

## Parameterisation of the NCSOIL model to simulate C and N short-term mineralisation of exogenous organic matter in different soils



P.E. Noirot-Cosson, K. Dhaouadi, V. Etievant, E. Vaudour, S. Houot\*

UMR ECOSYS, INRA, AgroParisTech, Université Paris-Saclay, 78850 Thiverval-Grignon, France

### ARTICLE INFO

#### Article history:

Received 23 June 2016

Received in revised form

16 October 2016

Accepted 19 October 2016

Available online 31 October 2016

#### Keywords:

Exogenous organic matter

Compost

NCSOIL

C and N mineralisation

Lab incubation

Biochemical fractionation

Parameterisation

### ABSTRACT

The recycling of exogenous organic matter (EOM) through agriculture is an efficient way to enhance soil organic matter (SOM) and to supply crops with readily available nutrients. It can also cause environmental damage, such as nitrate leaching. Characterisation of EOM to predict the C and N dynamics of mineralisation when applied to cropped soils is essential to improve its use in agriculture. The measurement of C and N mineralisation through soil laboratory incubation of 18 types of EOM and EOM biochemical fractionation were used to parameterise the NCSOIL model to simulate the mineralisation kinetics of C and N. The soil type did not significantly interfere with EOM mineralisation and parameterisation, enabling extrapolation of the parameters for one soil to other soil types. Four groups of EOM were distinguished based on their C and N dynamics: (1) stable compost, (2) more reactive compost and stable manure, (3) manure and (4) very reactive EOM as sludge and litter that should be used as fertiliser. The use of easily accessible indicators, such as  $I_{ROC}$  (Lashermes et al., 2009) and the measured organic C:N ratio ( $CN_{EOM}$ ), was appropriate for parameterising groups 1 and 4. Regression relating the optimised resistant pool size and Van Soest fractions and  $CN_{EOM}$  was found ( $R^2$  of 0.967) to improve the pool sizes for the remaining EOM. Further research is required to improve the parameterisation.

© 2016 Published by Elsevier Ltd.

### 1. Introduction

The recycling of exogenous organic matter (EOM), i.e., organic matter that is not directly derived from crop residues, via agriculture has recently become a major interest in peri-urban areas that are sources of urban-waste-derived EOM. EOM provides a supply of nutrients for plants and enhances the soil organic matter (SOM) contents (Stratton et al., 1995; Marmo et al., 2004). The use of EOM becomes even more relevant in the context of increasing fertiliser prices and cropland soil organic carbon (SOC) depletion (Ciais et al., 2010). However, the progressive release of mineral nitrogen (N) to the soil after EOM application makes the assessment of N availability for crops more difficult and raises the environmental risk of excess mineral N leaching (Chalhoub et al., 2013). For optimal EOM use, the mineralisation behaviour of EOM in terms of the C and N dynamics requires further research (Parnaudeau and Générumont, 2014).

Studies conducted to predict EOM mineralisation behaviour

through biochemical characterisation of EOM (Pansu et al., 2003; Gabrielle et al., 2004; Morvan et al., 2006; Morvan and Nicolardot, 2009; Kaboré et al., 2011; Chalhoub et al., 2013) have attempted to relate the biochemical composition to simple models (Pansu et al., 2003; Kaboré et al., 2011). Biochemical indicators and models have improved the understanding of EOM behaviour in controlled laboratory conditions. The NCSOIL model simulates SOM dynamics through C and N flows between a series of pools, describing the addition of SOM and EOM (Molina et al., 1983; Nicolardot et al., 1994). This model has successfully simulated C and N soil dynamics in various soils under laboratory conditions (Nicolardot et al., 1994; Corbeels et al., 1999; Trinsoutrot et al., 2000; Antil et al., 2011). Moreover, the NCSOIL model has been coupled to the crop model CERES-EGC, enabling the simulation of EOM mineralisation under field conditions (Gabrielle et al., 2005).

Several authors have simulated the dynamics of EOM mineralisation using NCSOIL (Hadas and Portnoy, 1994; Beraud et al., 2005; Burger and Venterea, 2008; Morvan and Nicolardot, 2009; Antil et al., 2011). Various types of EOM have been considered, but few were simultaneously studied with contrasting soil types. Further research is required to develop a more generic description and parameterisation of EOM in NCSOIL. EOM is described within

\* Corresponding author.

E-mail address: [Sabine.Houot@grignon.inra.fr](mailto:Sabine.Houot@grignon.inra.fr) (S. Houot).

NCSOIL using several conceptual pools characterised by size, C to N ratio and rate of degradation. This parameterisation enabled good simulation of experimental results, but these parameters were poorly related to simple indicators or measurable fractions, such as biochemical fractions (Hadas and Molina, 1993). The existing indicators characterising EOM can be used, such as the  $I_{ROC}$ , which determines the potential residual fraction of OM remaining in the soil after EOM application (Lashermes et al., 2009). The  $I_{ROC}$  indicator has been used to predict the increase in soil organic C following repeated application of EOM using the RothC model (Peltre et al., 2012). The C:N ratio has also been used to predict the dynamic parameters and to simulate N mineralisation (Chadwick et al., 2000; Morvan et al., 2006), including in models simulating crop residue mineralisation (Nicolardot et al., 2001). The biochemical fractions determined through the Van Soest fractionation method (AFNOR, 2009a) have been used to simulate organic N mineralisation from EOM (Parnaudeau et al., 2004; Chalhouh et al., 2013). Thus, the integration of simple indicators or analytically accessible characteristics in models may provide a method to address the parameterisation challenge of simulation models. Similar research has been performed for other models (Pansu et al., 2003; Pansu and Thuriès, 2003). NCSOIL and CERES-EGC were parameterised and used to simulate the C and N dynamics in the long-term QualiAgro experiment, where EOM was regularly applied for 15 years (Noirod-Cosson et al., 2016). The NCSOIL model was parameterised for EOM based on the  $I_{ROC}$  and C:N ratio indicators.

This was the first step of a more general objective dedicated to the optimisation of EOM insertion in fertilisation practices at the regional scale. The region was the “Plain of Versailles”, a peri-urban region located 30 km west of Paris, France. In the present work, the C and N mineralisation rates of all EOM materials that could be found in this region were studied in the four dominant soils of the region. The objectives were (1) to evaluate the variation of EOM C and N mineralisation in the different soils, (2) to find generic NCSOIL parameterisation variables for the large panel of EOM based on their characteristics, and (3) to characterise EOM materials for their potential N availability for crops and their efficiency to increase SOM.

## 2. Materials and methods

### 2.1. Soils and EOM

#### 2.1.1. Soils

The “Plain of Versailles”, located 30 km west of Paris (Ile-de-France), has an area of 221 km<sup>2</sup> with 99 km<sup>2</sup> of cropped surfaces, mainly under arable crops. Four soil types representing the main cropping soils of the region were sampled in several replicates (Table 1). According to the World Reference Base for Soil Resources, the soil types corresponded to: (1) “Fontenay” (3 replicates); a

calcaric cambisol, (2) “Feucherolles” (3 replicates); an arenic cambisol, (3) “Grignon” (6 replicates); a haplic luvisol; and (4) “QualiAgro”, a haplic luvisol (retic) (11 replicates). The plough horizons were sampled in cropped plots, air-dried and 2 mm-sieved for further characterisation. All analyses were performed at the central analytical laboratory of INRA (LAS, Arras, France) and included: particle size distribution (g/kg) in coarse sand (200–2000  $\mu$ m), fine sand (50–200  $\mu$ m), coarse silt (20–50  $\mu$ m), fine silt (2–20  $\mu$ m), and clay (<2  $\mu$ m) (AFNOR, 2003), pH in water (AFNOR, 2005), carbonate contents (AFNOR, 2014), total organic C (TOC) and N by dry combustion using elemental analysis after the removal of carbonates by acidification (AFNOR, 1995). The C to N ratio was also calculated.

#### 2.1.2. Exogenous organic matter

The 18 EOM types available or potentially available in the region were collected and analysed (Table 2). They included EOM from urban activities: 2 green waste composts (GWb, GWa), a co-compost of home-sorted and separately collected biowaste mixed with green waste (BIO), a mixture of GW compost and bone meal (Fertylis), a co-compost of sewage sludge and GW (GWS), a dead leaf compost (Lc), a mulch (Mul), a municipal solid waste compost (MSW) and two sewage sludges, one dried (SSd) and one limed (SSI). They also included EOM derived from animal effluents: four horse manures, mixed with a high amount of straw (HMh), low amount of straw (Hml), wooden shavings (HMw) or composted (HMc); a cattle manure (CM); poultry litter, either dried (PL) or composted (PLc); and an imported dried pig slurry (Humival). BIO, MSW and GWS composts did not exist in the area. All municipal solid wastes are incinerated. Since composting could be an interesting treatment to increase the recycling of the organic fraction of urban waste, BIO and MSW composts were also considered, representing the 2 main composting processes for urban waste. Additionally, sludge composting is common in France, increasing the acceptability of this EOM but modifying the availability of nutrients compared to other sludge treatments. Thus, the GWS compost was studied together with dried and limed sludge (SSd and SSI).

Mineral N was extracted with 200 mL of 0.5 mol L<sup>-1</sup> KCl from 50 g fresh samples and was analysed by colorimetry on a continuous flow analyser (Skalar, The Netherlands). The EOM organic C and organic N contents ( $C_{EOM}$  and  $N_{EOM}$ ) were determined by elemental analysis of air-dried 200  $\mu$ m ground soil samples, and the corresponding organic C:N ratios ( $CN_{EOM}$ ) were then calculated for all EOM.

Total organic matter (OM) was measured based on mass loss after calcination at 550 °C (AFNOR, 2011). Total organic matter was fractionated into soluble (SOL) and hemicellulose- (HEM), cellulose- (CEL) and lignin-like (LIG) fractions according to their solubility in detergents using crude-fibre analysis derived from the Van Soest and Wine method (Van Soest and Wine, 1967), as described in the French standard XP U 44-162 (AFNOR, 2009a). The SOL fraction

**Table 1**

Characteristics of the four soils used (World Reference Base for Soil Resources). Particle size fractions: clay (<2  $\mu$ m), Fine Silt (2–20  $\mu$ m), Coarse Silt (20–50  $\mu$ m), Fine Sand (50–200  $\mu$ m), Coarse Sand (200–2000  $\mu$ m). TOC stands for Total Organic Carbon. Within a column, results and their standard deviation ( $\pm$ sd), followed by different letters are significantly different according to multiple comparison Bonferroni test.

Location	Soil type	Texture					Calcareous content g/kg	pH	TOC g/kg	C/N
		Clay	Fine silt	Coarse silt	Fine sand	Coarse sand				
		g/kg								
Fontenay	calcaric cambisol	357 <sup>a</sup> ± 8	178 <sup>a</sup> ± 39	196 <sup>a</sup> ± 47	216 <sup>a</sup> ± 72	48 <sup>a</sup> ± 11	73 <sup>a</sup> ± 112	8.1 <sup>a</sup> ± 0.2	19.7 <sup>a</sup> ± 2.6	11.1 <sup>a</sup> ± 0.2
Feucherolles	arenic cambisol	159 <sup>b</sup> ± 13	135 <sup>a</sup> ± 12	245 <sup>a</sup> ± 26	411 <sup>b</sup> ± 53	51 <sup>a</sup> ± 7	0.6 <sup>ab</sup> ± 1.0	7.1 <sup>b</sup> ± 0.4	14.8 <sup>ab</sup> ± 2.7	11.3 <sup>a</sup> ± 1.0
Grignon	haplic luvisol	321 <sup>a</sup> ± 32	233 <sup>b</sup> ± 24	342 <sup>b</sup> ± 26	79 <sup>c</sup> ± 21	23 <sup>c</sup> ± 17	25.3 <sup>ab</sup> ± 14	8.0 <sup>a</sup> ± 0.3	17.8 <sup>a</sup> ± 3.1	11.3 <sup>a</sup> ± 2.7
QualiAgro	haplic luvisol (retic)	154 <sup>b</sup> ± 9	272 <sup>c</sup> ± 6	497 <sup>c</sup> ± 9	65 <sup>c</sup> ± 9	11 <sup>c</sup> ± 1	1 <sup>b</sup> ± 0	6.7 <sup>b</sup> ± 0.3	10.5 <sup>b</sup> ± 1.5	10.1 <sup>a</sup> ± 0.5

**Table 2**  
Physico-chemical characteristics of EOM.  $C_{EOM}$ ,  $N_{EOM}$ ,  $N_{min}$  and  $CN_{EOM}$  stand for organic C content, organic N content, mineral N content and EOM organic CN ratio. Coefficients of variation (*CV expressed in %*) have been calculated based on 10 replicates analysed samples for Bio, GWS, MSW and CM, and 3 for the other EOM. Statistical analysis of these replicated samples are presented in Table 1S. SOL, HEM, CEL and LIG stand for Soluble, hemicellulose-, cellulose- and lignin-like EOM fractions.

EOM	$C_{EOM}$		$N_{EOM}$		$N_{min}$		$CN_{EOM}$		SOL	HEM	CEL	LIG	$C_{3d}$	$I_{ROC}$
	g/kg dry matter		g/kg dry matter		g/kg dry matter		g/kg dry matter		(% OM)				(% $C_{EOM}$ )	
Green Waste compost (GWA)	314.0	(1%)	13.6	(0%)	0.02	(42%)	23.1	(1%)	54.2	3.9	19.6	22.2	2.3	78.0
Green Waste compost (GWb)	187.8	(1%)	17.6	(3%)	0.55	(6%)	10.6	(2%)	51.5	4.9	11.5	31.2	1.9	85.9
Biowaste Compost (Bio)	68.6	(33%)	8.0	(30%)	0.45	(50%)	8.6	(7%)	49.2	8.8	12.9	29.1	1.3	84.0
Green waste and bone meals ("Fertylis")	250.9	(1%)	14.9	(7%)	0.01	(7%)	16.7	(6%)	78.0	3.5	6.2	12.5	2.5	85.3
Green Waste and Sludge compost (GWS)	265.6	(15%)	20.9	(11%)	2.46	(30%)	12.1	(18%)	45.4	7.2	21.9	25.6	6.7	74.8
Leaves composted (Lc)	174.7	(3%)	13.3	(1%)	0.25	(5%)	13.2	(2%)	61.9	1.0	7.6	29.6	1.6	90.9
Mulch (Mul)	454.7	(0%)	5.2	(19%)	0.19	(11%)	87.9	(20%)	61.3	7.6	22.7	8.5	2.3	71.2
Municipal Solid Waste compost (MSW)	308.0	(13%)	17.2	(12%)	0.09	(66%)	16.1	(21%)	47.6	6.6	23.3	22.5	18.1	63.8
Dried Sewage Sludge (SSd)	380.9	(0%)	69.1	(2%)	2.38	(4%)	5.6	(2%)	80.8	13.6	1.6	4.0	26.6	26.2
Limed Sewage Sludges (SSI)	263.0	(1%)	44.5	(0%)	0.14	(24%)	5.9	(1%)	92.7	5.5	0.8	1.0	27.5	28.1
Horse manure high straw content (HMh)	359.5	(1%)	15.8	(0%)	0.11	(5%)	22.8	(1%)	54.2	13.9	22.4	9.5	2.5	67.9
Horse Manure, low straw content (HMI)	251.3	(2%)	7.9	(13%)	0.06	(5%)	31.9	(14%)	43.9	47.2	1.9	7.0	5.4	58.7
Horse manure with wood shavings (HMw)	385.2	(0%)	13.1	(0%)	0.07	(5%)	29.3	(0%)	58.9	6.5	26.3	8.3	8.6	54.7
Horse manure composted (HMc)	178.7	(0%)	14.0	(0%)	0.62	(29%)	12.8	(0%)	59.8	6.1	12.6	21.5	2.2	81.9
Cattle manure (CM)	363.3	(19%)	19.4	(13%)	0.51	(74%)	18.7	(14%)	59.8	12.2	16.6	11.4	2.8	72.6
Dried Poultry Litter (PL)	315.3	(0%)	35.8	(4%)	2.16	(7%)	8.8	(1%)	62.2	21.5	14.4	1.9	34.8	0.0
Poultry litter composted (PLc)	175.3	(2%)	18.5	(24%)	1.14	(9%)	9.5	(21%)	57.8	12.0	18.9	11.3	10.3	53.9
Dried Pig Slurry ("Humival")	402.8	(0%)	52.1	(5%)	0.60	(5%)	7.8	(7%)	82.8	7.3	5.6	4.2	15.5	52.1

included both organic matter extractable in boiling water (100 °C) and hot neutral detergent (NDF fraction of the Van Soest extraction procedure). The  $I_{ROC}$  indicator, which reflects the proportion of EOM that may be retained in the soil for decades (Lashermes et al., 2009), was calculated based on the Van Soest fractions and the proportion of EOM-TOC mineralised after 3 days of laboratory incubation ( $C_{3d}$ ), as described in the French standard XP U 44-162 (AFNOR, 2009a):

$$I_{ROC} = 44.5 + 0.5 SOL - 0.2 CEL + 0.7 LIG - 2.3 C_{3d} \quad (1)$$

where *SOL*, *CEL* and *LIG* are expressed as % of OM and  $C_{3d}$  is expressed as % of  $C_{EOM}$ . The biochemical and chemical EOM characteristics are presented in Table 2. All analyses except the biochemical fractionation were realised in four replicates for most EOM types, in ten replicates for BIO, GWS, CM and MSW.

### 2.1.3. Incubation experiments

The potential mineralisation of soil organic C and N was assessed in the 4 representative soils during 91- to 175-day incubations under controlled conditions considered optimal for microbial activity (28 °C and gravimetric water content of 24–28%, corresponding to a water content of pF2.5, equivalent to field capacity). Fresh 4-mm-sieved soil samples (equivalent to 25 g of dry soil) were incubated in airtight 500 mL jars, with four replicates, for either organic C or N mineralisation measurements in separate parallel experiments. The C-CO<sub>2</sub> was trapped in 10 mL of NaOH (0.5 mol L<sup>-1</sup>), which was periodically sampled and replaced. The C-CO<sub>2</sub> trapped in NaOH was analysed by colorimetry on a continuous flow analyser (Skalar, The Netherlands). Opening the jar renewed the atmosphere and maintained aerobic conditions. On the same dates, the mineral N (N-NH<sub>4</sub><sup>+</sup> and N-NO<sub>3</sub><sup>-</sup>) was extracted with 100 mL of 0.5 mol L<sup>-1</sup> KCl and was then analysed by colorimetry on a continuous flow analyser (Skalar, The Netherlands). All jars incubated for N mineralisation were opened simultaneously with those used for C mineralisation to ensure aerobic conditions.

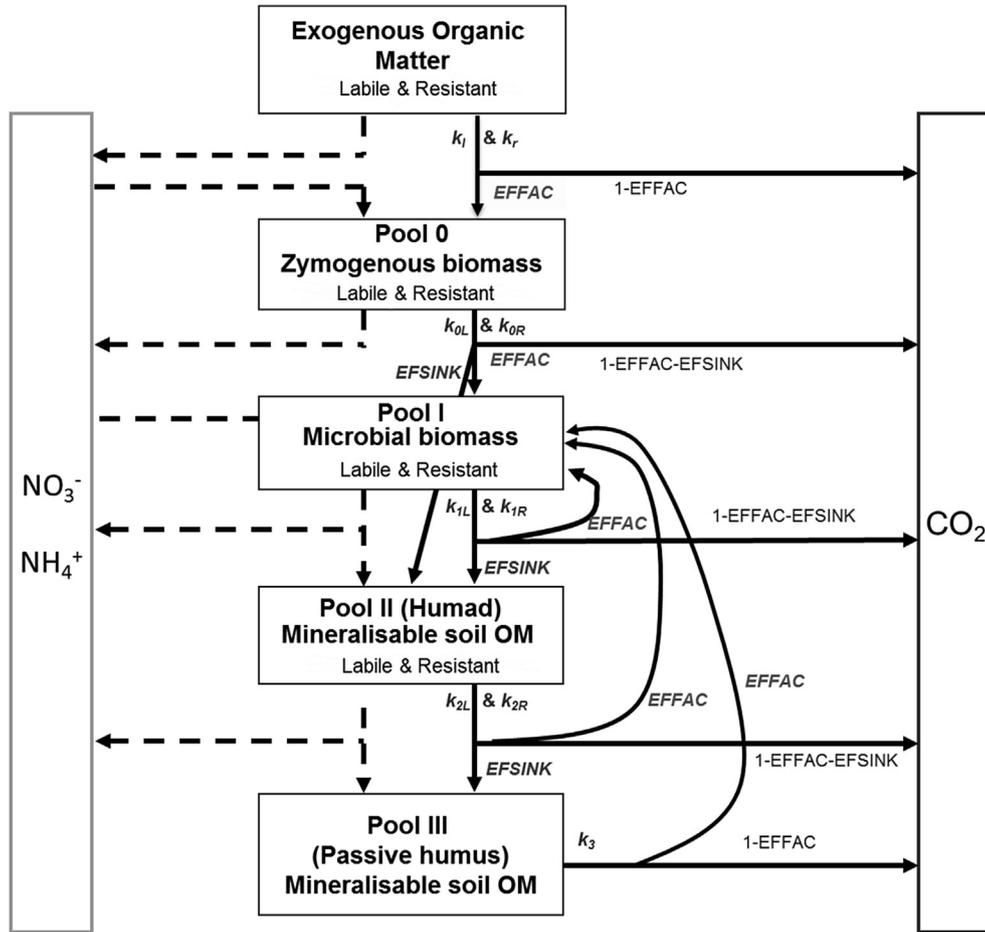
The kinetics of C and N mineralisation were also measured for all applied organic amendments during the 91- to 175-day incubations of the soil organic amendment mixtures, in four replicates, under similar controlled laboratory conditions following a standard method (AFNOR, 2009b). "QualiAgro" soil was prepared and used as previously described. The equivalent of 25 g of dry soil was

mixed with 0.5–1 g of EOM and placed in airtight 500 mL jars for C-CO<sub>2</sub> or mineral N measurements. Mineral N was added at the beginning of the incubation (to reach an initial content of 25 mg N-NO<sub>3</sub> kg<sup>-1</sup> soil) to prevent mineral N stress from affecting the EOM organic matter degradation. C-CO<sub>2</sub> was measured as previously described. Inorganic N was measured as for soil alone, but the extraction was performed with 200 mL of 1 mol L<sup>-1</sup> KCl with a soil/solution ratio of 1:5. Additionally, 4 EOM types (SSd, HMI, GWb and GWS) were incubated in the 4 soils for 91 days following the same procedure. The incubation data for the four soils were used to study the soil effect on EOM mineralisation, whereas the results of EOM incubated in the same soil were used to compare the EOM behaviour and model parameterisation.

## 2.2. Modelling

### 2.2.1. The NCSOIL model

The NCSOIL model (Molina et al., 1983; Barak et al., 1990; Hadas and Molina, 1993; Nicolardot et al., 1994) was used to simulate the C and N mineralisation of SOM during the lab experiment. Assuming a homogeneous soil and constant temperature and water content, NCSOIL simulates EOM decomposition after incorporation into soil, nitrification, immobilisation and mineralisation of N, along with SOM decomposition and formation using a system to control the rates and decisional switches amongst a series of pools (Haskett et al., 1986). The OM flow series were described by 4 SOM pools involved in N and C turnover (Fig. 1): (i) pool 0, termed the "zymogenous biomass", developed from the degraded EOM pool, (ii) pool I, representing the endogenous microbial biomass; (iii) pool II, a fraction of humified OM termed "mineralisable SOM"; and (iv) pool III, corresponding to highly humified OM with a very low decomposition rate. Each pool *i* was defined by its C content (or "pool size"),  $C_{p_i}$ , its C to N ratio,  $R_i = C_{p_i}/N_{p_i}$  (where  $N_{p_i}$  is the N content), its decomposition rate,  $k_i$ , and a microbial use efficiency factor (EFFAC), i.e., the fraction of decomposed C that is incorporated into the microbial biomass pool I or the zymogenous biomass pool 0 for EOM (Hadas et al., 2002), and a humification factor (EFSINK) i.e., the fraction of decomposed C that is incorporated into the following mineralisable soil pool (II or III). EOM and soil pools 0, I and II were divided into labile and resistant "fractions" with different degradation rates ( $k_l$  and  $k_r$ ) and C:N ratios ( $CN_l$  and  $CN_r$ ).



**Fig. 1.** Structure of the NCSOIL model,  $k_{ij}$  stands for decomposition rate of pool  $ij$  in days<sup>-1</sup>,  $i$  varying from 0 to 3 and  $j$  being either labile or resistant,  $EFFAC$  for the proportion of decomposed pool recycled in biomass pool,  $EFSINK$  for the proportion of the decomposed pool recycled in the following mineralisable soil organic pool.

The OM decomposes following first-order kinetics:

$$-(dC_i/dt) = k_i \times C_i \quad (2)$$

The N flows follow the C flows with respect to the C:N ratio of the pool being decomposed; inorganic N is added or withdrawn by the following pool to maintain its C:N ratio. The parameters are summarised in Table 3.

### 2.2.2. Model parameterisation

**2.2.2.1. “QualiAgro” soil parameterisation.** Only the “QualiAgro” soil was parameterised for NCSOIL simulations. The model was parameterised using a set of parameters from Molina et al. (1983), Nicolardot et al. (1994), Corbeels et al. (1999) and Hadas et al. (2004) (Table 3). The initial pool II size and C:N ratio were parameterised using the optimisation module of NCSOIL (Barak et al., 1990). This module adjusts the unknown parameters by fitting simulations against experimental data of C–CO<sub>2</sub> mineralisation and inorganic N accumulation during the incubation of control soils, using the Marquardt algorithm, which minimises the merit function:

$$\chi^2 = \sum_{i=1}^N \left[ \frac{(y_i - y(x_i, a))}{\sigma_i} \right]^2 \quad (3)$$

where  $i = 1, 2, \dots, N$  is the number of observations;  $y_i$  is the  $i$ th measured dependent variable;  $y(x_i, a)$  is the predicted value of a variable at time  $x_i$  based on the parameter values  $a$  being

optimised; and  $\sigma_i$  is the standard deviation of  $y_i$ .

### 2.2.2.2. EOM parameterisation

**2.2.2.2.1. EOM decomposition rates.** Fig. 2 summarises the successive steps used for the EOM parameterisation in the NCSOIL model. The C and N mineralisation kinetics of the 18 EOM types incubated with the “QualiAgro” soil were used.

First (Step 1 and 2 in Fig. 2), the decomposition rates of the labile and resistant pools of EOM ( $k_{EOM}$ :  $k_l$  and  $k_r$ ) were obtained by non-linear regression (NLR) of the experimental kinetics of C mineralisation, as described in Gabrielle et al. (2004). The NLR used a two-compartment, exponential C-decay model fitted against the CO<sub>2</sub> release data of the incubated soil-EOM mixtures, after subtracting the contribution of endogenous soil OM, assuming, as Mamo et al. (1999), that the mineralisation of endogenous SOM did not interfere with the application of EOM. This model can be written as:

$$C_{release} = C_l[1 - \exp(-k_l t)] + C_r k_r t \quad (4)$$

where  $C_{release}$  is in mg C kg<sup>-1</sup> dry soil,  $t$  is time (days);  $C_l$  and  $C_r$  are the sizes of the labile and resistant fractions, respectively (mg C kg<sup>-1</sup> dry soil); and  $k_l$  and  $k_r$  are the decomposition rates of the labile and resistant fractions, respectively (day<sup>-1</sup>).

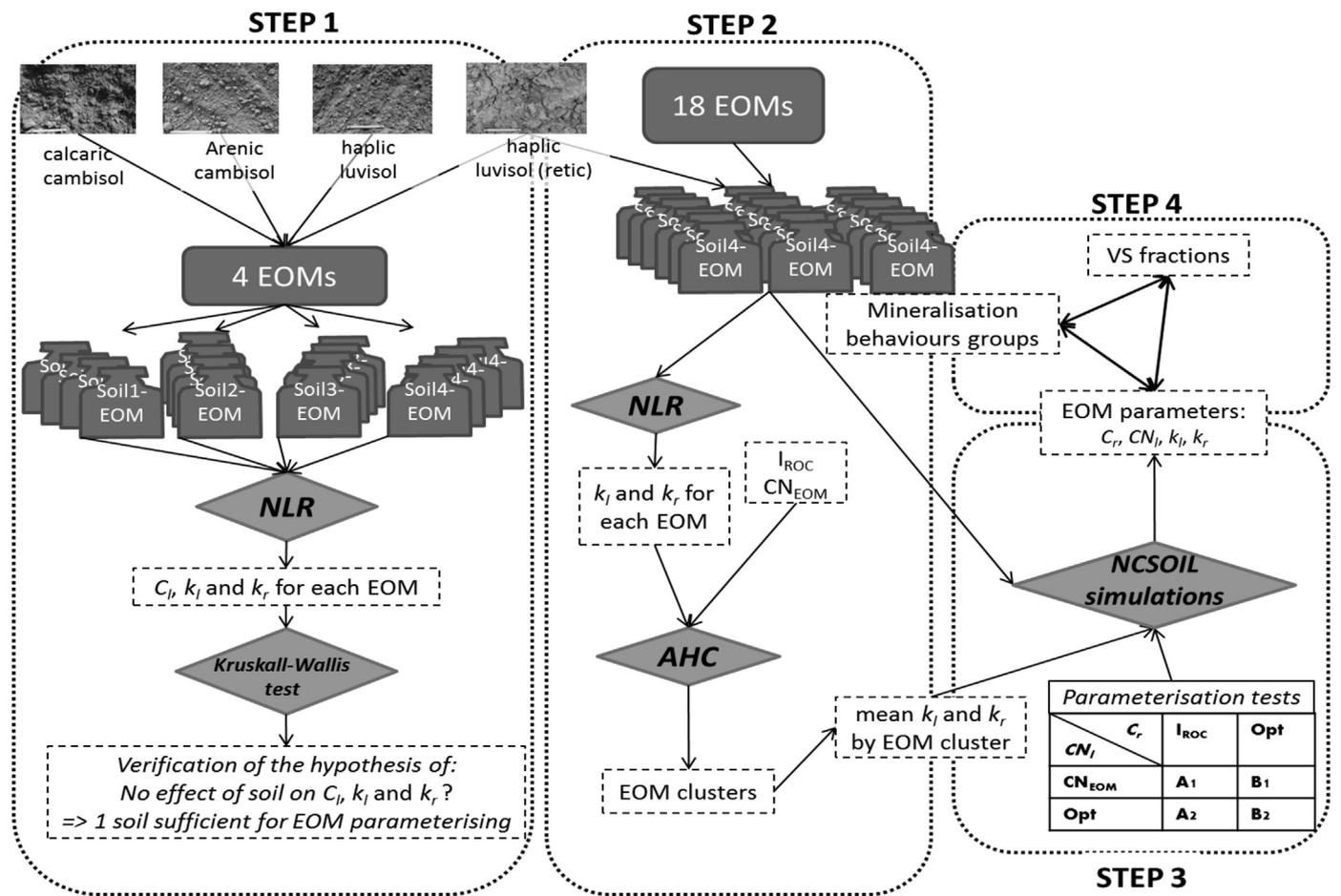
As  $C_r$  can be calculated from  $C_l$  as  $(C_i - C_l)$ , where  $C_i$  is the total EOM carbon content in mg C kg<sup>-1</sup> dry soil,  $C_l$ ,  $k_l$  and  $k_r$  are the only unknown parameters.  $C_r$  and  $C_l$  were expressed in % of  $C_i$ .

The NLR procedure fits all parameters simultaneously. When the

**Table 3**  
NCSOIL parameters for soil organic pools and exogenous organic matter (EOM): sources and setting methods.

NCSOIL pools	Pool 0 and I	Pool II	Pool III	EOM
Initial Size (mg C.kg <sup>-1</sup> soil)	$C_{P0} = 0$ $C_{P1} = 2.6\%$ of TOC <sup>2</sup>	Optimised	TOC- $C_{P11}$ - $C_{P1}$	$C_{EOM}$
Labile fraction (% total C of pool)	56 <sup>2</sup>	16 <sup>4</sup>	–	$C_l = 100 - C_r$
Resistant fraction (% total C of pool)	44 <sup>2</sup>	84 <sup>4</sup>	–	$C_r = I_{ROC}$ or optimised (see in text 2.4.3)
C decay rate constants (k in day <sup>-1</sup> )			0.000055 <sup>2</sup>	
Labile	0.332 <sup>1;2</sup>	0.16 <sup>1</sup>	–	$k_l = \text{Predicted}$ (see §3.2)
Resistant	0.0404 <sup>1;2</sup>	0.002 <sup>5</sup>	–	$k_r = \text{Predicted}$ (see §3.2)
Fraction of decomposed C recycled into following pool (see Fig. 1) (EFFAC)	0.6 <sup>1;2</sup>	0.4 <sup>1</sup>	0.25 <sup>1</sup>	0.6
Fraction of decomposed C incorporated into the following pool (see Fig. 1) (EFSINK)	0.2 <sup>1;2</sup>	0.2 <sup>1;2</sup>	–	–
C/N ratio	6.0 <sup>1;2</sup>	Optimised	$CN_{P111} = C_{P111}/[(TOC/CN_{TOC}) - (C_{P11}/CN_{P11})]$	$CN_{EOM}$
Labile	–	–	–	$CN_l = \text{Set as } CN_{EOM} \text{ or optimised}$
Resistant	–	–	–	$CN_r = C_r/(C_{EOM}/CN_{EOM} - C_l/CN_l)$

PI stands for pool I, PII for Pool II,  $r$  for EOM resistant pool and  $l$  for labile, TOC for Total Organic Carbon Content, EOM for total Exogenous Organic Carbon, C for pool size (mg C kg<sup>-1</sup> soil), CN for organic C/N ratio, k for C decay rate constant; <sup>1</sup>Corbeels et al. (1999), <sup>2</sup>Nicolardot et al. (1994), <sup>3</sup>Hadas et al. (2004), <sup>4</sup>Molina et al. (1983); <sup>5</sup>Noirot-Cosson et al., 2016.



**Fig. 2.** Overall approach used for model parameterisation.  $C_l, k_l, CN_l$  and  $C_r, k_r, CN_r$  stand for pool size, decomposition rate and organic C/N ratio of EOM labile and resistant pools respectively. NLR and AHC stand for Non-Linear Regression and Ascending Hierarchical Classification. Opt stands for optimised and VS for Van Soest.

first part of the curve was not well fitted, it tended to be offset by the fitting of the second part, resulting in strong biases in slopes i.e.,  $k_r$  estimates. However, the latter slope was more sensitive to fitting bias as it was generally 100 times lower than the slope of the first part. Therefore, a new  $k_r$  was calculated by directly using the slope of the second phase between day 49 and the last incubation day.

Both  $k_l$  and  $k_r$  were multiplied by 1.5 because NLR does not consider microbial recycling in the NCSOIL model (Gabrielle et al., 2004).

The decomposition rates ( $k_l$  and  $k_r$ ) were then grouped (Step 2 in Fig. 2) using ascending hierarchical classification (AHC) with the Ward's method (Ward, 1963) based on 3 discriminative characteristics:  $k_r, I_{ROC}$ , and  $CN_{EOM}$  or  $k_r, I_{ROC}$ , and  $CN_{EOM}$ . Clustering was

performed avoiding isolated EOM. Within each cluster,  $k_l$  and  $k_r$  were averaged and assigned to all EOM types in the cluster for the NCSOIL simulations.

**2.2.2.2. EOM pool sizes.** We tested two methods to parameterise the fraction sizes for NCSOIL: method A used the  $I_{ROC}$  indicator to define the size of the resistant pool and method B optimised the fraction sizes using the optimisation module (Step 3 in Fig. 2).

**2.2.2.3. EOM pool C:N ratios.** We also tested two methods of parameterisation: in method-1, both pools used the measured  $CN_{EOM}$  as the C:N ratio, whereas in the method-2, we optimised  $CN_l$  and recalculated  $CN_r$ .

We tested all method combinations (A; B) × (1; 2), resulting in 4 parameterisation tests for each EOM.

**2.2.2.3. Parameterisation evaluation.** To evaluate the goodness of fit of the simulation to the measurements, we first visually compared the simulated with the experimental kinetics. To evaluate the appropriateness of the use of  $I_{ROC}$  and  $CN_{EOM}$ , we evaluated the difference between  $I_{ROC}$  and the optimised  $C_r$  and between  $CN_{EOM}$  and the optimised  $CN_l$  or recalculated  $CN_r$ .

### 2.2.3. Statistical evaluation of the soil effect on EOM mineralisation

The influence of soil characteristics on the parameters of the EOM mineralisation kinetics was assessed through statistical comparison of the NLR results of the C-CO<sub>2</sub> kinetics of C mineralisation for the 4 EOM types incubated in the 4 soils (Step 1 in Fig. 2). The parameters were subjected to a Kruskal-Wallis test at  $P < 0.05$  to determine the significance of effects and differences related to soils or EOM. Statistical analyses were performed using XLSTAT 2014 software.

### 2.2.4. Factor analysis: relation between EOM parameters and characteristics

Factorial analyses were performed using XLSTAT 2014 software to determine the relations between the EOM characteristics, NCSOIL parameters and EOM groups of similar mineralisation behaviour (Step 4 in Fig. 2). The Pearson correlation between the VS fractions (LIG, CEL, HEM, SOL) and NCSOIL parameters ( $k_{EOM}$ ,  $I_{ROC}$ , optimised  $C_r$ ,  $CN_{EOM}$ ) was calculated.

## 3. Results

### 3.1. Variation of the C mineralisation kinetics of EOM with soil type

The effect of soil type on the dynamics of EOM C mineralisation was tested on 4 EOM types (GWb, GWS, HMh, SSd). The kinetics of C mineralisation (Fig. 1S) were fitted with the NLR model for these 4 EOM types, and the effect of soil on the parameters of the NLR equations was statistically tested (Table 4). Soil type was not significant ( $P$ -values  $> 0.05$ ). In contrast, the EOM effect was significant ( $P$ -values  $< 0.05$ ).

These results indicated a lack of soil effect on the net EOM C mineralisation compared to the differences between EOM and therefore confirmed the relevance of studying EOM parameterisation based on incubations performed in only one type of soil.

### 3.2. EOM mineralisation behaviour

The kinetics of C and N mineralisation for all EOM incubated in “QualiAgro” soil are presented in Figs. 2S, 3S and 4S, 5S. Four groups of mineralisation behaviour were identified. Fig. 3 shows examples of the mineralisation kinetics for one EOM type from each group: HMc, MSW, HMh and SS1.

In the first group (e.g., HMc in Fig. 3), the C and N mineralisation

rates were very low, with 10% of  $C_{EOM}$  and  $-10$  to 10% of exogenous organic nitrogen (EON) mineralised after 91 days of incubation. This group of 6 EOM types included only composted EOM.

The second group of EOM (e.g., MSW) was characterised by higher C mineralisation rates (approximately 30% of  $C_{EOM}$ ) and low ( $-4\%$  of EON for CM) to high N immobilisation at day 7 ( $-51\%$  of EON for GWa). This group could be considered a transition group between the first and the third groups and included 2 composts and CM.

The third group was characterised by high C mineralisation rates (between 51 and 81%) and strong N immobilisation ( $-39$  to  $-151\%$ ). This third group included mulch and 3 horse manures. CM was the only manure excluded from this group.

The fourth group was characterised by high C (37–97%) and high N (12–48%) mineralisation rates. It included 5 EOM types: 2 sludges, 2 poultry litters and the dried pig slurry Humival.

### 3.3. Classification of EOM for $k_{EOM}$ parameterisation

The  $k_r$  parameter could not be determined for 5 EOM types because the mineralisation slopes were negative. They were therefore excluded from the classifications. Dendrogram trees for  $k_l$  and  $k_r$  are presented in Fig. 4a and b with the associated cluster characteristics in Fig. 5a and b.

For  $k_l$ , the height differences suggested a division of the EOM groups into 4 clusters (Fig. 4a). However, to avoid a cluster with only one EOM and because the clusters had similar  $k_l$ , we grouped three sub-clusters together in the  $k_l$ -S cluster, leading to a distinction of cluster  $k_l$ -U and cluster  $k_l$ -S for  $k_l$  attribution. Cluster  $k_l$ -U was characterised by low  $CN_{EOM}$  (average 7.0), low  $I_{ROC}$  (average 26.8) and high  $k_l$  (average 0.376). Cluster  $k_l$ -S was characterised by high  $CN_{EOM}$  (22.4), high  $I_{ROC}$  (73.1) and low  $k_l$  (0.114). Cluster  $k_l$ -S included all composts and manures, and cluster  $k_l$ -U included the sludges, non-composted litter and slurry (Humival).

For  $k_r$ , the height differences suggested 5 clusters (Fig. 4b). Again, to avoid a cluster with only one EOM and since HMI and Mul had both high  $CN_{EOM}$  and high  $k_r$ , they were grouped into cluster  $k_r$ -U with high  $CN_{EOM}$ , leading to 4 distinct clusters for  $k_r$ . Clusters  $k_r$ -Sr and  $k_r$ -Sl included all the composts and manures (except HMI) and were similar in terms of  $CN_{EOM}$  (average values of 17.6 and 17.1, respectively) but differed with respect to  $I_{ROC}$  (78.3 and 58.1%, respectively) and  $k_r$  ( $0.971E-3$  and  $1.59E-3$ , respectively). Cluster  $k_r$ -Un was characterised by high  $k_r$  ( $2.09E-3$ ), very low  $I_{ROC}$  (27%) and very low  $CN_{EOM}$  (5.8), while  $k_r$ -Uc presented the highest  $k_r$  ( $2.59E-3$ ), quite high  $I_{ROC}$  (46%) and very high  $CN_{EOM}$  (59.9).

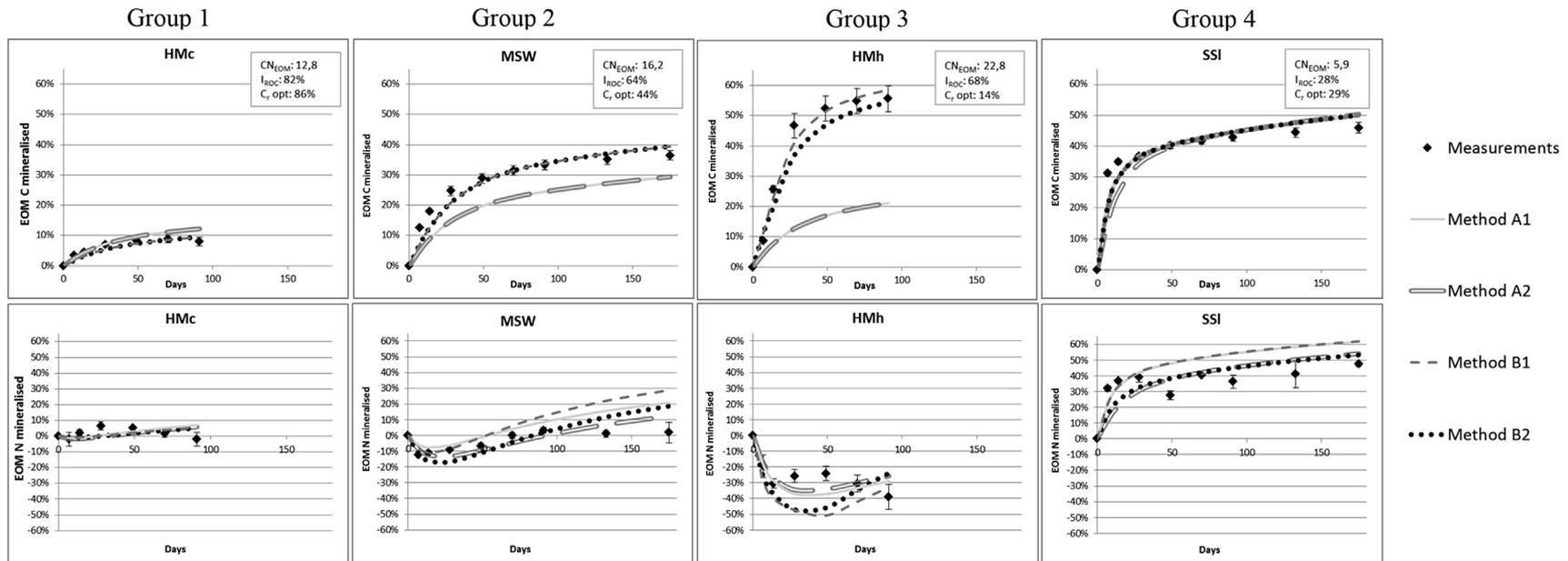
The cluster characteristics could be used to facilitate further  $k_{EOM}$  parameterisation. In our dataset, EOM types for which  $k_r$  could not be calculated were close to the  $k_r$ -Sr cluster based on their  $I_{ROC}$  and  $CN_{EOM}$ ; therefore, they were attributed the  $k_r$  value of this cluster.

### 3.4. Simulation of EOM mineralisation

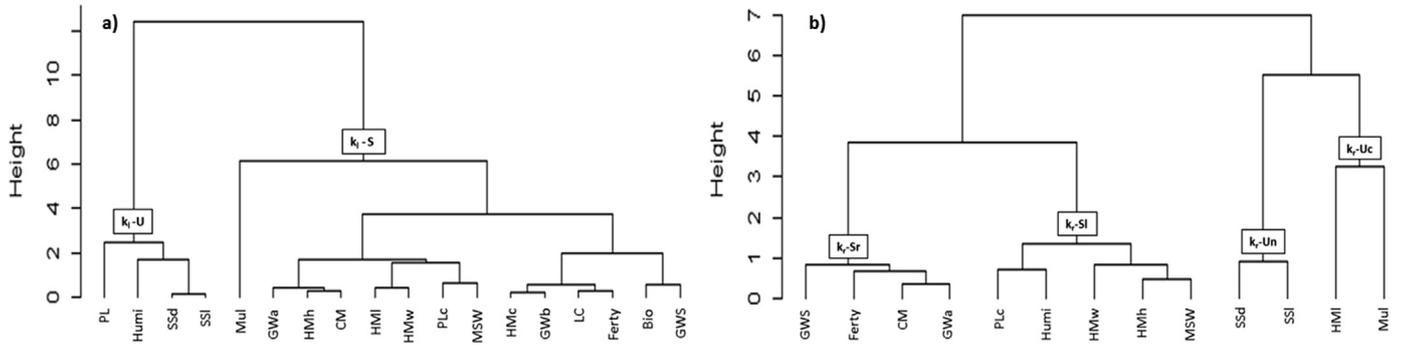
The simulated C and N mineralisation kinetics, for all EOM types and the 4 tested methods of parameterisation are presented in

**Table 4**  
Effects of soil and EOM type on the parameters of EOM C mineralisation ( $P$ -value of Kruskal Wallis test).

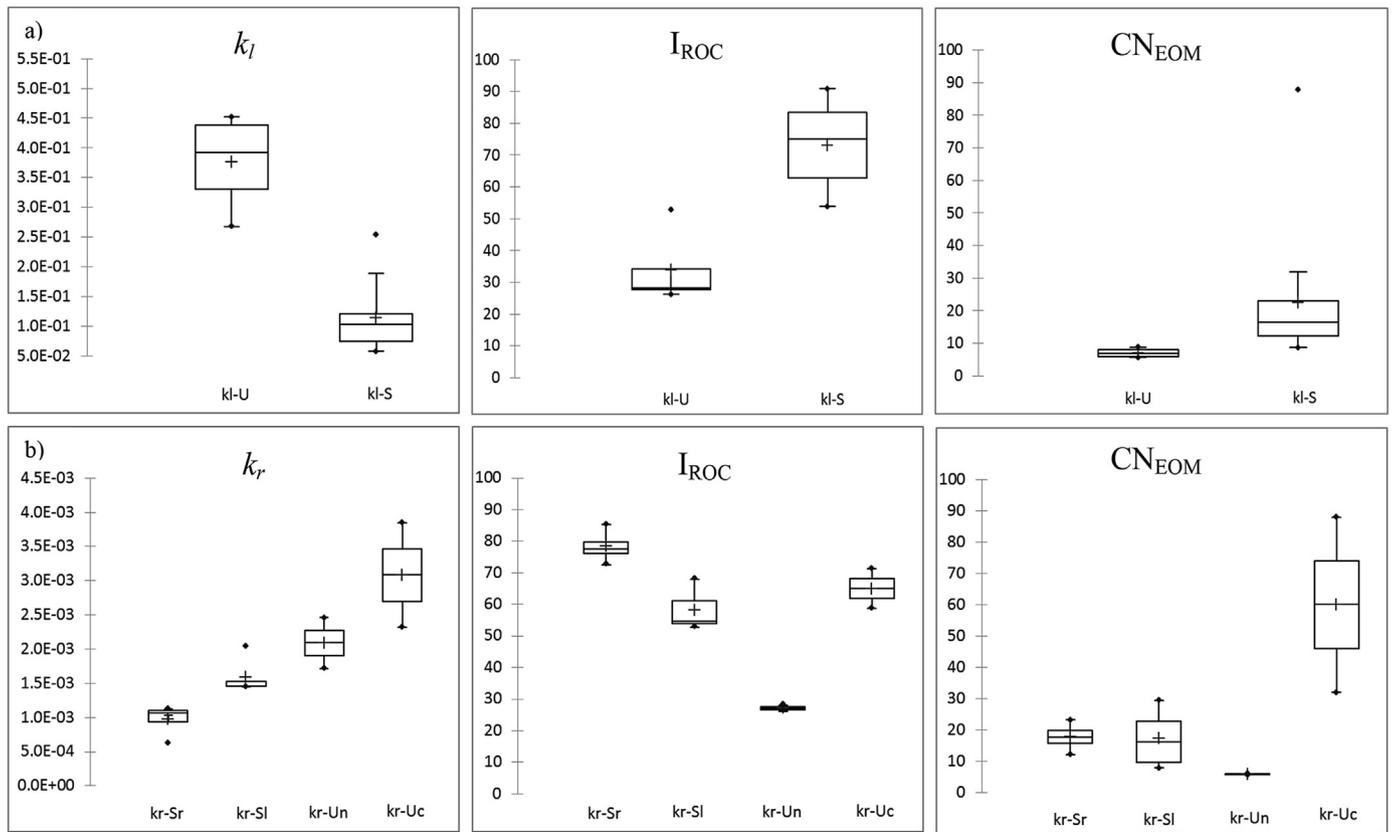
Parameters of EOM C mineralisation kinetics (equation (4))	EOM type	Soil type
$k_l$	0.006597	0.9778
$C_l$	0.004848	0.7924
$k_r$	0.01904	0.6785



**Fig. 3.** C and N kinetics of mineralisation for one EOM from each group; examples of group 1 (HMc, Horse Manure composted), group 2 (MSW, for Municipal Solid Waste compost), group 3 (HMh, Horse Manure with high amount of straw) and group 4 (SSI, for limed Sewage Sludge). Bar errors referred to standard deviations. All experimental results are presented in Figs. 2S, 3S and 4S, 5S. Methods A and B refer to resistant pool ( $C_r$ ) initial parameterisation with  $I_{ROC}$  or optimisation, respectively, and methods 1 and 2 refer to  $CN_i$  and  $CN_r$  parameterisation using  $CN_{EOM}$  for both pools or the optimisation of  $CN_i$ , respectively (see § 2.2.2.2).



**Fig. 4.** Dendrogram trees for  $k_l$  clustering (a), and  $k_r$  clustering (b). In clusters names, S stands for stable, U for Unstable, l for labile, r for resistant. EOM labels: Dried Sewage Sludge (SSd), Green Waste compost BYS (from Bio Yvelines Service) (GWb), Green Waste and Sludge compost 2009 (GWS), Horse Manure, low straw content (HMI), Municipal Solid Waste compost (MSW), Horse manure high straw content (HMh), Horse manure with wood shavings (HMw), Horse manure composted (HMc), Cattle manure (CM), Dried Poultry Litter (PL), Poultry litter composted (PLc), Leaves composted (Lc), Green Wastes Sep (from SEPUR) (GWa), Mulch (Mul), Biowastes Compost (Bio), Limed Sewage Sludges (SSI), Dried Pig Slurry (“Humival”), Green waste and bone meals (“Fertylis”).



**Fig. 5.** Characteristics of the EOM clusters for  $k_l$  parameterisation (a) and  $k_r$  parameterisation (b) in terms of  $k_{EOM}$  (days<sup>-1</sup>),  $I_{ROC}$  (% of  $C_{EOM}$ ) and  $CN_{EOM}$ . In cluster names, S stands for stable, U for Unstable, l for labile, r for resistant, n for rich in nitrogen and c for rich in carbon.

Fig. 1S, examples are presented in Fig. 3 and the results are summarised in Table 5.

For the EOM in the first group, C mineralisation was well simulated (Figs. 3 and 1S) regardless of the resistant pool size parameterisation method.  $\chi^2$  ranged between 0.04 and 0.32 (except for GWS method A). The resistant pool size estimated with  $I_{ROC}$  (method A) and the optimised value (method B1) differed little (<12% absolute difference) (Table 5). The N mineralisation dynamics were also well simulated. Optimising the C:N ratios decreased  $\chi^2$  by 0–47% and the optimised C:N ratios for the labile and resistant pools differed little from the simulations using  $CN_{EOM}$  for both pools.

For the EOM in the second and third groups, C mineralisation was always underestimated using method A. Using method B improved the C mineralisation simulations for all EOM types compared to method A; however,  $\chi^2$  increased for four EOM types out of seven due to the poorer N mineralisation simulations. The optimised resistant pool sizes were always smaller than  $I_{ROC}$  by at least 19% for CM up to 61% for mulch. Optimising the C:N ratios generally resulted in lower  $\chi^2$  values (changes of –82% to +7%). To better fit the N mineralisation measurements, the optimisation of  $CN_l$  resulted in a higher  $CN_l$  for the 2nd group: slightly for CM (from 13.6 to 14.1), with larger differences for MSW (from 16.2 to 21.6) and GWa (from 23.1 to 39.7). For group 3, the optimisation did not

**Table 5**  
EOM parameterisation NCSOIL tests results.

EOM	Group 1						Group 2			Group 3			Group 4					
	Bio	GWb	HMc	LC	GWS	Fertylis	CM	MSW	GWa	HMw	HMh	HMI	Mulch	SSd	SSI	PL	Humival	PLc
<b>Resistant pool size</b>																		
$I_{ROC}(A)$	84%	86%	82%	91%	75%	85%	73%	64%	78%	55%	68%	59%	71%	26%	28%	0%	52%	54%
$C_r$ optimised (B)	92%	87%	86%	84%	87%	79%	54%	44%	45%	21%	14%	0%	10%	17%	29%	0%	40%	13%
<b>Labile C/N ratio</b>																		
$CN_{EOM}(1)$	8.6	10.6	12.8	13.2	12.1	16.7	13.6	16.2	23.1	29.3	22.8	31.9	87.9	5.6	5.9	8.8	7.8	9.5
$CN_i$ optimised (A2)	11.9	20.9	13.7	30.7	17.4	18.3	13.1	21.6	2674.4	30.2	67.4	232.7	40.3	6.3	6.8	8.8	6	10.5
$CN_i$ optimised (B2)	9.6	21.7	13.1	21.7	16.2	17.9	14.1	20.3	39.7	NA	20.5	31.9	82.2	6.8	6.8	8.8	6.9	12.3
<b>Resistant C/N ratio</b>																		
$CN_{EOM}$	8.6	10.6	12.8	13.2	12.1	16.7	13.6	16.2	23.1	29.3	22.8	31.9	87.9	5.6	5.9	8.8	7.8	9.5
$CN_r$ calculated (A2)	8.2	9.8	12.6	12.5	11	16.5	13.8	14.2	18.1	28.6	17.3	19.9	168.3	4.3	4.3	8.8	10.9	8.8
$CN_r$ calculated (B2)	8.5	9.9	12.7	12.3	11.7	16.5	13.2	12.9	15.3	NA	74.7	31.9	104.2	3.2	4.3	8.8	10	3.8
$\chi^2$																		
A1	0.24	0.20	0.07	0.24	0.70	0.26	0.10	0.33		0.41	0.48	1.12	0.89	0.15	0.33	0.48	0.38	0.33
A2	0.13	0.15	0.07	0.11	0.39	0.23	0.11	0.17	0.96	0.44	0.48	0.68	0.62	0.10	0.30	0.48	0.12	0.32
B1	0.05	0.20	0.04	0.32	0.22	0.31	0.09	0.49	1.60	0.55	0.75	0.21	4.56	0.30	0.33	0.48	0.22	1.08
B2	0.05	0.15	0.04	0.12	0.15	0.32	0.09	0.22	0.30	NA	0.56	0.21	4.86	0.09	0.21	0.48	0.13	0.27

converge for HMw and was not performed for HMI since 100% of the carbon was in the labile pool. The value of  $CN_i$  decreased for HMh (from 22.8 to 20.5) and for mulch (from 87.9 to 82.2) without well-fitting the N mineralisation dynamics for the mulch. Additionally, the simulated N immobilisation was not sustained, and the simulations showed re-mineralisation at the end of the experiment. Therefore, the C:N ratios optimisation was inefficient for improving the simulations.

In the fourth group, C mineralisation was well simulated for the sludges and Humival regardless of the parameterisation method, with a slight underestimation for Humival using method A that was corrected by method B. The  $\chi^2$  values were lower than 0.38. However, method A resulted in a strong underestimation for PLc that was also corrected by method B, and for PL, both methods led to underestimation of mineralisation. The  $C_r$  optimised was equivalent to the  $I_{ROC}$  for SSI (28 and 29%) and lower for SSd, Humival and PLc (17, 40 and 13% rather than 26, 52 and 54%, respectively). The model did not accurately simulate the PL mineralisation dynamics because this EOM only contained a labile fraction with very high  $k_i$ . The C:N ratios optimisation improved the simulations of N mineralisation for the sludges and slightly changed  $CN_i$  from 5.6 and 5.9 to <6.8 for SSd and SSI, respectively, with the two methods A and B. For Humival, method B2 also slightly changed  $CN_i$  (from 7.8 to 6.9) but better simulations were obtained using method A2 with  $I_{ROC}$ , with  $CN_i$  changed to 6.0. For PLc, better simulations were obtained with B2, which implied consequent change in  $CN_i$  (from 9.5 to 12.3). The C:N ratios did not change for PL since 100% of the organic matter was in the labile pool for both methods A or B.

Finally, for the first group with composts, using  $I_{ROC}$  for the  $C_r$  size and  $CN_{EOM}$  for both pool C:N ratios was adequate for the parameterisation. For the second and third EOM groups, including the less stable compost and manures, optimisation was necessary to determine the resistant pool  $C_r$ . Total  $CN_{EOM}$  was acceptable for group 2, but for group 3, an increase in  $CN_i$  was needed to better represent the N dynamics. For group 4,  $I_{ROC}$  was adequate for sludges but underestimated  $C_r$  for PLc and slightly for Humival. Additionally, despite better simulations when optimising  $CN_i$ , the changes in the C:N ratios were small.

### 3.5. Relation between EOM groups, model parameters and chemical characteristics

The 4 groups of EOM were characterised by different chemical

characteristics (Fig. 6). Relationships between the EOM simulation parameters ( $I_{ROC}$ , optimised  $C_r$ ,  $CN_{EOM}$  and averaged  $k_i$  and  $k_r$  for each EOM cluster) and VS fractions were found (Table 6). The value of  $k_i$  was closely and positively related to SOL and slightly and negatively related to CEL and LIG.  $k_r$  was slightly related to HEM (positively) and LIG (negatively) (Table 6). The optimised  $C_r$  and  $I_{ROC}$  were positively related to LIG.  $CN_{EOM}$  was only weakly related to the VS fractions but positively related to CEL and HEM (Table 6).

The EOM groups based on mineralisation behaviour could also be distinguished based on the Van Soest fractions and simulation parameters (Fig. 6). Groups 1 and 2 had higher LIG fractions,  $I_{ROC}$  and Opt  $C_r$  than the other groups, particularly group 1. Groups 2 and 3 were characterised by higher CEL fractions, and group 3 by higher  $CN_{EOM}$ . Group 4 had higher SOL fractions and very low  $CN_{EOM}$ .

The EOM types that did not require optimisation of parameters to correctly simulate C and N mineralisation were the EOM types from group 1 and the 2 sludges from group 4-2 (Fig. 6).

The 9 EOM types that required a consequent  $C_r$  increase compared to their  $I_{ROC}$  (EOM types from group 2 and 3 and also group 4-1, i.e., Humival and PLc) corresponded to EOM types with  $CN_{EOM} > 20$  and  $I_{ROC}$  ranging from 50 to 73 (Fig. 6). They had high CEL and intermediate LIG fractions. These EOM types also required C:N ratios optimisation but were not enough to define any trends.

For these 9 EOM types, regression between the optimised  $C_r$  and the analytical characteristics, including the Van Soest fractions, were performed, as was done to elaborate the  $I_{ROC}$  indicator. CM was always an outlier and was removed to build the regression. The best regression was found with HEM, CEL, LIG and  $CN_{EOM}$ , with an  $R^2$  of 0.967,  $R^2$ -adj of 0.923 and a P-value for the Fischer test of 0.015.

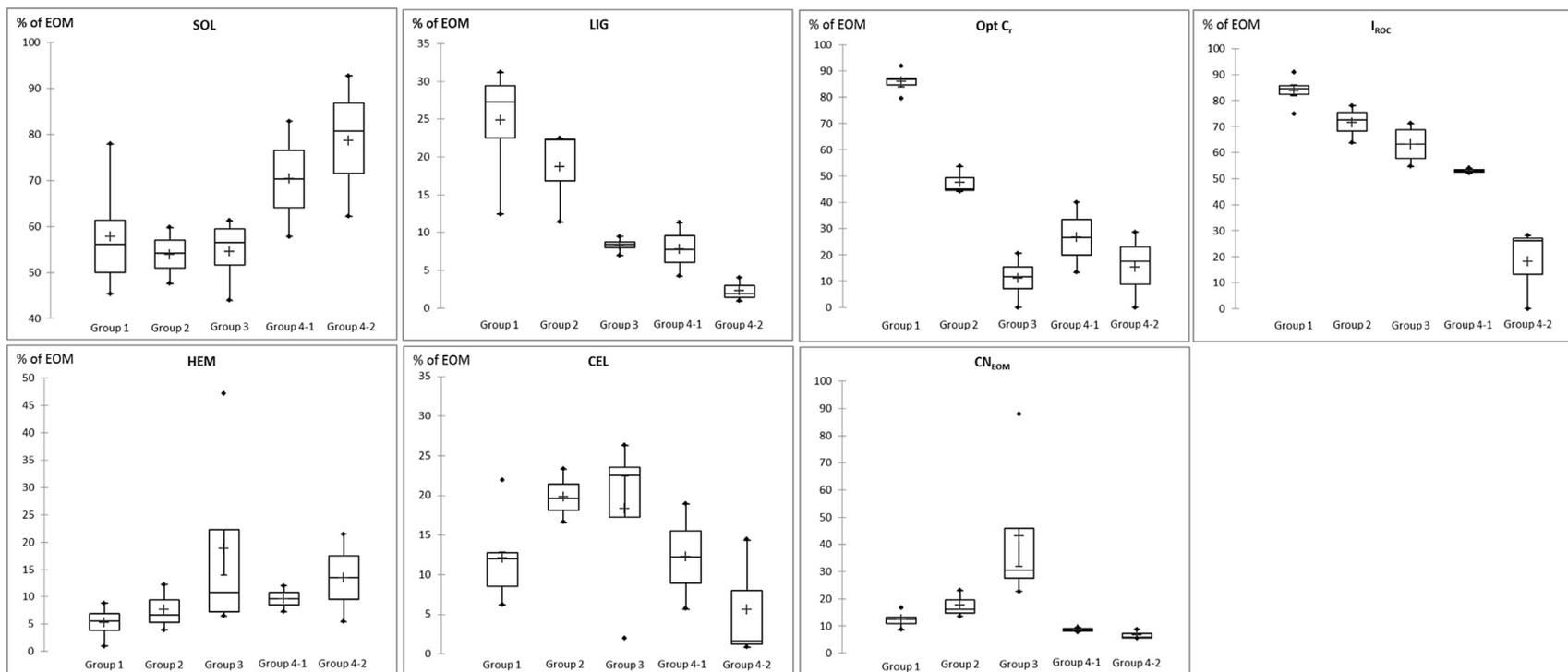
$$C_r = 49.514 - 1.8228 \times \text{HEM} - 2.0345 \times \text{CEL} + 1.2705 \times \text{LIG} + 1.00891 \times \text{CN}_{EOM} \quad (5)$$

where  $C_r$  is the resistant pool size (% of  $C_{EOM}$ ); HEM, CEL, and LIG are the Van Soest fractions (% OM); and  $CN_{EOM}$  is the organic C:N ratio of EOM.

## 4. Discussion

### 4.1. Parameterisation methods

In this study, the EOM parameterisation in the NCSOIL model



**Fig. 6.** Characterisation of EOM groups: SOL, HEM, CEL and LIG fractions from the VS fractionation and parameters of mineralisation kinetics: Optimised  $C_n$ ,  $I_{ROC}$  and  $CN_{EOM}$ . Groups 4-1 includes PLC and Humival, Group 4-2 SSd, SSI and PL.

**Table 6**  
Correlation matrix between EOM parameters and VS fractions.

Variables	I <sub>ROC</sub>	Opt C <sub>r</sub>	CN <sub>EOM</sub>	HEM	CEL	LIG	SOL	k <sub>l</sub>	k <sub>r</sub>
I <sub>ROC</sub>	1	0.714	0.184	-0.356	0.220	0.772	-0.435	-0.821	-0.535
Opt C <sub>r</sub>		1	-0.347	-0.546	-0.061	0.820	-0.158	-0.377	-0.809
CN <sub>EOM</sub>			1	0.102	0.379	-0.145	-0.198	-0.340	0.578
HEM				1	-0.261	-0.407	-0.295	0.077	0.632
CEL					1	0.240	-0.583	-0.538	-0.162
LIG						1	-0.577	-0.635	-0.664
SOL							1	0.736	0.113
k <sub>l</sub>								1	0.315
k <sub>r</sub>									1

was based on the experimental kinetics of C and N mineralisation.

We first found that the effect of soil on EOM mineralisation and parameterisation was not significant, allowing the use of parameters that depended only on the EOM type and not the soil with which the EOM was mixed. This result is in agreement with Coppens (2005), who found that soil type had little influence on the C decomposition of crop residue, and Lundquist et al. (1999), who found that crop residue decomposition was similar when incubating in differently managed soils. The results of Kaboré et al. (2011) also validate the initial TAO model used to simulate EOM C and N mineralisation with a different soil than used for calibration.

The parameterisation of  $k_{EOM}$ , and especially  $k_r$ , based on incubations was very sensitive to the data, and small error or variation in the experimental results resulted in poor parameterisation. We initially set  $k_r$  using the calculated slopes at the end of the incubations rather than the fitted NLR parameters considered using the complete experimental kinetics. However, we still faced issues due to experimental uncertainties, leading to negative slopes that could not be used as parameters. Thuriès et al. (2002) also found that the estimations of  $k_{EOM}$  were always less accurate than the estimations of the pool fraction size. Thus, the dataset of the EOM types and their characteristics were clustered, and the average  $k_{EOM}$  values were calculated for each cluster and attributed to each EOM in the cluster. This made possible to attribute the dynamic parameters to EOM without information about C and N mineralisation based on their characteristics, avoiding time-consuming incubations. Using the same NCSOIL model, Antil et al. (2011) determined the  $k_{EOM}$  values of the same order of magnitude for similar EOM types, between 0.031 and 0.461 day<sup>-1</sup> for  $k_l$  and between 5.2E-4 and 1.24E-3 day<sup>-1</sup> for  $k_r$ . (Beraud et al., 2005). found similar  $k_r$  (1.19E-4 and 1.42E-4 day<sup>-1</sup>) but lower  $k_l$  (approximately 0.024 day<sup>-1</sup>) for two composted EOM types.

The I<sub>ROC</sub> indicator represented the stable fraction of EOM, that was potentially incorporated into SOM and was calculated as the proportion of non-degraded EOC when the decomposition rate reached 0.02 y<sup>-1</sup> or 5E-5 d<sup>-1</sup> (Lashermes et al., 2009). In this study, this indicator was used to determine the proportion of C<sub>EOM</sub> in the resistant pool, where the decomposition rate varied from 0.971 to 3.085E-3 d<sup>-1</sup>. This was adequate for stable EOM types, such as composts (Noiro-Cosson et al., 2016), and very unstable types, such as sludge and litter. However, I<sub>ROC</sub> was not suitable to parameterise the C<sub>r</sub> fraction for 9 EOM types, and a new regression was obtained for these EOM types, except the CM outlier, based on the analytical results and biochemical fractions. Thuriès et al. (2002) also used the biochemical fractions to estimate C<sub>r</sub>. The organic C:N ratio (CN<sub>EOM</sub>) was used for the resistant and labile EOM fractions, even when N mineralisation was not well simulated, mostly because of a lack of experimental data for calculating different C:N ratios for both fractions. More EOM should be studied to develop a generic method of parameterisation.

In this study, a 2-compartment model was used to parameterise EOM for NCSOIL. Other models describe EOM based on more

fractions: 3 fractions in the TAO model (Thuriès et al., 2002) and 4 fractions in the CANTIS model (Garnier et al., 2003). However, this would require more parameters to be set, when the objective is to find a generic parameterisation.

Predicting EOM N fate based on experimental data or through classification or typology has previously been performed (Lashermes et al., 2010; Morvan et al., 2006), but doing it to parameterise a model is rare (Pansu et al., 2003). Finally, the following parameters should be used for further simulations with NCSOIL: the optimised carbon pool sizes, the total organic C:N ratio (CN<sub>EOM</sub>) for both EOM pools and the averaged  $k_{EOM}$  for each cluster (Table S2).

#### 4.2. General scheme for relating model parameters to measured values

The stable fraction size C<sub>r</sub> was positively related and  $k_r$  was negatively related with the LIG fraction, while  $k_l$  was positively related with the SOL fraction. LIG may be the most recalcitrant and SOL the most reactive fractions in the EOM. It is often considered that EOM with large SOL or LIG fractions behave as reactive or stable matter, respectively (Thuriès et al., 2002). However, the SOL fraction was not related with the size of the labile fraction of EOM, probably because this fraction is heterogeneous and its chemical composition changes during EOM treatment by composting (Peltre et al., 2010). The HEM fraction was positively related with  $k_r$ , corresponding to a more biodegradable resistant pool. The CEL fraction was negatively related with  $k_l$ , meaning that a high CEL fraction corresponded to EOM with a less biodegradable labile pool. The HEM and CEL fractions described the diversity of the intermediate EOM from groups 2 and 3. When the CEL fractions were similar, the large HEM fractions in group 3 were associated with low C<sub>r</sub>. Larger HEM fractions were associated with high CN<sub>EOM</sub> and explained the large N immobilisation observed for the EOM types in group 3. However, more EOM types need to be studied to better relate the biochemical fractions with parameter dynamics (Thuriès et al., 2002). Near infrared reflectance could also be used (Peltre et al., 2011; Kaboré et al., 2012) as a rapid and non-destructive method for characterising EOM.

#### 4.3. EOM types available in the "Plain of Versailles" region

Four groups of EOM were classified based on their C and N mineralisation kinetics. With a larger number of EOM, Morvan et al. (2006) distinguished 6 classes based on C and N mineralisation and described them based on their biochemical fractions. Our classes were in accordance with their results except for the need to subdivide the groups 2 and 4. Within each group, the EOM showed similar C and N mineralisation dynamics. However, all groups, with the exception of group 1, showed intra-group heterogeneity, even with our small set of 18 EOM.

These 4 groups could be distinguished when represented with

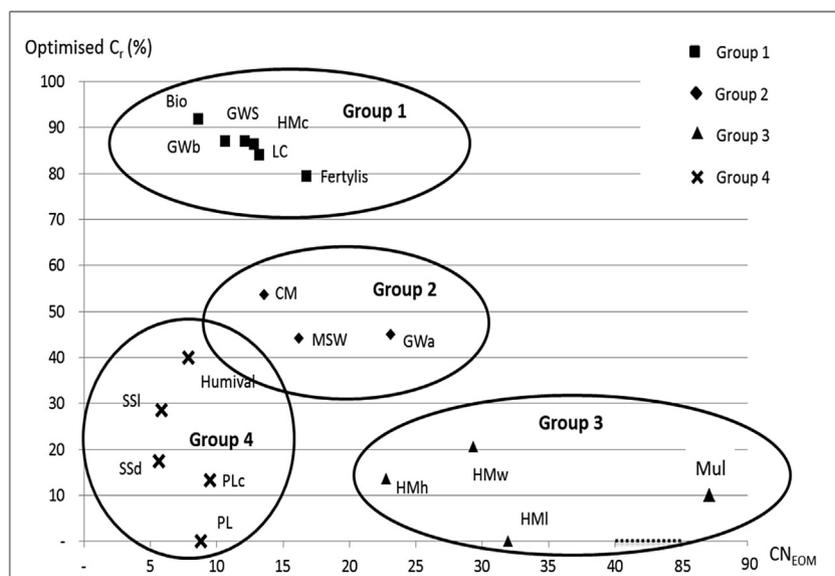


Fig. 7. Distribution of EOM groups based on their optimised resistant pool  $C_r$  and their  $C:N_{EOM}$ . EOM labels defined in Table 2.

their optimised  $C_r$  and  $C:N_{EOM}$  (Fig. 7). No other parameters could be added to further define the groups probably because they interacted in different ways.

All EOM types available or potentially available in the “Plain of Versailles” region have been studied, including (Fig. 7) highly decomposable N-rich EOM, leading to high availability of N (group 4); highly degradable EOM with a high  $C:N_{EOM}$  ratio, leading to strong N immobilisation (group 3); very stable compost EOM (group 1); and some intermediate EOM (group 2). Based on this group identification, EOM may be selectively placed within technical itineraries for crop production. For instance, group 4 should be used as a fertiliser because of the large amount of available N (and probably phosphorus and potassium), i.e., it should be applied immediately before large crop N demand occurs. Group 1, with very stable EOM, should be applied as an organic amendment to increase SOM stocks. The EOM in Group 3, despite their low ability to enhance SOM, might cause N immobilisation depleting crop production but if applied during a period corresponding to low crop N uptake; however they could be useful to prevent N leaching and be used as an amendment.

## 5. Conclusion

This study aimed to characterise the available EOM in the “Plain of Versailles”. Both the potential availability of N for crops and their potential use as organic amendment to increase SOM were studied in relation to their chemical and biochemical characteristics. The soil type did not affect the C and N mineralisation behaviour of EOM, and the same dynamic parameters could be used for all soils in the studied area.

Based on the potential C and N mineralisation kinetics, four groups of EOM were defined: (1) stable compost, (2) more reactive compost and stable manure, (3) manure, all useable for organic amendment and (4) reactive EOM as sludge, litter, useable as organic fertiliser. The groups were characterised by slow C and N mineralisation (group 1), high C mineralisation along with N immobilisation (group 3), intermediate C and N dynamics (group 2), and high C and N mineralisation (group 4).

The NCSOIL model was parameterised to simulate the kinetics of C and N mineralisation. In the model, EOM are divided into labile and resistant fractions characterised by their relative sizes, their decomposition rates and their C:N ratios. The use of easily

accessible indicators, such as the  $I_{ROC}$  indicator to characterise the resistant pool size and measured  $C:N_{EOM}$  to define the C:N ratio of both pools, was appropriate for groups 1 and 4. However, for some EOM types characterised by intermediate  $I_{ROC}$ , high C:N ratios and intermediate biochemical compositions, such as manure, both pool sizes and C:N ratios should be defined differently. Regression linking the resistant pool size retrieved by optimisation and the biochemical characteristics of 8 EOM types was significant and should be tested on additional EOM types.

Despite the remaining issues with model parameterisation, the NCSOIL model accurately simulated C and N mineralisation, allowing further study of the C and N dynamics under field conditions after EOM application using the crop model CERES-EGC, in which the NCSOIL model was integrated. All available EOM types on the “Plain of Versailles” were parameterised in NCSOIL. This parameterisation will be used to simulate scenarios where EOM is used in crop succession to evaluate the consequences in terms of C storage in soil and the potential substitution of mineral N fertilisation.

## Acknowledgements

This publication benefited from the financial and technical support of the French Environment and Energy Management Agency (ADEME) and the Ministry of Environment in the framework of the Prostock-Gessol3 project (grant 1060C0094) and the LabEX BASC of Campus Paris-Saclay in the framework of the SOC-SENSIT project. The field experiment QualiAgro was started in 1998 in cooperation with INRA-Véolia Environment Research and Innovation. The experimental C and N mineralisation data were obtained during ANR ISARD.

## Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.soilbio.2016.10.015>

## References

- AFNOR, 2014. NF EN ISO 10693. Qualité du sol - Détermination de la teneur en carbonate - Méthode volumétrique. AFNOR, Paris.
- AFNOR, 2011. NF EN ISO 13039. Amendements du sol et supports de culture -

- Détermination de la matière organique et des cendres. AFNOR, Paris.
- AFNOR, 2009a. Norme XP U 44–162. Amendements organiques et supports de culture - Caractérisation de la matière organique par fractionnement biochimique et estimation de sa stabilité biologique. AFNOR, Paris.
- AFNOR, 2009b. Norme XP U 44–163. Amendements organiques et supports de culture - Caractérisation de la matière organique par la minéralisation potentielle du carbone et de l'azote. AFNOR, Paris.
- AFNOR, 2005. NF ISO 10390. Qualité du sol - Détermination du pH. AFNOR, Paris.
- AFNOR, 2003. NF X 31–107. Qualité du sol - Détermination de la distribution granulométrique des particules du sol - Méthode à la pipette. AFNOR, Paris.
- AFNOR, 1995. Norme NF ISO 10694. Qualité du sol - Dosage du carbone organique et du carbone total après combustion sèche. Qualité des sols, vol. 1. AFNOR, Paris.
- Antil, R.S., Bar-Tal, A., Fine, P., Hadas, A., 2011. Predicting nitrogen and carbon mineralization of composted manure and sewage sludge in soil. *Compost Science & Utilization* 19, 33–43. <http://dx.doi.org/10.1080/1065657X.2011.10736974>.
- Barak, P., Molina, J.A.E., Hadas, A., Clapp, C.E., 1990. Optimization of an ecological model with the Marquardt algorithm. *Ecological Modelling* 51, 251–263. [http://dx.doi.org/10.1016/0304-3800\(90\)90069-5](http://dx.doi.org/10.1016/0304-3800(90)90069-5).
- Beraud, J., Fine, P., Yermiyahu, U., Keinan, M., Rosenberg, R., Hadas, A., Bar-Tal, A., 2005. Modeling carbon and nitrogen transformations for adjustment of compost application with nitrogen uptake by wheat. *Journal of Environment Quality* 34, 664. <http://dx.doi.org/10.2134/jeq2005.0664>.
- Burger, M., Venterea, R.T., 2008. Nitrogen immobilization and mineralization kinetics of cattle, hog, and Turkey manure applied to soil. *Soil Science Society of America Journal* 72, 1570. <http://dx.doi.org/10.2136/sssaj2007.0118>.
- Chadwick, D.R., John, F., Pain, B.F., Chambers, B.J., Williams, J., 2000. Plant uptake of nitrogen from the organic nitrogen fraction of animal manures: a laboratory experiment. *The Journal of Agricultural Science* 134, 159–168.
- Chalhoub, M., Garnier, P., Coquet, Y., Mary, B., Lafolie, F., Houot, S., 2013. Increased nitrogen availability in soil after repeated compost applications: use of the PASTIS model to separate short and long-term effects. *Soil Biology and Biochemistry* 65, 144–157. <http://dx.doi.org/10.1016/j.soilbio.2013.05.023>.
- Ciais, P., Wattenbach, M., Vuichard, N., Smith, P., Piao, S.L., Don, A., Luyssaert, S., Janssens, I.A., Bondeau, A., Dechow, R., Leip, A., Smith, P., Beer, C., Van Der Werf, G.R., Gervois, S., Van Oost, K., Tomelleri, E., Freibauer, A., Schulze, E.D., CarboEurope Synthesis Team, 2010. The European carbon balance. Part 2: croplands. *Global Change Biology* 16, 1409–1428. <http://dx.doi.org/10.1111/j.1365-2486.2009.02055.x>.
- Coppens, F., 2005. *Water, Carbon and Nitrogen Dynamics in Soil, Influence of Crop Residue Location and Quality*. Katholieke Universiteit, Leuven (Belgique).
- Corbeels, M., Hofman, G., Cleemput, O.V., 1999. Simulation of net N immobilisation and mineralisation in substrate-amended soils by the NCSOIL computer model. *Biology and Fertility of Soils* 28, 422–430. <http://dx.doi.org/10.1007/s003740050515>.
- Gabrielle, B., Da-Silveira, J., Houot, S., Francou, C., 2004. Simulating urban waste compost effects on carbon and nitrogen dynamics using a biochemical index. *Journal of Environment Quality* 33, 2333. <http://dx.doi.org/10.2134/jeq2004.2333>.
- Gabrielle, B., Da-Silveira, J., Houot, S., Michelin, J., 2005. Field-scale modelling of carbon and nitrogen dynamics in soils amended with urban waste composts. *Agriculture, Ecosystems & Environment* 110, 289–299. <http://dx.doi.org/10.1016/j.agee.2005.04.015>.
- Garnier, P., Néel, C., Aita, C., Recous, S., Lafolie, F., Mary, B., 2003. Modelling carbon and nitrogen dynamics in a bare soil with and without straw incorporation. *European Journal of Soil Science* 54, 555–568. <http://dx.doi.org/10.1046/j.1365-2389.2003.00499.x>.
- Hadas, A., Doane, T.A., Kramer, A.W., Van Kessel, C., Horwath, W.R., 2002. Modelling the turnover of <sup>15</sup>N-labelled fertilizer and cover crop in soil and its recovery by maize. *European Journal of Soil Science* 53, 541–552. <http://dx.doi.org/10.1046/j.1365-2389.2002.00483.x>.
- Hadas, A., Kautsky, L., Goek, M., Erman Kara, E., 2004. Rates of decomposition of plant residues and available nitrogen in soil, related to residue composition through simulation of carbon and nitrogen turnover. *Soil Biology and Biochemistry* 36, 255–266. <http://dx.doi.org/10.1016/j.soilbio.2003.09.012>.
- Hadas, A., Molina, J. a. E., 1993. Simulation of nitrogen assimilation by heterotrophic soil microbial biomass. *Physiologia Plantarum* 89, 664–668. <http://dx.doi.org/10.1111/j.1399-3054.1993.tb05231.x>.
- Hadas, A., Portnoy, R., 1994. Nitrogen and carbon mineralization rates of composted manures incubated in soil. *Journal of Environment Quality* 23, 1184. <http://dx.doi.org/10.2134/jeq1994.00472425002300060008x>.
- Haskett, J.D., Molina, J.A.E., Clapp, C.E., 1986. User's Manual for NCSOIL, Version 1.0. Dep. of Soil Science, University of Minnesota, Saint Paul, MN.
- Kaboré, T.W., Pansu, M., Hien, E., Houot, S., Zombré, P., Masse, D., 2011. Usefulness of TAO model to predict and manage the transformation in soil of carbon and nitrogen forms from West-Africa urban solid wastes. *Waste Management* 31, 154–167. <http://dx.doi.org/10.1016/j.wasman.2010.06.010>.
- Kaboré, T.W., Pansu, M.A., Hien, E., Brunet, D., Barthès, B.G., Houot, S., Coulibaly, A., Zombré, P., Thuriès, L., Masse, D., 2012. Near infrared reflectance spectroscopy applied to model the transformation of added organic materials in soil. *Journal of Near Infrared Spectroscopy* 20, 339–351.
- Lashermes, G., Nicolardot, B., Parnaudeau, V., Thuriès, L., Chaussod, R., Guillotin, M.L., Linères, M., Mary, B., Metzger, L., Morvan, T., Tricaud, A., Villette, C., Houot, S., 2010. Typology of exogenous organic matters based on chemical and biochemical composition to predict potential nitrogen mineralization. *Bioresource Technology* 101, 157–164. <http://dx.doi.org/10.1016/j.biortech.2009.08.025>.
- Lashermes, G., Nicolardot, B., Parnaudeau, V., Thuriès, L., Chaussod, R., Guillotin, M.L., Linères, M., Mary, B., Metzger, L., Morvan, T., Tricaud, A., Villette, C., Houot, S., 2009. Indicator of potential residual carbon in soils after exogenous organic matter application. *European Journal of Soil Science* 60, 297–310. <http://dx.doi.org/10.1111/j.1365-2389.2008.01110.x>.
- Lundquist, E., Jackson, L., Scow, K., Hsu, C., 1999. Changes in microbial biomass and community composition, and soil carbon and nitrogen pools after incorporation of rye into three California agricultural soils. *Soil Biology & Biochemistry* 31, 221–236.
- Mamo, M., Molina, J.A.E., Rosen, C.J., Halbach, T.R., 1999. Nitrogen and carbone mineralization in soil amended with municipal solid waste compost. *Canadian Journal of Soil Science* 79, 535–542.
- Marmo, L., Feix, I., Bourmeau, E., Amlinger, F., Bannick, C.G., De Neve, S., Favoino, E., Gendebien, A., Gibert, J., Givélet, M., Leifert, I., Morris, R., Rodriguez Cruz, A., Ruck, F., Siebert, S., Tittarelli, F., 2004. Reports of the Technical Working Groups Established under the Thematic Strategy for Soil Protection, vol. 3, taskgroup 4 Exogenous Organic Matter.
- Molina, J. a. E., Clapp, C.E., Shaffer, M.J., Chichester, F.W., Larson, W.E., 1983. NCSOIL, a model of nitrogen and carbon transformations in soil: description, calibration, and behavior. *Soil Science Society of America Journal* 47, 85–91. <http://dx.doi.org/10.2136/sssaj1983.03615995004700010017x>.
- Morvan, T., Nicolardot, B., 2009. Role of organic fractions on C decomposition and N mineralization of animal wastes in soil. *Biology and Fertility of Soils* 45, 477–486. <http://dx.doi.org/10.1007/s00374-009-0355-1>.
- Morvan, T., Nicolardot, B., Péan, L., 2006. Biochemical composition and kinetics of C and N mineralization of animal wastes: a typological approach. *Biology and Fertility of Soils* 42, 513–522. <http://dx.doi.org/10.1007/s00374-005-0045-6>.
- Nicolardot, B., Molina, J.A.E., Allard, M.R., 1994. C and N fluxes between pools of soil organic matter: model calibration with long-term incubation data. *Soil Biology and Biochemistry* 26, 235–243. [http://dx.doi.org/10.1016/0038-0717\(94\)90163-5](http://dx.doi.org/10.1016/0038-0717(94)90163-5).
- Nicolardot, B., Recous, S., Mary, B., 2001. Simulation of C and N mineralisation during crop residue decomposition: a simple dynamic model based on the C:N ratio of the residues. *Plant and Soils* 228, 83–103.
- Noirot-Cosson, P.E., Vaudour, E., Gilliot, J.M., Gabrielle, B., Houot, S., 2016. Modelling the long-term effect of urban waste compost applications on carbon and nitrogen dynamics in temperate cropland. *Soil Biology and Biochemistry* 94, 138–153. <http://dx.doi.org/10.1016/j.soilbio.2015.11.014>.
- Pansu, M., Thuriès, L., 2003. Kinetics of C and N mineralization, N immobilization and N volatilization of organic inputs in soil. *Soil Biology and Biochemistry* 35, 37–48. [http://dx.doi.org/10.1016/S0038-0717\(02\)00234-1](http://dx.doi.org/10.1016/S0038-0717(02)00234-1).
- Pansu, M., Thuriès, L., Larré-Larrouy, M.-C., Bottner, P., 2003. Predicting N transformations from organic inputs in soil in relation to incubation time and biochemical composition. *Soil Biology and Biochemistry* 35, 353–363. [http://dx.doi.org/10.1016/S0038-0717\(02\)00285-7](http://dx.doi.org/10.1016/S0038-0717(02)00285-7).
- Parnaudeau, V., Générmont, S., 2014. Valeur fertilisante azotée et pertes azotées influençant la valeur fertilisante. pp 369–396, in: Valorisation Des Matières Fertilisantes D'origine Résiduaire Sur Les Sols À Usage Agricole Ou Forestier. Impacts Agronomiques, Environnementaux, Socio-Économiques. Houot et Al., 2014. Expertise Scientifique Collective. INRA-CNRS-Irstea. Synthèse 113pp (<http://Institut.inra.fr/Missions/Eclairer-Les-Decision/Expertises/Toutes-Les-Actualites/Expertise-Mafor-Effluents-Boues-et-Dechets-Organiques#>).
- Parnaudeau, V., Nicolardot, B., Pagès, J., 2004. Relevance of organic matter fractions as predictors of wastewater sludge mineralization in soil. *Journal of Environmental Quality* 33, 1885–1894. <http://dx.doi.org/10.2134/jeq2004.1885>.
- Peltre, C., Christensen, B.T., Dragon, S., Icard, C., Katterer, T., Houot, S., 2012. RothC simulation of carbon accumulation in soil after repeated application of widely different organic amendments. *Soil Biology & Biochemistry* 52, 49–60. <http://dx.doi.org/10.1016/j.soilbio.2012.03.023>.
- Peltre, C., Dignac, M.-F., Derenne, S., Houot, S., 2010. Change of the chemical composition and biodegradability of the Van Soest soluble fraction during composting: a study using a novel extraction method. *Waste Management* 30, 2448–2460. <http://dx.doi.org/10.1016/j.wasman.2010.06.021>.
- Peltre, C., Thuriès, L., Barthès, B., Brunet, D., Morvan, T., Nicolardot, B., Parnaudeau, V., Houot, S., 2011. Near infrared reflectance spectroscopy: a tool to characterize the composition of different types of exogenous organic matter and their behaviour in soil. *Soil Biology & Biochemistry* 1–9. <http://dx.doi.org/10.1016/j.soilbio.2010.09.036>.
- Stratton, M.L., Barker, A.V., Rechcigl, J.E., 1995. Compost. *Soil Amendments and Environmental Quality* 249–309.
- Thuriès, L., Pansu, M., Larré-Larrouy, M.-C., Feller, C., 2002. Biochemical composition and mineralization kinetics of organic inputs in a sandy soil. *Soil Biology & Biochemistry* 34, 239–250.
- Trinsoutrot, I., Recous, S., Bentz, B., Linères, M., Chèneby, D., Nicolardot, B., 2000. Biochemical quality of crop residues and carbon and nitrogen mineralization kinetics under nonlimiting nitrogen conditions. *Soil Science Society of America Journal* 64, 918. <http://dx.doi.org/10.2136/sssaj2000.643918x>.
- Van Soest, P.J., Wine, R.H., 1967. Use of detergents in the analysis of fibrous feeds. IV. Determination of plant cell-wall constituents. *Journal of the Association of Official Analytical Chemists* 50, 50–55.
- Ward, J.H., 1963. Hierarchical grouping to optimize an objective function. *Journal of the American Statistical Association* 58, 236–244. <http://dx.doi.org/10.1080/01621459.1963.10500845>.