Simulation with the NCSOIL model of carbon and nitrogen dynamics in a loamy soil after various compost applications.

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Abstract:
The organic carbon decline has been recognised as a threat for cultivated soils at European scale. It can be prevented by application of Exogenous Organic Matter (EOM). It is also a way of recycling the organic fraction of urban waste. Mechanistic models such as NCSOIL (Molina et al. 1983) can be used to understand and predict the soil organic carbon and nitrogen dynamic requiring nevertheless an accurate parameterization. Here we described the methods followed to parameterize NCSOIL by using an optimization module added to NCSOIL by Barack and al. (1990) in order to simulate both C and N dynamics after EOM addition in a long-term experiment. The parameters were optimized for soil and EOMs against experimental results of C and N mineralization during incubations in controlled condition sof soil-EOM mixtures for 7 years of EOM application. The optimization results were satisfactory with χ^2 ranging from 0.093 to 0.32 and simulations well reproduced carbon and nitrogen mineralization measurements. The parameterization will be further tested in the coupled model CERES-EGC/NCSOIL to study soil organic matter behaviour and N mineralization in field conditions.

Introduction
Repeated applications of composts on cropped fields make possible the recycling of the organic fraction of urban wastes leading to increased soil availability in nitrogen (N) for crops and increased soil organic carbon (C). Although such practice has been widely applied over the last 30 years, the effects of repeated compost applications on soil C and N cycles and hence crop production are still uncertain and often controversial. Depending on complex biophysical processes and interactions, organic C and N are present under various states in soil, which make *in situ* measurements extremely challenging. However, mechanistic models have merged as useful tools to understand and predict C and N dynamics at the ecosystem level. The NCSOIL model (Molina et al. 1983) has been used to simulate C and N mineralization after compost and manure application on soil. The results of C and N dynamics in laboratory conditions are presented here. The results will be further used to simulate the behaviour of C and N in field conditions.

Material and Methods
Field experiment
The QualiAgro long-term field experiment located near Feucherolles 35 km west of Paris (Ile de France) has been initiated in 1998 (INRA-Veolia Environment collaboration) and cultivated with a Maize-Wheat crop rotation. Three composts and a manure were applied on an initially homogenous soil every second year, defining, with an unamended soil, five treatments. All treatments were present in 4 replicates. The EOM used were the following:

- GWS : compost derived from co-composting green-wastes with sewage sludge;
- BIO : biowaste compost produced by co-composting green wastes with a source-separated organic fraction of municipal wastes;
- MSW : municipal solid waste compost obtained by composting solid municipal waste after sorting of dry and clean packaging;
- FYM: farmyard manure.

The soil, a silt loam soil (76% silt, 17% clay, and 7% sand) was sampled for physico-chemical analyses before each EOM application. All EOMs were also sampled during application in 1998, 2000, 2002, 2004, 2006, 2007 and 2009 for chemical analysis. Average results are presented in Table 1. Alongside these measurements, the behaviour of EOM in soil was assessed in lab microcosms and measurement of C and N mineralization during incubation of soil-EOM mixtures during about 90 days (Francou et al. 2008; Houot et al. 2002). Control incubations with only soil were also performed. All incubation was run in triplicate.

Table 1 : Average results of Exogenous Organic Matter characteristics (DM: dry matter, FW: fresh weight, SOL: soluble fraction, HEM: hemicellulose fraction, CEL: cellulose fraction, LIC: lignin fraction)

	DM	Corg	Ntot	N-NH_4	N-NO_3	C/N	Fermentation	Maturation	SOL	HEM	CEL	LIC
	(%FW)	(g/kg DM)					month		% Corg			
MSW	69 (14)	302 (45)	17.9 (2.6)	0.4 (0.2)	0.0 (0.0)	18.3 (4.4)	1	0.2	41.4 (8.5)	7.1 (2.7)	34.4 (10.1)	17.1 (5.6)
BIO	69 (9)	195 (38)	16.7 (4.5)	0.2 (0.3)	0.1 (0.2)	12.1 (1.7)	1 to 3	2 to 4	44.6 (7.1)	4.4 (2.6)	20.9 (2.7)	30.1 (8.6)
GWS	62 (8)	252 (36)	23.5 (3.1)	2.0 (0.6)	0.3 (0.4)	11.5 (2.4)	1 to 3	3	45.6 (8.6)	5.4 (2.1)	20.5 (9.3)	28.5 (10.8)
FYM	39 (10)	339 (57)	22.9 (2.5)	0.1 (0.1)	0.6 (0.4)	14.9 (3.1)	x	x	37.9 (6.3)	12.7 (3.1)	27.1 (8.2)	21.9 (4.5)

Modelling and optimization process

The process-based model NCSOIL (Figure 1) simulates the daily variations in C and N during soil-EOM incubation (Molina et al., 1983) and is combined with an optimisation algorithm as described in Barak et al. (1990). The soil organic matter is split in three organic pools: pool I (endogenous microbial biomass), pool II (active organic matter or humads), pool III (stable organic matter, humus). When EOM is applied, it generates a new organic pool 0, a zymogenous microbial biomass that decomposes EOM organic matter. The EOMs are described through two organic pools. Additionally, all biomass pools are subdivided into labile and resistant fractions except pool III. All organic pools are characterized by their size (mgC/kg soil), their C/N ratio, and their constant rates of degradation. The N transformations followed the C transformations through the C/N ratio of the pools. N incorporation into organic pools was only possible through the N-NH_4 form.

The optimization process (Barak et al. 1990) minimizes the differences between simulated and experimental kinetics of C-CO_2 and mineral N during incubation by calculating a χ^2, and iteratively (15 times maximum) rerun the model with modified parameters until : (i) the χ^2 value is acceptable (less than 10^{-30}) or (ii)The χ^2 decrease between two iterations is inferior to 0.1%.

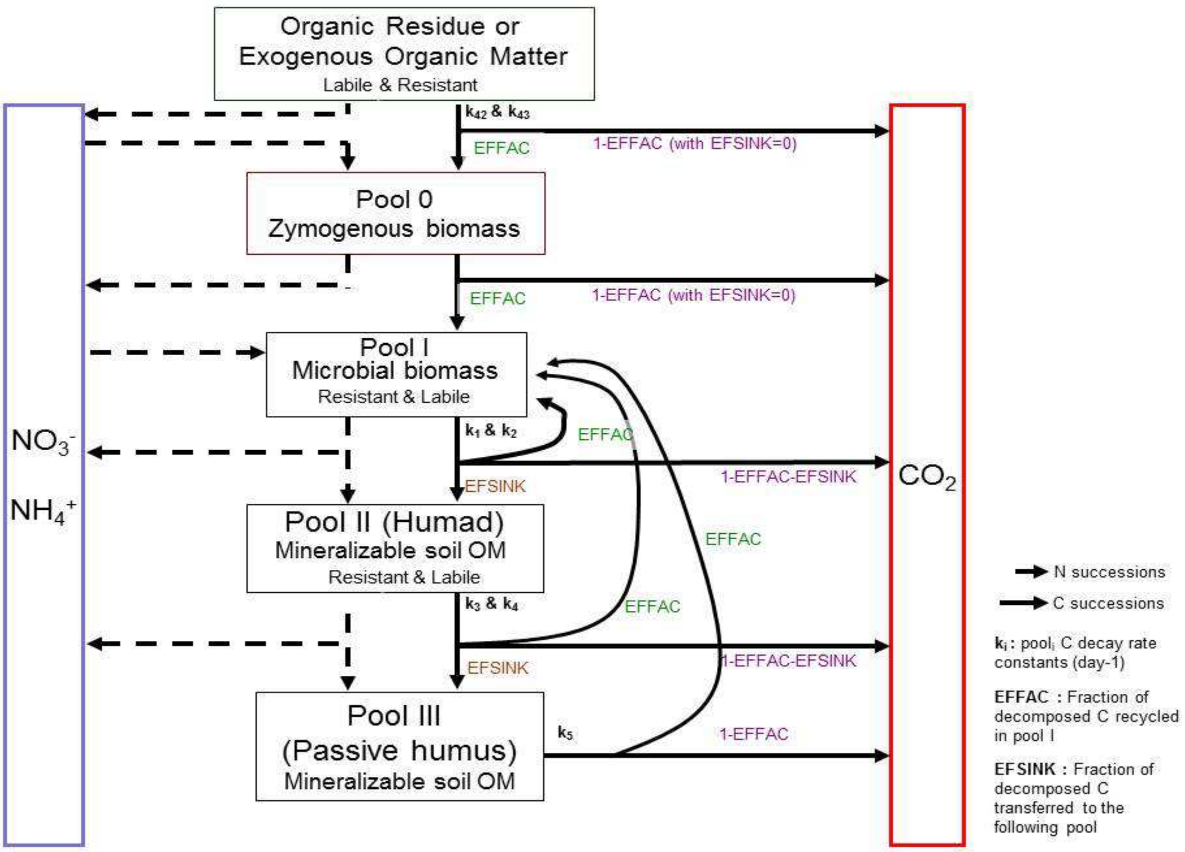

Figure 1 : Schematic C and N flows in the NCSOIL model. The term OM is organic matter.

Parameterization:
A total of 24 parameters and initial characteristics of soil organic pools are necessary to run the model (Table 2). 10 more parameters are required for EOMs. First, the parameters related to soil organic carbon were assessed from the control non-amended soil, then the parameters describing EOMs behaviour were determined used the results of soil-EOM mixture incubations..

Soil parameterization
Only the C size and C/N ratio of pool II were optimized. All other parameters or initial values were either measured (as EOM and soil Total Organic Carbon (TOC)) or set to previously used values by Nicolardot et al. (1994) and Corbeels et al.(1999). For Pool 0, we used the same parameters as for pool I because it concerns also microbial biomass (Molina, personal communication). At time 0, there was a negligible amount of zymogene biomass since we considered that it only grows when residue or compost is added to the soil. The optimization was performed for each control incubation, then average optimized parameters were calculated and used for the EOM parameterization.
EOM parameterization
The decay rate constants (day^{-1}) of the 2 EOM fractions (labile and resistant) were calculated as described in Gabrielle et al. (2004). However, we assumed that the EOMs differed only by their labile/resistant proportions and not by their decay rate constants, thus these 2 constants were averaged from the 28 results (4 composts × 7 years) and then used for the following optimizations.
The C/N ratios of the EOM were fixed through 2 different assumptions:

- for the EOMs that decomposed slowly with less than 10% organic C mineralized at the end of the incubation (BIO, GWS), the C/N ratio of both labile and recalcitrant fractions were set equal to the total C/N ratio;
- For more biodegradable EOM with larger labile fraction (MSW, FYM), the C/N ratio of the labile fraction was set to 100 (value close to straw C/N which composed most of the labile fraction in a FYM and cellulosic fraction that characterize the labile pool of MSW compost);

The optimizations were then performed on the carbon size of the EOM resistant fraction then the labile fraction carbon size was calculated from the difference between total EOM carbon and optimized resistant fraction.

Table 2 : NCSOIL soils and Exogenous Organic Matter (EOM) parameters and their setting

	Pool 0		Pool I		Pool II		Pool III	EOM	
Fraction	Labile	Resistant	Labile	Resistant	Labile	Resistant		Labile	Resistant
Size (mgC/kg soil)	0	0	[2]2.6% total SOC		[2] 0	Optimized	TOC-PII-PI	TOC_{EOM}-$Resistant_{EOM}$	Optimized
			[2]56%	[2]44%					
C decay rate constants (day^{-1})	0.332*	0.0404*	[1;2]0.332	[1;2]0.0404	[1]0.16	[1;2]0.006	0.00001	[3]Calculated	[3]Calculated
Fraction of decomposed C recycled in pool I (EFFAC)	0.6*		[1;2]0.6		[2]0.6		[2]0.6	0.6*	0.6*
Fraction of decomposed C to the following pool (EFSINK)	-		[1;2]0.2		[1;2]0.2		-	-	
C/N	6.0*		[1;2]6.0		Optimized		CN_{PIII}=PIII/[(TOC/CN_{TOC})-(PI/CN_{PI})-(PII/CN_{PII})])	Depending on the compost (as referred in the text)	Depending on the compost (as referred in the text)

In grey, value not required as NCSOIL parameter. PI stands for pool I, PII for Pool II.
[1](Corbeels et al. 1999) [2](Nicolardot et al., 1994) [3](Gabrielle et al. 2004). *Explained previously in the text.
* Taken as for Pool I

Results

Soil parameterization

The average values of optimization results of all years are presented in Table 3. The optimization properly performed for the control soil for every year, with average χ^2 lower than 0.1 over the 7 years. After optimization, the Pool III represented 80% (SD: 4%) of total soil organic carbon which means most soil organic carbon is in a stable humic form (pool III). The Pool II representing in average 18% of total SOC, had a C/N ratio of 22, more than twice greater than C/N ratio of the total SOC, confirming its more reactive property. Soil total organic carbon content measurement was low (10gC/kg soil) as 45% of European soil which contain less than 2% organic carbon (Turbé et al., 2010).

Table 3: Mean soil parameters resulting from optimization

Treatment without N addition		Pool I	Pool II	Pool III	Total SOC	*Opt.* χ^2
C content (% Corg)	mean	2.6	17.9	79.5	100 (9 353 **mgC/kg Soil)**	0.093
	standard deviation	-	4.3	4.3	5.4	0.10
C/N	mean	6.00	21.5	8.9	9.6	
	standard deviation	-	9.2	0.7	0.7	

EOM parameterization

The optimization correctly performed as shown by the $\chi 2$ value lower than 0.5 (Table 4) alongside the mineralization simulations properly following measurements results (Figure 2). The mineralization results showed similar dynamics over the years for all composts. The GWS and BIO were both characterized by slow linear mineralization dynamics over the 90 days (12% and 15% of compost organic C in the mixture mineralized after 90 days for GWS and BIO, respectively, while it was up to 43 and 21% for the MSW and FYM). Both GWS and BIO composts are characterized by the largest proportions in recalcitrant lignin (Table 1). The MSW compost had a different mineralization dynamic with a first intense mineralization (corresponding to half the total CO_2 emitted) followed by a second slower mineralization, matching with its optimized half/half labile/resistant fractions composition. The FYM showed inconstant results over the years in terms of mineralization dynamic: 1998, 2000 and 2009 showed two distinct fast and slower mineralization parts (poorly simulated in 1998), while the 4 other years were characterized by linear mineralization. This could be explained by variable labile/resistant composition, optimization results gave a labile fraction representing 20% and 40% of the total in 2000 and 2009, and less than 12% the other years (yearly detailed results not shown). Farmyard manure was eventually characterized by a high proportion of resistant carbon (87%) with the highest variability (standard deviation 14%).

Nitrogen mineralization simulations properly fitted measurements, showing linear kinetics for BIO and GWS for all the years, and for FYM for 2002, 2004, 2006, 2007 and 2009. MSW for all the years and FYM in 2000 and 2009 showed N immobilization at the beginning of the incubation and it was successfully reproduced by the simulations except in 1998 for MSW and in 2000 for FYM where immobilization was over estimated. FYM revealed also variable nitrogen mineralization dynamics over the years

Table 4 : Optimized size and C/N ratio of the labile and resistant fractions for all Exogenous Organic Matters (Average of seven optimized parameters and standard deviation)

	EOM Labile fraction		EOM Resistant fraction		*Opt.* $\chi 2$
	Organic C (% Corg)	C/N ratio	Organic C (%Corg)	C/N ratio	
BIO	2 (*3*)	12 (*2*)	98 (*3*)	12 (*2*)	0.18 (*0.12*)
MSW	46 (*11*)	100.0 (-)	54 (*11*)	11 (*2*)	0.16 (*0.16*)
GWS	2 (*2*)	12 (*2*)	99 (*2*)	12 (*2*)	0.32 (*0.42*)
FYM	13 (*14*)	100 (-)	87 (*14*)	13 (*2*)	0.28 (*0.44*)

Discussion

Various assumptions were made to parameterize the NCSOIL entry file and must be discussed. The size of soil organic carbon Pool II was successfully optimized using the same dynamic parameters than previously proposed. Similar proportion of TOC for pool II, 13%, with a CN ratio of 16.7 were also found by Corbeels et al. (1999). Small labile fractions were found for FYM, BIO and GWS (13, 2 and 1% respectively), in accordance with Corbeels et al (1999) who obtained also for sewage sludge compost a labile fraction inferior to 10%.
However, for some cases, the simulation did not fit well the observed results of C and N mineralization during incubation (Figure 2): N mineralization for BIO in 1998, C for BIO in 2009, N for MSW in 1998 and 2000, C & N for GWS in 2009, C for FYM in 1998 and N and C for FYM in 2000. Various reasons could explain these poor simulations thus parameterizations:

- All EOMs were characterized with the same constant rate of decomposition for resistant and labile fraction for all the years which make parameterization more simple but restrain heterogeneity between different EOM in term of decomposition dynamic. The EOMs may also not be constant over the years depending on composting conditions.
- GWS and BIO were considered as being mostly composed by resistant carbon, and thus we used the total C/N ratio measured as the resistant pool C/N ratio. This was confirmed by the optimization results: 98% of C in the resistant pool. These assumptions may lead to linear simulations where incubations showed slight concave shape. Assumptions made on EOM C/N ratio was maintained since they globally lead to acceptable simulations.

Conclusion and perspectives

The parameterization using methods from Barak (1990) and Gabrielle (2004) was successfully performed with the NCSOIL model, as validations using $\chi 2$ value and visual assessment of mineralization dynamics. We obtained low $\chi 2$, simulated proper mineralization regarding to measurements, and also found consistent sizes and C/N ratio. The parameterization especially succeeded in reproducing differences between EOM properties. This method with some assumptions allowed us to correctly parameterize the NCSOIL, these parameters will be further used in the NCSOIL/CERES-EGC coupled model to simulate the total soil-plant-water system and calculate the C and N balance after repeated applications of composts in field conditions.

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Figure 2. C and N mineralization during soil-EOM incubation in controlled conditions. The EOMs were applied in the Qualiagro experimental site, measured: CO_2-C (●), mineral N (○); and simulated (─ and ---, respectively)