa} = f_s \; b_c \; (\frac{B_{hh}}{HI} - B_{hh})\,. \tag{I.39}$$

The average carbon pool in fast decomposing crop residues, C_{rfa}, can only be calculated numerically, since the decomposition varies from day to day with the temperature and moisture conditions. The total amount of carbon in crop residues, C_{ra}, equals

$$C_{ra} = C_{rsa} + C_{rfa}. \tag{I.40}$$

I.3.1.4 Carbon in soil organic matter (C_{sa})

The steady-state expression for the carbon pool in soil organic matter is

$$C_{sa} = \frac{f_s\, h_c \left(\dfrac{B_{hh}}{HI} - B_{hh}\right)}{r_{sa}}, \tag{I.41}$$

where r_{sa} is the annual relative soil organic matter decrease rate, calculated as

$$r_{sa} = 1 - \prod_{d=0}^{365} (1 - r_s)\,. \tag{I.42}$$

In the calculation, the average value of B_{hh} over years should be used, and B_{hh} should implicitly be divided by a time step of 1 year. The daily values of r_s should be based on long-term average weather conditions.

I.3.2 Grassland

I.3.2.1 Hayfields

I.3.2.1.1 Carbon in living biomass (C_{la})

The average carbon pool in living harvestable biomass, C_{haa}, is calculated by averaging the carbon present in living biomass during the growing season over the whole year,

$$C_{haa} = \frac{f_l\, 0.5\,(d_e - d_s)(B_{hhtot} / HI)}{365\, n}, \tag{I.43}$$

where n is the number of harvests per year.
The average carbon pools in stubble, C_{sta}, and roots, C_{roa}, are approximated by

$$C_{sta} = \frac{f_l\; f_{st}\; (B_{hhtot} / HI)}{365\, r_{st}} \tag{I.44}$$

and

$$C_{roa} = \frac{f_l\; f_{ro}\; (B_{hhtot} / HI)}{365\, r_{ro}}\,. \tag{I.45}$$

The average amount of total living biomass, C_{la}, amounts to

$$C_{la} = C_{haa} + C_{sta} + C_{roa}. \quad \text{(I.46)}$$

I.3.2.1.2 Carbon in harvested dry matter (C_{ha})

The average carbon pool in harvested biomass, C_{ha}, is calculated by eq. (I.38), where B_{hhtot} should be used instead of B_{hh}.

I.3.2.1.3 Carbon in crop residues (C_{ra})

The average carbon pool in crop residues is approximated by eqs. (I.39) and (I.40), where B_{hhtot} should be used instead of B_{hh}.

I.3.2.1.4 Carbon in soil organic matter (C_{sa})

The steady-state amount of carbon in soil organic matter is calculated by eqs. (I.41) and (I.42), where B_{hhtot} should be used instead of B_{hh}.

I.3.2.2 Meadows

I.3.2.2.1 Carbon in living biomass (C_{la})

The carbon pool in living harvestable biomass, C_{haa}, is approximately zero, so that the average amount of total living biomass, C_{la}, amounts to

$$C_{la} = C_{sta} + C_{roa}. \quad \text{(I.47)}$$

I.3.2.2.2 Carbon in harvested dry matter (C_{ha})

The average carbon pool in harvested biomass, C_{ha}, is approximately zero.

I.3.2.2.3 Carbon in crop residues (C_{ra})

The average carbon pool in crop residues is calculated by eq. (I.40). In the numerical calculation of C_{rfa}, the extra addition of fast decomposing organic material amounting to $(1-h_{faec})\, f_{faec}\, B_{hhtot}$ should be taken into account.

I.3.2.2.4 Carbon in soil organic matter (C_{sa})

The steady-state amount of carbon in soil organic matter is calculated as

$$C_{sa} = \frac{f_s \, h_c \left(\dfrac{B_{hhtot}}{HI} - B_{hhtot} \right) + h_{faec} \, f_{faec} \, B_{hhtot}}{r_{sa}}, \tag{I.48}$$

where r_{sa} is calculated by eq. (I.42).

Table I-1. Summary of variables and parameters in CESAR. Variables may vary between days, parameters are constant for one location in one year, but may vary between years and locations. Subcript o.m. denotes organic dry matter, subscript C denotes carbon, subscript f.m. denotes fresh matter.

Symbol	Variable	Dimension	Arable crops	Grassland	Environment
Variables calculated by the model					
B_h	amount of harvested biomass	$t_{o.m.}$ ha^{-1}	x	x	-
B_{ha}	amount of harvestable biomass	$t_{o.m.}$ ha^{-1}	-	x	-
B_l	amount of living biomass	$t_{o.m.}$ ha^{-1}	x	x	-
B_{lh}	amount of living biomass at harvest	$t_{o.m.}$ ha^{-1}	x	-	-
B_r	amount of crop residues	$t_{o.m.}$ ha^{-1}	x	x	-
B_{rf}	amount of fast decomposing crop residues	$t_{o.m.}$ ha^{-1}	x	x	-
B_{rfh}	amount of fast decomposing crop residues at harvest	$t_{o.m.}$ ha^{-1}	x	-	-
B_{rh}	amount of crop residues at harvest	$t_{o.m.}$ ha^{-1}	x	-	-
B_{ro}	amount of biomass in roots	$t_{o.m.}$ ha^{-1}	-	x	-
B_{rs}	amount of slowly decomposing crop residues	$t_{o.m.}$ ha^{-1}	x	x	-
B_{rsh}	amount of slowly decomposing crop residues at harvest	$t_{o.m.}$ ha^{-1}	x	-	-
B_s	amount of soil organic matter	$t_{o.m.}$ ha^{-1}	x	x	-
B_{st}	amount of biomass in stubble	$t_{o.m.}$ ha^{-1}	-	x	-
C_f	carbon in fast decomposing crop residues	t_C ha^{-1}	x	x	-
C_{fa}	annual average amount of carbon in fast decomposing crop residues	t_C ha^{-1}	x	x	-
C_h	carbon in harvested dry matter	t_C ha^{-1}	x	x	-
C_{ha}	annual average amount of carbon in harvested dry matter	t_C ha^{-1}	x	x	-
C_{haa}	annual average amount of carbon in harvestable biomass	t_C ha^{-1}	-	x	-
C_l	carbon in living biomass	t_C ha^{-1}	x	x	-
C_{la}	annual average amount of carbon in living biomass	t_C ha^{-1}	x	x	-
C_r	carbon in crop residues	t_C ha^{-1}	x	x	-
C_{ra}	annual average amount of carbon in crop residues	t_C ha^{-1}	x	x	-
C_{rfa}	annual average amount of carbon in fast decomposing crop residues	t_C ha^{-1}	x	x	-
C_{roa}	annual average amount of carbon in roots	t_C ha^{-1}	-	x	-
C_{rsa}	annual average amount of carbon in slowly decomposing crop residues	t_C ha^{-1}	x	x	-
C_s	carbon in soil organic matter	t_C ha^{-1}	x	x	-

Symbol	Variable	Dimension	Arable crops	Grassland	Environment
C_{sa}	annual average amount of carbon in soil organic matter	$t_C\ ha^{-1}$	x	x	-
C_{sta}	annual average amount of carbon in stubble	$t_C\ ha^{-1}$	-	x	-
D_f	rate of decrease in fast decomposing crop residues	$t_{o.m.}\ ha^{-1}\ d^{-1}$	x	x	-
D_{ro}	mortality rate of roots	$t_{o.m.}\ ha^{-1}\ d^{-1}$	-	x	-
D_s	rate of decrease in soil organic matter	$t_{o.m.}\ ha^{-1}\ d^{-1}$	x	x	-
D_{st}	mortality rate of stubble	$t_{o.m.}\ ha^{-1}\ d^{-1}$	-	x	-
E_a	actual evapotranspiration	$mm\ d^{-1}$	-	-	x
e_m	soil moisture response function	dimensionless	-	-	x
E_p	potential evapotranspiration	$mm\ d^{-1}$	-	-	x
e_s	saturation water vapor pressure at T_a	kPa	-	-	x
e_T	soil temperature response function	dimensionless	-	-	x
F_{Cs}	annual flux of carbon to soil organic matter	$t_C\ ha^{-1}\ y^{-1}$	x	x	-
G	growth rate of total (above- and below-ground) biomass	$t_{o.m.}\ ha^{-1}\ d^{-1}$	x	x	-
G_{ha}	growth rate of harvestable biomass	$t_{o.m.}\ ha^{-1}\ d^{-1}$	-	x	-
G_{ro}	growth rate of roots	$t_{o.m.}\ ha^{-1}\ d^{-1}$	-	x	-
G_{st}	growth rate of stubble	$t_{o.m.}\ ha^{-1}\ d^{-1}$	-	x	-
I_r	increase rate of crop residues	$t_{o.m.}\ ha^{-1}\ d^{-1}$	-	x	-
I_{rf}	increase rate of fast decomposing crop residues	$t_{o.m.}\ ha^{-1}\ d^{-1}$	-	x	-
I_{rs}	increase rate of slowly decomposing crop residues	$t_{o.m.}\ ha^{-1}\ d^{-1}$	-	x	-
r_{rf}	relative rate of decrease in fast decomposing crop residues	d^{-1}	x	x	x
r_s	relative rate of decrease in soil organic matter	d^{-1}	x	x	x
r_{sa}	annual relative rate of decrease in soil organic matter	y^{-1}	x	x	-
s	slope of the saturation water vapor temperature curve at T_a	$kPa\ °C^{-1}$	-	-	x
T_s	soil temperature	°C	-	-	x
θ	soil moisture content	$m^3\ m^{-3}$	-	-	x
Variables input to the model					
d	Julian day number	d	x	x	-
K	global radiation	$J\ m^{-2}\ d^{-1}$	-	-	x
P	precipitation	$mm\ d^{-1}$	-	-	x
T_a	air temperature	°C	-	-	x

Symbol	Variable	Dimension	Arable crops	Grassland	Environment
Crop parameters calculated by the model					
d_{cc}	day of canopy closure	d	x	-	-
d_e	last day of the growing season	d	-	x	-
d_h	day of harvest	d	x	-	-
d_s	first day of the growing season	d	-	x	-
f_{rf}	fraction carbon in fast decomposing crop residues	$t_C\ t_{o.m.}^{-1}$	x	x	-
Crop parameters input to the model					
d_r	rooted depth	m	-	-	x
f_{faec}	faeces biomass as fraction of total grazed biomass per year	dimensionless	-	x	-
f_h	fraction carbon in harvested biomass	$t_C\ t_{o.m.}^{-1}$	x	x	-
f_l	fraction carbon in living biomass	$t_C\ t_{o.m.}^{-1}$	x	x	-
f_{ro}	fraction growth partitioned to roots	dimensionless	-	x	-
f_s	fraction carbon in soil organic matter	$t_C\ t_{o.m.}^{-1}$	x	x	-
f_{st}	fraction growth partitioned to stubble	dimensionless	-	x	-
h_c	humification coefficient of crop residues	dimensionless	x	x	-
h_{faec}	humification coefficient of faeces	dimensionless	-	x	-
HI	harvest index (related to total, above- and below-ground biomass)	dimensionless	x	x	-
l_h	life-time of harvested biomass	d	x	x	-
m_h	moisture content of harvested product	$kg_{H2O}\ kg^{-1}_{f.m.}$	x	-	-
Q_{10}	factor change in decomposition rate with a 10 °C change in temperature	dimensionless	-	-	x
r_{fref}	reference relative rate of decrease in fast decomposing crop residues	d^{-1}	-	-	x
r_{ro}	turnover rate of roots	d^{-1}	-	x	-
r_{sref}	reference relative rate of decrease in soil organic matter	d^{-1}	-	-	x
r_{st}	turnover rate of stubble	d^{-1}	-	x	-
T_{ref}	reference temperature	°C	-	-	x
Physical constants					
γ	psychometric constant	kPa $°C^{-1}$	-	-	x
λ	latent heat of vaporization of water	J kg^{-1}	-	-	x

Symbol	Variable	Dimension	Arable crops	Grassland	Environment
<u>Site-specific parameters</u>					
L	latitude	degrees	x	-	-
<u>Soil parameters calculated by the model</u>					
θ_{cr}	critical soil moisture content	$m^3\ m^{-3}$	-	-	x
<u>Soil parameters input to the model</u>					
θ_{fc}	soil moisture content at field capacity	$m^3\ m^{-3}$	-	-	x
θ_{wp}	soil moisture content at wilting point	$m^3\ m^{-3}$	-	-	x
<u>Yield parameters input to the models</u>					
B_{hh}	amount of harvested biomass at harvest	$t_{o.m.}\ ha^{-1}$	x	x	-
B_{hhtot}	total amount of harvested biomass during the year	$t_{o.m.}\ ha^{-1}$	-	x	-
n	number of harvests per year	dimensionless	-	x	-

Table I-2. Crop parameters and physical parameters input to CESAR.

Symbol	Parameter	Value and dimension	Reference
<u>Crop parameters input to the model</u>			
<u>General</u>			
d_r	rooted depth	0.3 m	[1]
f_h	fraction carbon in harvested biomass	$0.45\ t_C\ t_{o.m.}^{-1}$	[2]
f_l	fraction carbon in living biomass	$0.45\ t_C\ t_{o.m.}^{-1}$	[2]
f_s	fraction carbon in soil organic matter	$0.58\ t_C\ t_{o.m.}^{-1}$	[2]
l_h	life-time of harvested biomass	365 d	[1]
Q_{10}	factor change in decomposition rate with a 10 °C change in temperature	2	[3]
r_{rfref}	reference relative rate of decrease in fast decomposing crop residues	$0.044\ d^{-1}$	[4]
r_{sref}	reference relative rate of decrease in soil organic matter	$0.000092\ d^{-1}$	[5]
T_{ref}	reference temperature	10 °C	
<u>Crop-specific</u>			
Wheat (cereals)			
Straw harvested			
h_c	humification coefficient of crop residues	0.31	[6]
HI	harvest index (related to total, above- and below-ground biomass)	0.67	[6]
m_h	moisture content of harvested product	$0.16\ kg_{H2O}\ kg^{-1}_{f.m.}$	[7]
	straw yield relative to grain yield	0.46	[6]
Straw not harvested			
h_c	humification coefficient of crop residues	0.31	[6]
HI	harvest index (related to total, above- and below-ground biomass)	0.46	[6]
m_h	moisture content of harvested product	$0.16\ kg_{H2O}\ kg^{-1}_{f.m.}$	[7]

Symbol	Parameter	Value and dimension	Reference
Potato (roots and tubers)			
h_c	humification coefficient of crop residues	0.22	[6]
HI	harvest index (related to total, above- and below-ground biomass)	0.69	[6]
m_h	moisture content of harvested product	0.79 $kg_{H2O}\ kg^{-1}_{f.m.}$	[8]
Sugar beet			
h_c	humification coefficient of crop residues	0.21	[6]
HI	harvest index (related to total, above- and below-ground biomass)	0.69	[6]
m_h	moisture content of harvested product	0.76 $kg_{H2O}\ kg^{-1}_{f.m.}$	[9]
Peas (pulses)			
h_c	humification coefficient of crop residues	0.24	[6]
HI	harvest index (related to total, above- and below-ground biomass)	0.69	[6]
m_h	moisture content of harvested product	0.125 $kg_{H2O}\ kg^{-1}_{f.m.}$	[10]
Rapeseed (oilcrops)			
h_c	humification coefficient of crop residues	0.33	[6]
HI	harvest index (related to total, above- and below-ground biomass)	0.52	[6]
m_h	moisture content of harvested product	0.18 $kg_{H2O}\ kg^{-1}_{f.m.}$	[11]
Flax (fibre crops)			
h_c	humification coefficient of crop residues	0.33	[6]
HI	harvest index (related to total, above- and below-ground biomass)	0.92	[6]
	dry fibre yield as fraction of harvested dry matter	0.2	[12]
Cabbage (vegetables and melons)			
h_c	humification coefficient of crop residues	0.23	[6]
HI	harvest index (related to total, above- and below-ground biomass)	0.42	[6]
m_h	moisture content of harvested product	0.9 $kg_{H2O}\ kg^{-1}_{f.m.}$	[13]

Symbol	Parameter	Value and dimension	Reference
Perennial rye-grass (grassland)			
f_{faec}	faeces biomass as a fraction of total grazed biomass per year	0.255	[14]
f_{ro}	fraction growth directed to roots	0.306	[15]
f_{st}	fraction frowth directed to stubble	0.25	[15]
h_{faec}	humification coefficient of faeces	0.44	[16]
h_c	humification coefficient of crop residues	0.33	[6]
HI	harvest index (related to total, above- and below-ground biomass)	0.444	[14]
r_{ro}	turnover rate of roots	0.011 d^{-1}	[17]
r_{st}	turnover rate of stubble	0.00274 d^{-1}	[17]
Physical parameters input to the model			
γ	psychometric constant	0.067 kPa $°C^{-1}$	
λ	latent heat of vaporization of water	2.4 10^6 J kg^{-1}	

References

[1] estimate
[2] Wolf & Janssen (1991)
[3] Kätterer *et al.* (1998)
[4] value for easily decomposable materials by Van der Linden *et al.*, 1987
[5] derived from daily weather data for Wageningen (1961-1990) with the assumption that the average annual relative rate of decrease in the Netherlands is 2.9 %
[6] derived from Consulentschap in Algemene Dienst voor Bodemaangelegenheden in de Landbouw (1980)
[7] Landbouw-Economisch Instituut (2000)
[8] R. Postma (pers. comm.)
[9] derived from Elliot & Weston (1993)
[10] Vogel (1996), Proefstation voor de Akker- en Weidebouw (1967)
[11] FAO (1999)
[12] Dempsey (1975)
[13] Vogel (1996)

[14] derived from Whitehead (1986)
[15] derived from Whitehead (1986), Schapendonk *et al.* (1997) and A.H.C.M. Schapendonk (pers. comm.)
[16] average for sand and clay given by De Haan (1977)
[17] derived from Schapendonk *et al.* (1997) and A.H.C.M. Schapendonk (pers. comm.)