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Modeling consequences of straw residues export on soil organic carbon

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Abstract

Cereal straw, which is most often returned to the soil in arable cropping systems, is of renewed interest as a potential source of bioenergy. However, the sustainability of this practice which implies systematic removal of aerial biomass of cereal crops is a controversial issue, particularly in soils having a low soil organic carbon (SOC) content. This study aims at evaluating a simple model (AMG) to predict the consequences of straw export on SOC evolution in various cropping and pedoclimatic conditions. The model was tested on nine long-term field experiments (18–35 yr) dominated by cereal crops and differing in climate, soil type and carbon inputs. The model was able to provide satisfactory simulations of the evolution of SOC in most experiments with a unique set of parameters. The sensitivity analysis indicated that the quality of fit was very sensitive to humification coefficient, moderately sensitive to the size of the stable SOC pool and weakly affected by the ratio of belowground: aerial C input. The dependence of model parameters (humification and mineralization rates) on pedoclimatic conditions (soil clay content and temperature) was analyzed and compared to those proposed in other models (DAISY, CENTURY, ROTHC, CN-SIM) since they vary widely between models. AMG functions provided the best fit in seven out of nine experiments. More generally, the best fit was obtained by assuming that clay content had a small or no effect on humification coefficient and a marked effect on mineralization rate, in accordance with incubation studies in literature. The AMG model was used to simulate the impact of a straw export scenario in nine experiments considering a systematic straw removal one year out of two. With this scenario, straw removal vs. incorporation would reduce carbon stocks by 2.5–10.9% of the initial SOC after 50 yr, depending primarily on the experiment (soil, climate, productivity) and secondarily on the size of the stable C pool (varying from 10% to 65%).

Keywords: Organic carbon; Model; Straw; Clay; Soil organic matter; Long term

1. Introduction

Soil organic matter (SOM) constitutes a reservoir of carbon, nitrogen and other plant nutrients and influences soil structure and quality. SOM formation (humification) in soil is a worldwide subject of concern and depends on several factors including the climate, the amount and quality of plant residues, soil management and land use. Crop residues and particularly cereal straw, most often returned to soil in arable farming in France, are of renewed interest as a potential source of bioenergy. The sustainability of agrosystems including intensive export of biomass is a crucial and controversial point, particularly in cropping systems with low content of soil carbon (Wilhelm et al., 2004; Lal, 2005). Simulation models may be valuable tools to predict the impacts of such massive export of residues on soil carbon on the long term.

There is a wide body of literature on the development, comparison and evaluation of simulation models for predicting carbon and/or nitrogen dynamics in soil (Parton et al., 1987; Powlson et al., 1996; Andrén and Kätterer, 1997; Smith et al., 1997; Andriulo et al., 1999; Shaffer et al., 2001; Bruun et al., 2003; Petersen et al., 2005; Grace et al., 2005). They vary from simple analytical models to more sophisticated research models according to the number of phenomena which are considered, the input data which are required, and their mathematical formula-

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tion. They differ by the number of pools taken into account, by the initialization and the size of such pools, as well as by the number of parameter considered and their estimation.

To test the capacity of these models to simulate the dynamics of organic carbon in soils, long-term field experiments are essential. Long-term field data found in literature provide a unique resource to investigate long-term influences of climate, crop rotation and crop residue management on soil fertility (Morel et al., 1981; Sudarsono, 1988; Paustian et al., 1992; Plénet et al., 1993; Kirchmann et al., 1994; Christensen and Johnston, 1997; Bruun et al., 2003; Thomsen and Christensen, 2004; Shirato et al., 2005).

Here we focus on AMG model which is a simple model that simulates the evolution of soil organic carbon (SOC) over long periods. In contrast to other complex simulation models, simple models require minimal data inputs and few numbers of parameters. Less effort is needed to obtain estimates of parameters values and to test the sensitivity of the model to these parameters. The present study aims at evaluating the consequences of straw export on SOC using AMG model. Our main objectives were (i) to evaluate AMG model using a data set of international long-term experiments with straw export presenting widely differing inputs, initial soil carbon and treatments, (ii) to discuss the validity of model parameters for various pedoclimatic conditions and (iii) simulating scenarios studies with straw export.

2. Materials and methods

2.1. Model description

AMG is a simple model designed to simulate humified organic matter evolution and is embedded in the soil–plant simulation model STICS (Brisson et al., 2003). However, the decomposition of fresh organic matter is simulated in STICS on a daily time step with a specific module (Nicolardot et al., 2001), whereas AMG runs on an annual time step and assumes that fresh organic matter is either decomposed or humified in soil after a year of decay. AMG is derived from a simple model used in France (Hénin and Dupuis, 1945; Bayer et al., 2006) and was successfully evaluated to simulate SOC evolution over one or several decades in Great Britain (Mary and Guerif, 1994), on the rolling pampas in Argentina (Andriulo et al., 1999) and in a long-term experiment in France (Mary and Wylleman, 2001). It considers three pools of organic matter: crop residues and humified OM which is separated into a stable and an active compartments (Fig. 1). The stable pool is considered to be completely stable, i.e. having a mean residence time (MRT) much greater than the range of prediction time. The model can be considered as a simplification of well-known models such as ROTHC (Coleman and Jenkinson, 1996), CENTURY (Parton et al., 1987), CN-SIM (Petersen et al., 2005), ICBM

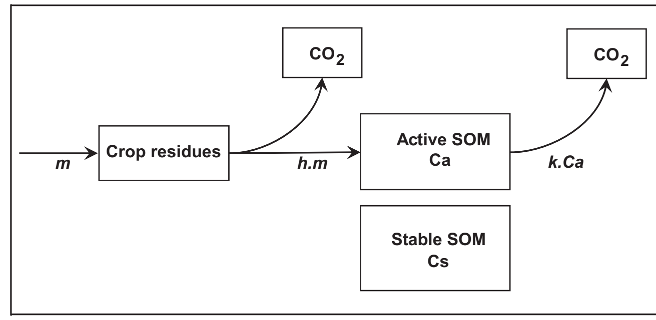

Fig. 1. Diagram of AMG model.

(Andrén and Kätterer, 1997) or SOCRATES (Grace et al., 2005), by skipping the pools having a fast turnover, i.e. an MRT smaller than 1 year. Its stable fraction is similar to the IOM pool of ROTH-C and CN-SIM models whose MRT is infinite and the passive pool of CENTURY whose MRT is about 1000 yr. These three models vary in the size of the stable pool which represents about 10%, 40–50% and 50–60% of total SOC, respectively. In contrast, ICBM and SOCRATES models only consider a homogeneous humus pool, i.e. assume that the inert pool is nil.

The basic equations of AMG model are the following:

$$C = C_S + C_A, \quad (1)$$

$$\frac{dC_A}{dt} = mh - kC_A, \quad (2)$$

where C is the total SOC content ($Mg\,ha^{-1}$), C_S is the stable carbon content ($Mg\,ha^{-1}$), C_A is the active carbon content ($Mg\,ha^{-1}$), m is the annual carbon input ($Mg\,ha^{-1}\,yr^{-1}$), h is the humification coefficient of the fresh organic residues (unitless) and k is the mineralization rate constant of the soil active fraction (yr^{-1}). m represents the total mass of organic carbon returned to soil through all crop residues (straw, stubble, roots and rhizodeposits). If m is constant every year, these equations can be integrated:

$$C = C_S + (C_0 - C_S)\,e^{-kt} + \frac{mh}{k}(1 - e^{-kt}), \quad (3)$$

where C_0 is the initial SOC content ($Mg\,ha^{-1}$). In this equation, the second term of the right side represents the decomposition of the 'old carbon' (i.e. existing at time 0) while the third term represents the (net) newly humified carbon which reaches an asymptote: $C_{A\infty} = mh/k$. These two terms can be determined separately in $C3/C4$ chronosequences by using ^{13}C natural abundance technique which allows to obtain a unique evaluation of the parameters k and h in long-term experiments (Andriulo et al., 1999).

2.2. Environmental functions

In AMG model, the mineralization rate k depends on pedoclimatic characteristics, particularly soil temperature

(T) and clay content (A):

$$k = k_0 f_1(T) f_2(A), \quad (4)$$

where k_0 is the potential mineralization rate (yr^{-1}) in reference conditions and $f_1(T)$ and $f_2(C)$ are the temperature and clay functions, equal to 1 in reference conditions. The reference conditions are defined here as a 15 °C soil temperature and zero clay content. The effect of clay content on mineralization of SOC is described by an exponential law:

$$f_2(A) = \exp(-aA), \quad (5)$$

where A is the clay content ($g\,g^{-1}$ soil) and a is a constant ($g\,soil\,g^{-1}$ clay). This formulation allowed to describe N mineralization kinetics in incubation experiments performed on various soil types and is used in STICS model (Brisson et al., 2003), the value of a being 2.72.

The effect of temperature (T, °C) on mineralization of humified organic matter is assumed to obey a logistic law:

$$f_1(T) = \frac{c}{1 + (c-1)\exp(-K(T - T_{ref}))} \quad \text{if } T \geqslant 0, \qquad f_1(T) = 0 \quad \text{if } T < 0. \quad (6)$$

This formulation allows to account for a quasi-exponential effect of temperature up to a given temperature, followed by a slower increase. It is based on various incubation studies of non-amended soil, such as those reported by Balesdent and Recous (1997) for the mineralization of humified organic carbon. On the basis of this work and other unpublished results, we set the c coefficient at 20 and the K factor at $0.120\,K^{-1}$ in AMG model, which yields an exponential effect up to about 25 °C with a Q_{10} coefficient equal to 3.16.

In the original AMG model, the humification coefficient h is supposed to depend only on the nature (or quality) of organic residues. However, several models in the literature consider a relation between the humification coefficient and clay content. We therefore evaluated the possible effect of clay on the humification coefficient in AMG model by considering the following linear relationship:

$$h = h_0 f_3(A), \quad (7)$$

$$f_3(A) = 1 - bA, \quad (8)$$

where h_0 is the humification coefficient (unitless) of a given organic residue decomposing in a soil without clay and b is a constant (unitless). The assumption that h does not depend on soil type ($b = 0$) is based on results of Nicolardot et al. (2001) obtained in long incubation experiments. This study shows that kinetics of carbon mineralization coming from crop residues decomposition hardly differ between soil types (for the same temperature and water potential conditions) but mainly vary with residue quality.

2.3. Experimental data set

Our aim was to collect data from long-term experiments (at least 10 yr old) performed in various soil and climatic conditions with measured kinetics of SOC evolution with systematic removal or incorporation of cereal straw in soil. We compiled nine published and well-documented experiments in the literature. They vary in climatic conditions and in the duration of straw export which ranged from 12 to 35 yr (Table 1a). They also vary in soil types, initial carbon content and agronomic management (Table 1b). The experiments 1–7 come from Europe with cold or temperate climate. They were used to calibrate the model (parameter k_0). The experiment 8 (Khon Kaen) comes from a tropical region and was used exclusively to evaluate the model, due to the much higher temperature and the greater data variability. The last experiment (Askov 2) was also used only to evaluate the model because it included less measurements and had the same pedoclimatic conditions than experiment 2 (Askov). The SOC data were obtained from published papers except for Boigneville and Issoudun: in these two experiments, we collected soil samples since the beginning of experiments and analyzed them all. The evolution of soil carbon under two (straw exported, straw incorporated) or three (bare fallow soil) treatments was simulated and compared to the observed data.

2.4. Model parameters

AMG was previously calibrated for k_0, h_0 and C_S/C_0 on the results of Boigneville experiment using organic C and ^{13}C measurements (Mary and Wylleman, 2001). The best fit was obtained using a least-squares method on all data: the humification coefficient h_0 was estimated at 0.21 for a mixture of maize and wheat straw, and the initial stable fraction C_S/C_0 was set as 65%. For the present work, we assume that these values could apply to all data sets, except k_0 which was optimized. For each experiment, the annual amount of C input to soil was estimated from measurements of above-ground material or derived from crop yield and harvest index (grain:straw ratio). The mass of below-ground carbon (BGC) left in soil, including roots and rhizodeposits (m_R, in $Mg\,C\,ha^{-1}$), was calculated as a function of crop yield:

$$m_R = \alpha \cdot Y + \beta, \quad (9)$$

where Y is the dry matter yield ($Mg\,C\,ha^{-1}$), β is the minimum root mass (obtained for very low yields). The values adopted for cereals were $\alpha = 0.30$ and $\beta = 0.30\,Mg\,C\,ha^{-1}$. Carbon concentration in residues was assumed to be 40% of the fresh matter and water content 10% of dry matter (Nicolardot et al., 2001; Shirato et al., 2005).

The model was run using the mean annual air temperature as basic input. However, this mean value is not directly applicable because the temperature functions are non-linear and have a discontinuity ($f_1(T)$ is nil

Table 1
(a) *Description of the selected experiments*

Site		Symbol	Duration (yr)	Rainfall[a] (mm)	Mean temperature		Reference
					Actual[b] (°C)	Equivalent[c] (°C)	
Ultuna	Sweden	U	35	527	5.5	8.3	Kirchmann et al. (1994)
Askov	Denmark	A	31	862	7.7	9.5	Bruun et al. (2003)
Issoudun	France	I	32	704	10.8	13.4	Sudarsono (1988)
Grignon	France	G	18	642	10.3	12.8	Morel et al. (1981)
Boigneville	France	B	28	650	11.0	13.6	Thévenet et al. (2004)
Serreslous	France	S	21	1120	13.4	16.6	Plénet et al. (1993)
Doazit	France	D	24	1120	13.4	16.6	Plénet et al. (1993)
Khon Kaen[d]	Thailand	K	26	1184	27.6	28.0	Shirato et al. (2005)
Askov 2[d]	Denmark	A2	21	862	7.6	9.4	Thomsen and Christensen (2004) annual temperature, c equivalent constant temperature for C mineralization, d Experiments used for model validation only

(b) *Main characteristics of the experiments*

Site	Soil texture	Depth (cm)	Clay (g kg^{-1})	C_0[a] (Mg ha^{-1})	Crops	Treatments		C input[b] (Mg ha^{-1} yr^{-1})
U	Clay loam	20	365	39	No rotation	Bare fallow	–N	0.00
						Straw removed	–N	0.76
						Straw incorporated	+N	2.68
						Straw removed	+N	1.00
						Straw incorporated	+N	2.92
A	Sandy loam	50	90	100[c]	No rotation	Bare fallow	–N	0.00
						Straw removed	+N	1.56
						Straw incorporated	+N	3.06
I	Calcareous clay	23	373	44	Rotation	Straw burnt[d]	+N	0.95
						Straw $\frac{1}{2}$ incorporated[e]	+N	2.11
						Straw incorporated	+N	2.56
G	Sandy clay loam	25	290	40	No	Straw removed	–N	0.00
					No	Straw incorporated	–N	2.52
					No	Straw removed	+N	0.00
					No	Straw incorporated	+N	2.52
B	Clay loam	25	230	39	Rotation	Straw removed	+N	2.42
						Straw incorporated	+N	3.94
S	Sandy loam	23	121	32	No	Bare fallow	–N	0.00
					Maize	Straw removed	+N	0.97
					Maize	Straw incorporated	+N	3.20
D	Sandy loam	25	138	41	No	Bare fallow	–N	0.00
					Maize	Straw removed	+N	1.00
					Maize	Straw incorporated	+N	3.34
K	Sand	20	69	12	Rotation	Straw removed	–N	1.33
					Rotation	Straw incorporated	–N	2.42
					Rotation	Straw removed	+N	2.30
					Rotation	Straw incorporated	+N	4.90
A2	Sandy loam	20	110	45	Rotation	Straw removed	+N	0.91
					Rotation	Straw incorporated	+N	2.27
					Rotation	Straw incorporated	+N	3.63
					Rotation	Straw incorporated	+N	4.99

[a] C_0 = initial SOC content.
[b] C input = total mass of organic carbon returned to soil each year through crop residues (straw, stubble, roots and rhizodeposits).
[c] Reconditioned soil taken in the 10–30 cm layer of a field and packed into a cylinder over 50 cm.
[d] Straw was burnt every year.
[e] Straw was burnt every 2 yr.

below 0 °C). Therefore, we used the monthly or daily (when available) temperature recordings (minimum and maximum) over several years to calculate the mean annual value of $f_1(T)$ using Eq. (6). This allowed us to calculate the mean 'equivalent temperature', i.e. the constant temperature which would have the same effects than the actual, fluctuating temperatures on SOC mineralization. Table 1a shows that the equivalent temperature is greater by 0.5–3 °C than the actual temperature.

The effect of soil moisture on mineralization was not taken into account explicitly in this work due to lack of data for some experiments. However, we run the STICS model on four data sets (Issoudun, Grignon, Boigneville and Serreslous) to simulate the daily water content and then calculate the mean annual moisture factor. The results indicated that this factor varied little between sites, from 0.70 to 0.83 (1 corresponds to optimum water content at field capacity). A similar conclusion was given by Petersen et al. (2005). We assume that this range of variation also applies for the other sites because all sites have a rather high annual precipitation (Table 1a). The moisture factor was then supposed to be the same for all sites and is included in the potential rate constant k_0. Therefore the model is not suitable in situations with severe water stress.

2.5. Comparison with other models

Although clay content has been shown for long to slow down SOC decomposition, its effect on microbial decomposition and stabilization (mineralization and humification) is described differently in SOC models. Similarly, the temperature functions differ markedly between models and may generate important variations in model outputs (Rodrigo et al., 1997). This leads us to compare the temperature and clay functions used in AMG with those proposed in four well-known models: DAISY, CN-SIM, CENTURY and ROTHC. The temperature functions used in these models are given in Appendix A, after normalizing for similar reference conditions. The corresponding curves do not differ much from each other in the range of the equivalent temperatures observed in temperate experiments (i.e. between 8 and 17 °C), except for CENTURY model (Fig. 2c). They diverge for the higher temperatures, the AMG model simulating a faster decomposition rate than the others.

The effects of clay content on mineralization and humification coefficients were calculated using the equations either given in the description of the models (DAISY and CN-SIM) or calculated using the model diagram (ROTHC and CENTURY, see Appendix A). It appears that the models vary very widely in the importance attributed to clay on these two processes (Figs. 2a, b). ROTHC simulates the smaller effect of clay on both processes while CENTURY attributes a great influence of clay (and fine silt) on humification and mineralization processes.

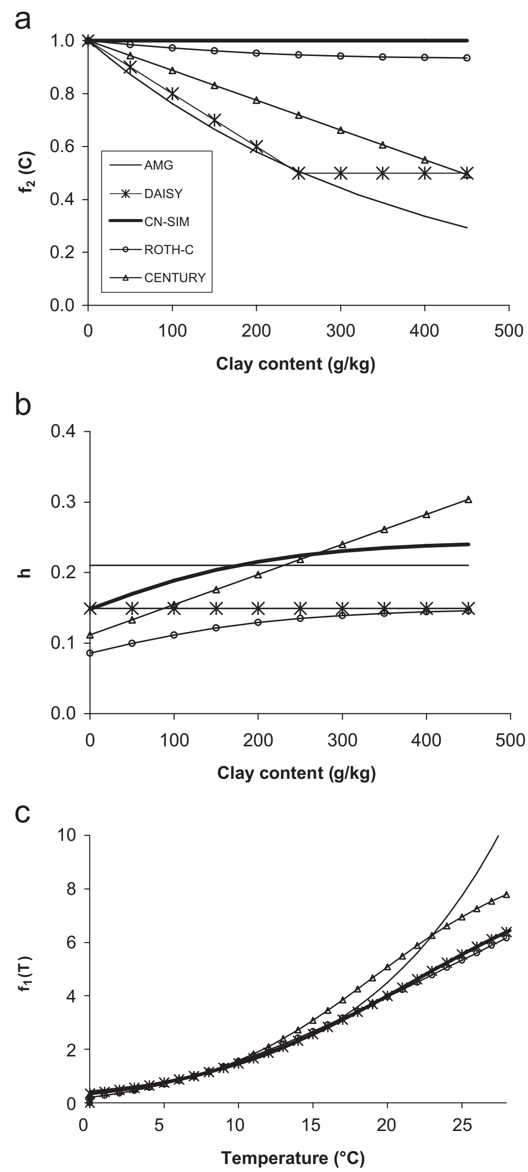

Fig. 2. Environmental factors used in the different models: (a) mineralization rate vs. clay content; (b) humification coefficient vs. clay content; (c) mineralization rate vs. temperature. In the case of Century model, the proportion of fine silt was supposed to represent 50% of clay content.

2.6. Model evaluation

Our study was realized in four steps:

Step 1: AMG model was evaluated by fitting the model on experiments 1–7 simultaneously. Only the potential mineralization rate k_0 was optimized (a single value for all experiments); the stable pool was fixed at 65% of the initial SOC content, the humification coefficient h_0 was 0.21 and the two clay related parameters were $a = 2.72$ and $b = 0$. The last two experiments were used for model validation.

The quality of fit was evaluated using two criteria: the absolute root mean square error ($\mathrm{Mg\,ha^{-1}}$) and the mean difference ($\mathrm{Mg\,ha^{-1}}$), defined as follows:

$$\mathrm{RMSE}(j) = \sqrt{\frac{1}{n_j}\sum_{i=1}^{n}(C_{ij} - \widehat{C}_{ij})^2},$$

$$\mathrm{MD}(j) = \frac{1}{n_j}\sum_{i=1}^{n_j}(C_{ij} - \widehat{C}_{ij}),$$

where n_j is the number of observations of each data set j, C_{ij} and $\widehat{C}_{ij}$ are the observed and simulated values of SOC, respectively. The optimization was conducted using the Newton's method of Excel solver. The minimized criterion was the mean value of the relative root mean square errors (RRMSE, in %) of the first seven data sets:

$$\mathrm{RRMSE} = \frac{1}{7}\sum_{j=1}^{7}\frac{\mathrm{RMSE}(j)}{\bar{C}_j},$$

where $\bar{C}_j$ is the mean SOC content in experiment j.

Step 2: We run a sensitivity analysis of the model to the parameters C_S/C_0, h_0 and α using a similar approach to that described by Petersen et al. (2005). We gave several possible values to one parameter and optimized the two other parameters each time. In the first time, the clay related parameters (a and b) were fixed. The optimization concerned the parameters which were correlated each other, i.e. k_0 and h_0 when C_S/C_0 was fixed, k_0 and C_S/C_0 when h_0 was fixed, and k_0 and C_S/C_0 when α was fixed. The range of variation chosen covered more or less the range of reported values: it was 0.10–0.30 for the parameter h_0, 0.20–0.60 for the parameter α and 10–65% for the initial size of the stable fraction. In a second time, we considered a possible variation of both k and h vs. clay content, so that the four parameters (k_0, h_0, a, b) were optimized simultaneously to obtain the best calibration and test the validity of the relationships with clay content. The optimization of these parameters was performed for three possible values of $C_S\,/C_0$ (10%, 40% and 65%).

Step 3: Using the structure of AMG model, we compared its environmental functions (clay and temperature functions) to those proposed in the other models. We also used the value of the stable fraction C_S/C_0 approximately recommended in these models, i.e. 65%, 0%, 40%, 50% and 10% in AMG, DAISY, CN-SIM, CENTURY and ROTHC models, respectively. In this comparison, the only parameter which was optimized was the potential mineralization rate k_0 (one value common to all data sets, but different for each model). The optimization also consisted in minimizing the RRMSE criterion for the first seven experiments.

Step 4: Finally we made a scenario study of the effect of straw removal on SOC evolution for each site by using AMG model. Since the importance of the recalcitrant SOC pool is a matter of debate and may have important effects on simulation outputs (e.g. Falloon and Smith, 2000), we have considered three possible values of the initial fraction C_S/C_0 (65%, 40% and 10%).

3. Results

3.1. Model evaluation

The observed and simulated evolutions of SOC in nine experiments are given in Fig. 3. The largest SOC decline occurred in the bare fallow treatments, as expected since there was no significant carbon input. SOC contents also declined in all cropped soils whose straw was exported, but the decline was smaller, indicating a significant contribution of below-ground material to the C balance. The soils with systematic straw incorporation underwent either an increase (Ultuna, Issoudun, Boigneville) or a decrease in SOC with time, but straw addition always exerted a positive effect on the final SOC content. The SOC contents seemed to have reached equilibrium only in the tropical situation (Khon Kaen). In the three experiments combining straw and nitrogen fertilizer level (Ultuna, Grignon and Khon Kaen), the effect of nitrogen was either negligible or slightly positive. The effect is mainly attributed to an increase in the amount of crop residues due to mineral fertilization.

The model was able to provide satisfactory simulations of the evolution of SOC contents. The RMSE values varied between 0.4 and $2.8\,\mathrm{Mg\,C\,ha^{-1}}$ (Table 2), the mean difference varied between -2.1 and $+1.3\,\mathrm{Mg\,C\,ha^{-1}}$ and the relative error (RRMSE) was between 1.0% and 6.5%, except for Khon Kaen experiment. The greater RRMSE found in Khon Kaen (15.2%) is mainly attributable to the greater variability of measurements. The poorest fits were obtained in Ultuna, Askov and Issoudun experiments which were simulated with a significant bias. The model overestimated SOC in all treatments at Ultuna and underestimated SOC content in the straw experiment at Askov. The reasons for this discrepancy are not clear. At Issoudun the model underestimated the SOC content in the treatment with straw burnt. This could be attributed to the production of 'black' carbon during the straw combustion which would be included in the C analysis but has no biological reactivity. The simulations at Khon Kaen and Askov 2 are satisfactory and validate the model. The optimized value of the potential mineralization rate (k_0) is $0.109\,\mathrm{yr^{-1}}$. The calculated mineralization rates k vary from $0.019\,\mathrm{yr^{-1}}$ at Ultuna to $0.348\,\mathrm{yr^{-1}}$ at Khon Kaen. For each site, we compared the observed and simulated values of SOC contents at the end of the experiment (Table 2). In order to reduce the data variability, we averaged SOC contents at the last two dates of measurements and for the treatments $\mathrm{N^+}$ and $\mathrm{N^-}$ (which were hardly different from

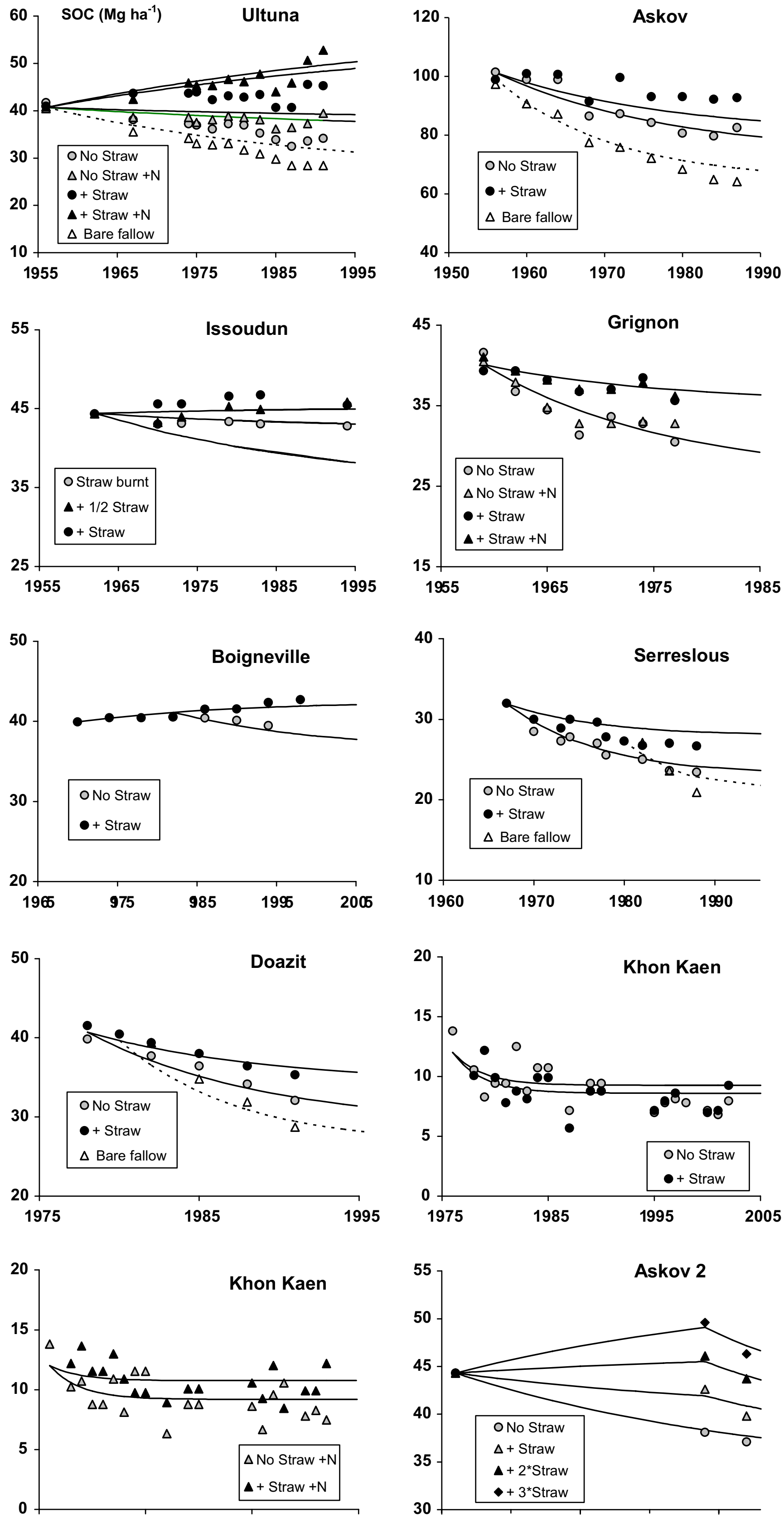

Fig. 3. Evolution of measured (symbols) and simulated (lines) SOC contents in the nine long-term experiments. The dotted lines refer to the simulated bare fallow treatments.

Table 2
Evaluation of AMG model: mineralization rate of SOC (k), quality of fit (RMSE = residual mean square error; MD = mean difference) obtained with the AMG model in nine experiments, and final SOC contents (observed and simulated)

Site	k (yr^{-1})	RMSE ($Mg\,ha^{-1}$)	MD ($Mg\,ha^{-1}$)	RRMSE (%)	SOC without straw[a]		SOC with straw[b]	
					Observed ($Mg\,ha^{-1}$)	Simulated ($Mg\,ha^{-1}$)	Observed ($Mg\,ha^{-1}$)	Simulated ($Mg\,ha^{-1}$)
U	0.019	2.7	−2.0	6.3	36.8	38.6	49.1	49.0
A	0.044	3.9	0.9	4.4	81.2	80.8	92.5	86.0
I	0.033	2.1	1.4	4.7	42.9	39.0	46.1	44.9
G	0.038	1.1	−0.3	3.3	31.6	31.1	35.9	37.0
B	0.050	0.5	0.1	1.1	39.8	39.2	41.9	41.7
S	0.094	1.2	−0.6	4.6	23.5	24.3	26.9	28.5
D	0.090	0.9	0.4	2.5	33.1	33.1	35.9	36.6
K	0.348	1.4	−0.3	15.7	7.7	8.9	10.7	10.0
A2	0.043	0.5	−0.1	1.3	38.5	39.3	45.0	45.6
Mean		1.6	−0.1	3.9	37.2	37.1	42.7	42.1

The only parameter optimized using the experiments 1–7 was the potential mineralization rate k_0. The humification coefficient of crop residues (h) was fixed at 0.21. Experiments 8 and 9 (K and A2) were used for validation.
[a]Final SOC contents in treatments with straw removal.
[b]Final SOC contents in treatments with straw incorporated. SOC contents are the mean of the last two dates and eventual N treatments (−N, +N).

Table 3
Sensitivity analysis of AMG model

Fixed parameters		Optimized parameters		RMSE ($Mg\,ha^{-1}$)	MD ($Mg\,ha^{-1}$)
α	C_S/C_0	h	k_0		
30%	65%	0.218	0.108	1.40	−0.16
30%	40%	0.169	0.048	1.36	−0.10
30%	10%	0.150	0.029	1.44	−0.08
α	h	C_S/C_0	k		
30%	0.10	0%	0.022	1.82	0.43
30%	0.21	58%	0.084	1.38	−0.08
30%	0.30	69%	0.165	1.57	−0.06
C_S/C_0	α	h	k_0		
65%	20%	0.231	0.106	1.41	−0.14
65%	40%	0.206	0.109	1.40	−0.19
65%	60%	0.182	0.110	1.44	−0.24

Mean RMSE and MD obtained after varying: the initial stable carbon fraction (C_S/C_0), the humification coefficient of crop residues (h) and the proportion of root and rhizodeposited material to shoot material (α). Two parameters were optimized for each combination: the potential mineralization rate k_0 (yr^{-1}) and another parameter (either h or C_S/C_0).

each other) when those were available. We obtained a good agreement between the simulated and the observed values: the regression equation was $y = 0.989.\ x$ ($r^2 = 0.980$). The mean effect of straw removal after 25 yr was an SOC decrease of 5.5 and 5.0 $Mg\,C\,ha^{-1}$ (observed and simulated values, respectively).

3.2. Parameterization sensitivity analysis

The RMSE values (mean of nine experiments) obtained for different values of h_0, α and C_S/C_0 are given at Table 3. Results show that the model was more sensitive to C_S/C_0 and h_0 than to α parameter. The effect of varying the initial size of the stable fraction had varied effects: reducing C_S/C_0 from 65% to 10% slightly improved the quality of fit in Askov, Issoudun and Doazit experiments, but deteriorated it in Grignon, Askov 2 and Khon Kaen experiments. In the latter experiment, the reduction of the stable fraction from 65% to 10% leads to simulate a much greater decline in SOC than observed, since the mean difference increased from −0.05 to 1.93 $Mg\,C\,ha^{-1}$. We conclude that it is difficult to recommend a precise value for this parameter, but the 40–65% range provides the best results.

Increasing the humification coefficient from 0.21 to 0.30 decreased the quality of fit in almost all experiments. Reducing it from 0.21 to 0.10 also increased the RMSE in most experiments, particularly in Boigneville, Khon Kaen and Askov 2. Therefore the default value of the model (0.21) appears to be close to optimum and we can reject the low and high values of humification coefficient of straw. Conversely, a variation in the belowground-C:shoot-C ratio (parameter α) has a very limited effect on the quality of fit. The RMSE were only slightly increased when α was set at 0.60, which is among the highest values reported in the literature.

It must be pointed out that the choice of two parameters (among C_S/C_0, h and α) modifies the value of the other two optimized parameters (Table 3). For example, choosing a low value for the stable fraction resulted in a moderate decrease of the humification coefficient and a strong reduction in the potential mineralization rate. When C_S/C_0 varies from 65% to 10%, the optimum value for h changes from 0.22 to 0.15 and the optimum value for k_0 drops from 0.108 to 0.029 yr^{-1}, without important change in simulation performance. This has to be taken into account when the parameters of different

Table 4
Set of model parameters optimized according to the initial value of the stable pool size (65%, 40% or 10% of initial SOC)

	AMG1	AMG2	AMG3
C_S/C_0	65%	40%	10%
k_0 (yr^{-1})	0.106	0.048	0.026
a	2.68	2.44	2.00
h_0	0.207	0.166	0.122
b	0.00	0.19	1.00

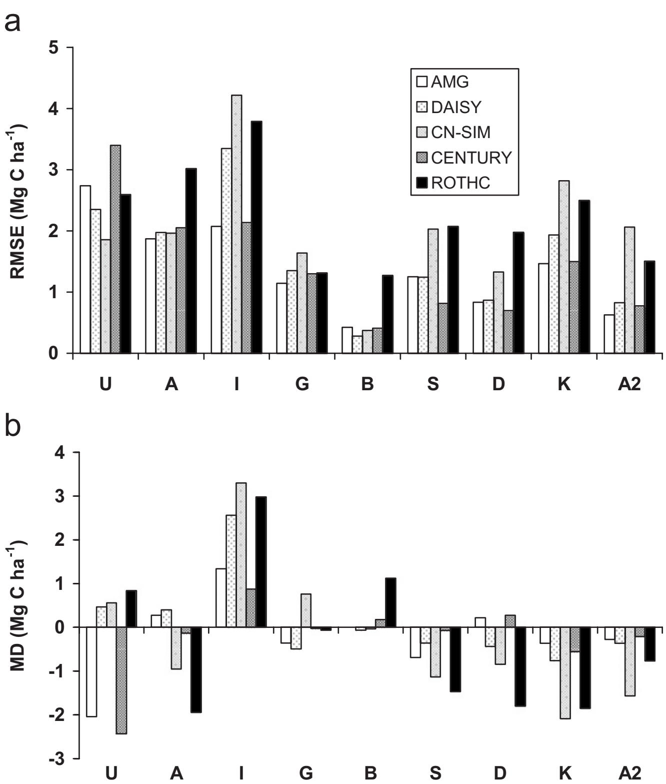

Fig. 4. Quality of fit obtained in the nine experiments using the environmental factors proposed in five models: AMG, DAISY, CN-SIM, CENTURY and ROTHC: (a) RMSE (Residual mean square error) and (b) MD (mean difference). The potential mineralization rate (k_0) was fitted for each model using the first 7 experiments.

models or different model versions are compared each other.

Finally, we determined the parameters providing the best quality of fit for all nine experiments, including the possible variation of h vs. clay content. The optimized values of potential rates (k_0 and h_0) and clay related rates (a and b) are shown at Table 4, for three possible values of the stable pool (versions called AMG1-2-3). The parameters of AMG1 version appear very close to those of the original model. The small value of b coefficient indicates that the humification coefficient is only slightly dependent on clay content, except for version AMG3.

3.3. Comparison of environmental functions of different models

Using the environmental functions (humification and mineralization rates vs. clay content and temperature) previously defined in AMG and in the four other models, we could compare their effect in AMG model structure. The quality of fit (RMSE and MD) is shown in Fig. 4 for each of nine experiments. The mean RMSE obtained using AMG, DAISY, CN-SIM, CENTURY and ROTHC functions was 1.59, 1.80, 2.25, 1.68 and 2.56 Mg C ha^{-1}, respectively. The mean difference was −0.18, +0.15, −0.33, −0.25 and −0.54 Mg C ha^{-1}, respectively. CENTURY functions provided a quality of prediction comparable to AMG, except for Boigneville experiment where they over-estimated the SOC contents (mean difference = −2.02 Mg C ha^{-1}). This is attributed to the fact that the environmental functions of these two models had similar patterns (see Fig. 2). This also applies for DAISY functions at a lower degree. CN-SIM functions gave the best predictions for Ultuna and Askov, confirming the good predictions obtained by Petersen et al. (2005) on these experiments. However, they resulted in a marked under-estimation of SOC contents at Issoudun and an over-estimation at Serreslous, Khon Kaen and Askov 2. This discrepancy is attributed to the absence of variation of the mineralization rate vs. clay content (see Fig. 2a), which results in a mineralization rate too high in clay soils (I) and too low in sandy soils (S, K and A2). On average, the ROTHC functions provided the poorest fit with observed values. They overestimated SOC contents in sandy soils (A, S, D, K, A2) and under-estimated them in the heavier soil (I). The mean difference was positively correlated with the clay content of the soil ($r = 0.85$, $p < 0.01$), suggesting that the effect of clay was insufficiently taken into account in this model. We conclude that clay content must exert an important effect on mineralization rate and a lower (or nil) effect on humification coefficient. The evaluation of the temperature functions is more difficult because they differ mainly above 15 °C. However, it is noticeable that the warmer sites (S, D and K) were better predicted by the models which had a greater response to higher temperatures (AMG and CENTURY) than the others.

3.4. Impact of straw removal on SOC evolution

We first compared the impact of straw return vs. disposal on the changes in SOC contents in the actual experiments. The observed SOC contents at the end of the experiments (average of the last two dates) were in good agreement with the simulated values using AMG1 model (Table 3). Over the duration of the experiments, the measured SOC increase due to straw return (as compared to straw removal) varied from 2.0 to 12.5 Mg C ha^{-1}, corresponding to an annual rate of 78–385 kg C ha^{-1} yr^{-1}. Expressed in % of added straw C, the increase ranged from 4.2% at Khon

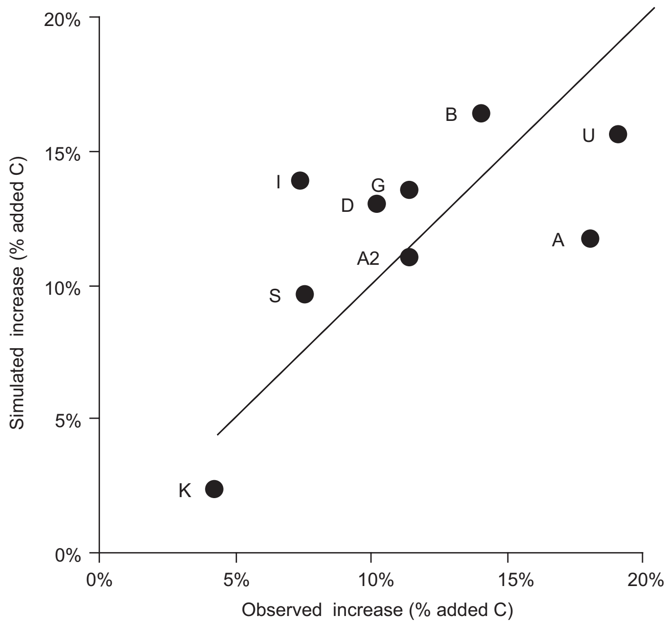

Fig. 5. Comparison of observed and simulated increase in SOC contents at the end of the experiments (average duration 25 yr). Increase in SOC due to straw incorporation in soil is expressed as a fraction of added *C* with straw. Each point is the mean of the last two dates and treatments N^+ and N^- (when they exist). The simulated values were obtained with AMG1 model.

Table 5
Scenario analysis: simulated decrease in SOC (expressed in % of initial SOC content) due to systematic straw C export during 50 yr according to the model version (defined in Table 4)

Site	C export ($Mg\,ha^{-1}\,yr^{-1}$)	Reduction in SOC after 50 yr % of initial SOC		
		AMG1	AMG2	AMG3
U	0.58	9.7	10.1	9.8
A	0.64	2.6	3.3	3.1
I	0.53	6.1	7.3	7.5
G	0.76	6.5	9.0	9.6
B	0.84	8.1	10.7	10.9
S	0.67	4.6	7.3	7.9
D	0.70	4.0	6.2	6.7
K	0.49	2.5	4.4	5.8
A2	0.41	4.0	5.0	4.6
Mean	0.62	5.3	7.0	7.3

Kaen to 19.1% at Ultuna (Fig. 5). The efficiency of straw incorporation into SOC is much greater under cold than warm climates. The annual rate of variation expressed in % of initial SOC content varied much less between sites: from 0.53% to 0.90% yr^{-1}. If we recall that the observed SOC variations have a rather large uncertainty because they are obtained by difference, we can consider that AMG model could reproduce adequately the observed variations in SOC contents, except at Askov where it simulated lower changes than observed and Issoudun where it exaggerated the variations (Fig. 5).

In view of collecting straw for bioenergy purposes, we also simulated the possible impact of systematic but partial straw removal in nine experimental sites. We supposed that harvestable straw represents 60% of total straw production and that straw is collected one year out of two. The impact of this practice on SOC evolution is shown at Table 5. Straw removal would allow to collect an average of 0.62 $Mg\,C\,ha^{-1}\,yr^{-1}$. Compared to a scenario with systematic straw incorporation, it would reduce the average SOC content by 3.6% (AMG1) to 4.0% (AMG3) of the initial SOC after 20 yr and by 5.3% (AMG1) to 7.3% (AMG3) after 50 yr. The results obtained with the three model versions are almost similar after 20 yr but differ more after 50 yr simulation, particularly in warmer climates. However, the relative variations in SOC contents are mainly site specific and depend on soil and climatic conditions.

4. Discussion

4.1. Partitioning carbon between the stable and the active pools

The SOC models described in the literature differ widely in the size of the stable pool. No stable pool (either completely inert or having a turnover time greater than 1000 yr) is considered in models such as ICBM and SOCRATES (Andrén and Kätterer, 1997; Grace et al., 2005) or in Bayer et al. (2006). The stable pool varies from 7–10% in ROTHC (Coleman and Jenkinson, 1996) to 40–60% in CENTURY (Parton et al., 1987) and 50–80% in DAISY (Hansen et al., 1991; Bruun et al., 2003). Falloon and Smith (2000) pointed out the importance of defining the size of this 'refractory' pool (RSOM) in model predictions. They reviewed radiocarbon dating and hydrolysis experiments which indicated that a significant proportion of SOC (15–60%) had a mean age greater than 1000 yr. Recent chemical or physical methods have been proposed recently to characterize the size of the stable pool (Helfrich et al., 2007; Zimmermann et al., 2007).

Using CN-SIM model and fitting techniques similar to ours, Petersen et al. (2005) concluded that the RSOM pool might constitute any amount between approx. 10% and 50% of total soil C, so that modeling cannot be used as a tool to obtain narrow estimates for this pool. Our work confirms this conclusion, although the optimum values found with our model seem to lie rather between 40% and 65%. Other studies also conclude to similar values. Huggins et al. (1998) simulated the long-term experiments of Sanborn Field and Morrow plots, varying in C inputs. Using a simple model and assuming that the SOC in the soil without C input only consisted in stable carbon, they calculated that the RSOM pool varied between 45% and 100% of SOC when the C input varied from 7 to 0 $Mg\,C\,ha^{-1}\,yr^{-1}$. The RSOM pool represented 65% of SOC in the mean C input treatment (3 $Mg\,C\,ha^{-1}\,yr^{-1}$) which is close to most experiments reported in this work.

Ludwig et al. (2003) used ROTHC model to simulate the evolution of total SOC and SOC derived from maize (using ^{13}C tracing) in a 39 yr experiment in Germany. They found that the accumulation of SOC derived from maize was strongly overestimated by the standard model (IOM = 8% SOC), but could be predicted if the inert pool was set at 53–64% of total SOC. Combining ^{13}C tracing, acid hydrolysis and extended incubation, Collins et al. (2000) calculated that the RSOM pool of surface layers should represent 39–51% of SOC. Paul et al. (2006) used long-term incubation on a wide range of soils and estimated the size of RSOM between 30% and 50% of total SOC. In fact, the proportion of stable to total SOC should vary according to the cropping or land use history. Huggins et al. (1998) showed that the fraction of stable C was smaller in the native grassland. A possible method to evaluate the stable pool consists in running simulations long before the initiation of the experiment, but it assumes steady state and requires a good knowledge of previous land use and cropping practices which may not be available (as here).

4.2. Estimation of carbon input to soil

The determination of carbon input by roots and rhizodeposition (root turnover, exudates and secretions) is associated with large uncertainties because this input is not easily measurable. Using our parameters, the calculated mass of BGC corresponds to 38–46% of straw-C mass (S). In ROTHC model, this ratio was estimated at 95% (Yang et al., 2003) or 110% (Diels et al., 2004) but these high values were obtained from model optimization and not measurements. In DAISY model, a fixed value is assigned to the BGC mass, a constant input of 870 or 435 kg C ha^{-1} was considered for cereal crops after harvesting under fertilized and unfertilized treatments, respectively (Bruun et al., 2003), which yields a BGC:S ratio of 27%. This ratio is assumed to be 53% in ICBM model (Andrén and Kätterer, 1997), and 33–38% in CENTURY model for two different wheat varieties (Parton and Rasmussen, 1994).

Different authors found that the quantity of root biomass measured at maturity (R) varies among species (Welbank et al., 1974; Gregory et al., 1978; Buyanovsky and Wagner, 1986; Paustian et al., 1992; Bolinder et al., 1997) and even between cultivars (Xu and Juma, 1992; Bolinder et al., 1997). Other factors such as fertilization and climate can contribute also to this variability. Reports of S:R ratio measured in cereals vary very widely, from 1.1 to 11. Some of this variation may be explained by the sampling method, the soil depth considered and the root separation methods. The S:R ratio used in this work lie between 2.2 and 2.6. These values are similar to those obtained experimentally by Gregory et al. (1978), higher than those reported by Buyanovsky and Wagner (1986) and lower than by Welbank et al. (1974), Paustian et al. (1992) or Bolinder et al. (1997).

The most integrative approach (accounting for root turnover) consists in characterizing carbon fluxes in the rhizosphere using ^{14}C or ^{13}C tracing under field conditions. Using ^{14}C–CO_2 pulse labeling, Jensen (1993) found a value of BGC:S ratio of 53% for barley, whereas Swinnen et al. (1995) obtained 31% for wheat. Balesdent et al. (1996) used the natural difference in ^{13}C/^{12}C between maize (C4 plant) and existing SOC, derived from previous C3 vegetation, in order to trace carbon in roots. They calculated a BGC:S ratio equal to 44%. Our estimates (38–46%) are in good agreement with these values.

4.3. Humification coefficient

There is a general agreement to say that humification coefficient, i.e. the fraction of exogenous carbon not respired during the initial decomposition phase and transformed into stable carbon, is strongly dependent on the nature of organic residues (e.g. Kätterer and Andrén, 2001). However, its dependence on other factors, particularly soil texture, is described very differently in the various simulation models (see Fig. 2b). In this work, we assumed dependence between humification coefficient and soil clay content and tested its impact on the quality of fit obtained in nine experiments. We found that the best fit was obtained by assuming that the humification coefficient was not affected by the soil clay content. In the present case of cereal straw, the humification coefficient corresponding to the standard value of C_S/C_0 (65%) lies between 0.21 and 0.23. This value is quite comparable to the humification coefficient which can be calculated in STICS model (Nicolardot et al., 2001) as the product $H \cdot Y$, where H is the microbial humification coefficient and Y is the microbial assimilation yield (see Fig. 1 in Nicolardot et al., 2001). Since the H parameter is 0.36–0.38 for crop residues with a high C/N ratio such as straw and Y is set at 0.62, the equivalent humification coefficient is equal to 0.22–0.24. This value is only slightly higher than the default value in AMG.

The hypothesis of independence between humification coefficient and soil texture is confirmed by several incubation studies showing that the kinetics of CO_2 evolved from the decomposing residue is hardly affected by clay content. Sorensen (1975) found that the rate of decomposition of ^{14}C-labeled cellulose was nearly similar in soils differing in clay content. He concluded that the clay (and silt) fraction ensures stabilization of amino acid metabolites produced during the period of intense biological activity that follows the addition of energy rich material to soil. Sorensen et al. (1996) found very little differences in C mineralization kinetics and biomass formed during decomposition of subclover in two soils with a very contrasting texture (Northfield 48%, Avon 10% clay) during a 40-day incubation. Ladd et al. (1981) observed that the net rates of decomposition of labeled Medicago residues in the field did not differ significantly between soils during most of the decomposition. The absence of variation of the humification coefficient with the soil type is confirmed by several other studies with Scott et al. (1996), Sharkov and Iodko (1997), Nicolardot et al. (2001) and Bertrand et al. (2006) have shown in incubation studies that the mineralization kinetics of plant residues is almost independent of soil texture. Abaye and Brookes (2006) studied the decomposition of three plant litter in three differently managed soils on the short term and found that the mineralized C was mainly influenced by substrate type and less by soil management or size of the original biomass.

4.4. Mineralization rate

All models consider that mineralization rate is affected by temperature, moisture and clay content. We focused here mainly on temperature and clay content effects because water effects have a smaller magnitude and are more difficult to simulate with simple models. Concerning the clay effect, results show that best simulations were obtained when the dependence between clay content and mineralization rate was considered in models. This is consistent with literature data. Sorensen (1981) studying cellulose decomposition found that the retention of labeled C in the soils was related to the clay content: it was about twice as large in the soil with the highest clay content compared to the sandy soil. Wattel-Koekkoek et al. (2003) found by ^{14}C dating experiments that the clay mineralogy was the most important factor explaining variance in the MRT of organic matter. Diels et al. (2004) simulated the evolution of SOC in subhumid tropical conditions using ROTHC and found that they had to double the decomposition rate constants to simulate SOC contents and their δ^{13}C composition. The soil of this study had a lower clay content than the soils used for model calibration. One hypothesis given by the authors was that the model did not account sufficiently for the low protection of organic matter due to the low clay content and 1:1 clay minerals. Hassink (1994) and Strong et al. (1999) found that the proportion of N mineralized during incubation in continuously moist soils was negatively correlated with the content of fine fractions (either clay or clay + silt). Bechtold and Naiman (2006) conducted long-term incubation studies and obtained a similar relationship to ours concerning nitrogen mineralization vs. clay or clay + silt content. This negative relationship could be simulated by the 'continuous quality' theory developed by Bosatta and Agren (1997).

5. Conclusions

In spite of its simplicity, AMG model adequately simulated the evolution of SOC in nine long-term experiments. Good predictions can be obtained by such simple model whose outputs are easier to analyze and which requires fewer inputs than models simulating C on a daily time step. The comparison of environmental functions (humification and mineralization rates dependence on clay and temperature) of AMG model to those proposed in other current SOM simulation models did not reveal any alternatives providing a better prediction than the AMG model. This allowed us to use the model for predicting the consequences of straw management on long-term evolution of SOC and defining strategies at farm level. Further improvements should consist in proposing methods to evaluate the size of RSOM fraction, in reference to ^{14}C dating techniques, and evaluate the inert fractions (black carbon), particularly in soils which had experienced significant straw burning.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at 10.1016:/j.soilbio.2007.08.022.

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