Scientific registration n° : 301
Symposium n° : 7
Presentation : oral - invit

Analytical Determination of Soil C Dynamics
Détermination analytique de la dynamique du carbone du sol

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The significance and possible management of soil organic C (SOC) in ecosystem functioning, global change and sustainable agriculture is best determined through a knowledge of its dynamics. This requires analytically determined measurements of SOC pool sizes and flux rates. The amount and quality of plant residues inputs, biotic activity, site characteristics and management are reflected in the size of the pools and their turnover rates. Some constituents are decomposed during periods of weeks; some persist for centuries and millenia. Fractionation of the soil and the use of tracers such as ^{14}C and ^{13}C makes possible the determination of the dynamics of the pools involved such that more meaningful estimates of the role of SOC in the many functions in which it plays a role can be calculated.

The use of ^{14}C and chemical and biological fractionation

The dynamics of SOC are most often represented by a sum of three first order reactions after the effects of residue decomposition have been separately calculated (Paustian et al., 1992; Nicolardot et al., 1994). We determined pool sizes and dynamics of a Michigan Corn Belt soil with the equation:

$$C_t = C_a e^{-kat} + C_s e^{-kst} + C_r e^{-krt}$$

where; C_a,k_a = Active pool; C_s,k_s = Slow pool; C_r,k_r = Resistant pool. Decomposition rate constants from laboratory incubation at 25°C were scaled to annual average field temperature of 9°C on the basis of a Q_{10} of $2 = 2^{\frac{(25-9)}{10}} = 3$. Where; 25 = the laboratory incubation temperature; 9 = average annual field temperature.

Laboratory incubations utilize the degradative enzymes of the soil biota to provide CO_2 evolution curves. Plotting the evolution data on the basis of CO_2 evolution per unit time provides statistically valid parameters (Hess and Schmidt, 1995) for calculating the pool sizes and decomposition rate constants of the active and slow pools. The sizes of the active fraction C_a and slow pool C_S were determined by non-linear regression of the rate of change of CO_2 evolution with time (Paul et al., 1998). The size of the slow pool C_s was defined as ($C_s = C_t - C_a$

-C_r). The mean residence time (MRT) was the reciprocal of the decomposition rate constants k_1 and k_2 derived from the laboratory incubation.

INCORPORERThe CO_2 data for the suface Michigan soil showed the sharp change in slope at approximately 50
days of incubation that demarcated the Ca and the Cs pools (Figure 1). The active pool, representing 5 % of the total soil with a field MRT of 61days (Table 1) is closely related to recent inputs. The slow pool of the surface layer has 49% of the SOC with a field MRT of 29 yr and represents the accumulation and turnover of the SOC that controls ecosystem productivity. The CO_2 evolution rates from the lower horizons were low when expressed per unit weight of soil (Figure 1), but equaled those of the surface horizon when expressed on a unit C basis (Paul et al., 1998). This is reflected in the MRT's for the active and slow pools of the deeper layers that were less than those of the surface horizon (Table 1). The active and slow SOC at depth is from root-derived materials and soluble organic C. Both have less lignin than surface residues and should decompose faster in the laboratory. The persistence in the field at depth could involve a lack of: appropriate microorganisms, nutrient availability or aeration as well physical protection factors.

The residue of acid hydrolysis represents the size of the oldest, resistant (Cr) fraction (Paul et al., 1997). Carbon dating (Paul et al., 1964; Anderson and Paul, 1984; Trumbore 1993;) measures its MRT. The Cr pool of the surface layer of a Michigan soil contained 46% of the SOC with a MRT of 1435 yr (Table 1). This rapidly increased to over 5000 yr at 25 to 50 cm and 7000 yr at 50 to 100 cm. The carbon dates for both the total soil and the resistant fraction of this loam textured soil are younger than those of finer textured soils in this area.

The use of ^{13}C and physical fractionation

The naturally occurring isotope ^{13}C together with a switch in crop plants provides a useful measure of the dynamics of SOC (Balesdent et al., 1988; Gregorich et al., 1995; Boutton1991). The site in Michigan was originally a deciduous forest with a ^{13}C of δ=-26.1‰. The growth of corn for 6 of the last 8 yr on this site (Smucker et al., 1997) changed the overall soil ^{13}C to -23.1‰ (Table 2) indicating that 33% of the 0 to 20 cm depth SOC was derived from the corn residues; 37% of the SOC was corn derived at 25 to 50 cm and 24% at 50 to 100 cm showing the stronger influence of the corn roots at the intermediate depth (Table 2).

The $^{13}CO2$ evolved during the first 10 days of incubation in the laboratory (Table 2) at -18.6‰ indicates that 82% of this CO_2 was derived from corn residues. It took 160 days of incubation for the CO_2 to equal the ^{13}C signature of the macroorganic matter at -21.1‰ and 1000 days for the CO_2 to equal that of the total surface soil at -23.1‰. The subsurface changed $^{13}CO_2$ signals rapidly. This corroborates our earlier observation that the root-derived materials are rapidly lost on incubation and have short MRT's even if the total soil is much older.
The annual production of ≈ 5000 Kg C ha^{-1} corn residues for 6 yr and 3000 Kg non-corn residues in the years when corn was not grown resulted in a calculated SOC δ of -17.5 5‰ (Paul et al., 1998). The light fraction at -19.7‰ (Table 3) had 69% of its C derived from corn. The

macroorganic matter at -21.1‰ contained 58% corn-derived materials, the silt contained 28% and the more active clay contained 32% corn-derived C. The organic materials sediment with the clay and silt sized fractions form as a layer on top of the inorganic particulates on drying and thus are not truly particle associated.

Aggregates have been long implicated in the physical protection of SOC constituents (Carter and Stewart, 1996). The ^{13}C signal in the residues at this site made it possible to calculate the distribution of the corn C in the various sized aggregates (Table 4). The soil was well aggregated; 80% of the soil weight and 57% of the SOC was located in the 4-6.3 mm aggregates. Thirty percent of the SOC was not aggregate associated. The ^{13}C showed large aggregates to be most active with 34% corn-derived C. All aggregate sizes contained corn-derived C showing that aggregation plays its major role in the protection of the Cs pool.

Measurement of corn-derived C in the field under a long term ^{13}C crop switch makes it possible to calculate the MRT for the total non-corn C in that field. We found that the MRT of the SOC determined in the field with ^{13}C was highly correlated to the size of the slow Cs pool determined by laboratory incubation and curve fitting. The Cs pool had MRT's of 30 to 60 yr for loam soils but 150 to 180 yr for silty clay loams (Collins et al., 1999).

Conclusions

We analytically determined the SOC pool sizes and fluxes by the use of chemical and biological fractionation in conjunction with ^{14}C dating and curve analyses of CO_2 produced during extended incubations. The size of the active pool in this soil at 4 % of the SOC is twice that of the microbial biomass but is not constituted only of this component for the active C also is associated with the light fraction determined in the physical separation. The Cs pool comprises nearly one half of the total C. This pool with a MRT of 26 yr at the surface comprises the seat of soil fertility and is the pool that must be most closely managed in global change scenarios.

The SOC at depth is clearly old but not all of it is recalcitrant. This is reflected in the short mean residence times of the Ca and Cs fraction obtained during laboratory incubation even though the resistant fraction had a MRT of 5,400 yr in the 25-50 cm depth and 7000 at 50-100 cm. The materials deposited at depth had lower lignin contents; fine root and exudate-C result in a labile faction that because of factors such as a lack of aeration, microbial inocula or mixing resulted in slower *in situ* turnover.

The physical fractions that include the light fraction, macroorganic matter, sand silt and clay and various sized aggregates augment the chemical-biological fractionation. The aggregate analysis used in this study left 57% of the SOC associated with the 4-6.3 mm aggregates. These contain a gradient of ^{13}C as demonstrated in the use of surface peeling techniques that fractionate the larger aggregates into more biologically meaningful pools (Smucker et al., 1998).
Soil is comprised of a range of SOC constituents that are protected by chemical physical and biotic

parameters. The techniques to study these controls are now available. Acid hydrolysis does not dissolve the lignin of plant residue; yet clearly differentiates SOC constituents on an age basis (Leavitt et al., 1997; Paul et al., 1997). Carbon dating is restricted in availability and expensive. The determination of the active and slow pools requires extensive incubation times but other wise is easily accomplished.

The readily measurable ^{13}C provides confirmation of the turnover of the Ca and Cs fractions if the C_3-C_4 plant switch extends over long enough time periods to label the pools involved. It also gives information on the fate of field derived residues (Monreal et al., 1997). The independent measure of the MRT of the slow pool of SOC determined with ^{13}C closely coincides with that determined by a combination of carbon dating and laboratory incubation (Collins et al., 1998). Analytical determination of pools as described in this paper does not consider microbial growth and transfers between pools. This is best done by modeling that uses the analytically derived pools and fluxes as a starting point.

References

Balesdent, J., G.H. Wagner, and A. Mariotti. 1988. Soil organic matter turnover in long-term field experiments as revealed by carbon-13 natural abundance. Soil Sci. Soc. Am. J. 52:118-124.

Carter, M.R. and B.A. Stewart (Editors). 1996. Structure and organic matter storage in agricultural soils. CRC Lewis Publishers, Boca Raton, FL.

Collins, H.P., E.A. Paul, R.L. Blevins, L.G. Bundy, D.R. Christenson, W.A. Dick, D.R. Huggins, D.J. Lyon, S.E. Peters, and R.F. Turco. 1998. Carbon pools and dynamics in Corn Belt agroecosystems. Soil Sci. Soc. Amer. J. In press.

Collins, H.P., D. Harris, and E.A. Paul. 1999. Carbon pools and fluxes in long-term Corn Belt agroecosystems. SSSAS. In preparation.

Gregorich, E.G., H.B. Ellert, and C.M. Monreal. 1995. Turnover of soil organic matter and storage of corn residue carbon estimated from natural ^{13}C abundance. Can. J. Soil Sci. 75:161-167.

Leavitt, S.W., R.F. Follett, and E.A. Paul. 1997. Estimation of slow and fast-cycling soil organic carbon pools from 6N HCI hydrolysis. Radiocarbon. 38:231-239.

Nicolardot, B., J.A.E. Molina, and M.R. Allard. 1994. C and N fluxes between pools of soil organic matter; model calibration with long-term incubation data. Soil Biol. Biochem. 26:235-243.

Paul, E.A., C.A. Campbell, D.A. Rennie, and K.J. McCallum. 1964. Investigations of the dynamics of soil humus utilizing carbon dating techniques. VIII Int. Congr. Soil Sci., Bucharest, Trans. Vol. 3: 201-209.

Paul, E.A., R.F. Follett, S.W. Leavitt, A. Halvorson, G.A. Peterson, and D.J. Lyon. 1997. Radio carbon dating for determination of soil organic matter pool sizes and fluxes. Soil Sci. Soc. Amer. J. 61:1058-1067.

Paul, E.A., D. Harris, H.P. Collins, U. Schulthess, and G.P. Robertson. 1998. Evolution of CO_2 and soil carbon dynamics in biologically managed, row-crop agroecosystems. Applied Soil Ecology. Submitted.

Paustian, K., W.J. Parton, and J. Perrson. 1992. Modeling soil organic matter in organic amended and N-fertilized long-term plots. Soil Sci. Soc. Am. J. 56:476-488.

Trumbore, S.E. 1993. Comparison of carbon dynamics in tropical and temperate soils using carbon dating. Global Biogeochem. Cycles. 7:275-290.

Smucker, A.J.M., D. Santos, and Y. Kavdir. 1997. Concentric layering of carbon, nitrogen and clay within soil aggregates from tilled and non-tilled agroecosystems. p.129-140. Third Eastern Canada Soil Structure Workshop Proc.

Smucker, A.J.M., D. Santos, Y. Kavdir, and E.A. Paul. 1998. Concentric gradients within stable soil aggregates. 16 Int. Congr. Soil Sci., Montpellier, France, Trans.

Key words: soil organic matter, tracers, pool sizes and fluxes, aggregates, carbon dating
Mots clés : matière organique du sol, traçage, cycle du carbone, agrégats, datation, radiocarbone, dynamique, carbone, isotopes

Table 1 Pool sizes and mean residence time of a Michigan Corn Belt soil

	Active Pool (Ca)			Slow Pool Cs		Resistant Pool Cr	
	Total C %	% of Total C	MRT Days	% of Total C	MRT Yr	% of Total C	MRT Yr
0-20	1.04	5	61	49	29	46	1435
25-50	0.22	3	31	68	15	29	5320*
50-100	0.15	4	30	71	14	25	6940*

*Estimated from ^{14}C age of total soils and average of non-hydrolyzable fraction of Corn Belt soils

Table 2 The ^{13}C content, % SOC from corn and $^{13}CO_2$ of a Michigan Corn Belt soil

	^{13}C	C from corn	Days of Incubation					
	‰	%	13	66	127	227	353	1110
			‰					
Depth								
0-20	-23.1	38	-18.6	-19.1	-20.5	-21.5	-22.1	-23.4
25-50	-22.0	27	-20.3	-21.5	-21.4	-21.7	-----	-----
50-100	-22.7	16	-20.0	-22.5	-21.7	-22.2	-----	-----

Table 3 Organic carbon and ^{13}C distribution in soil particulates

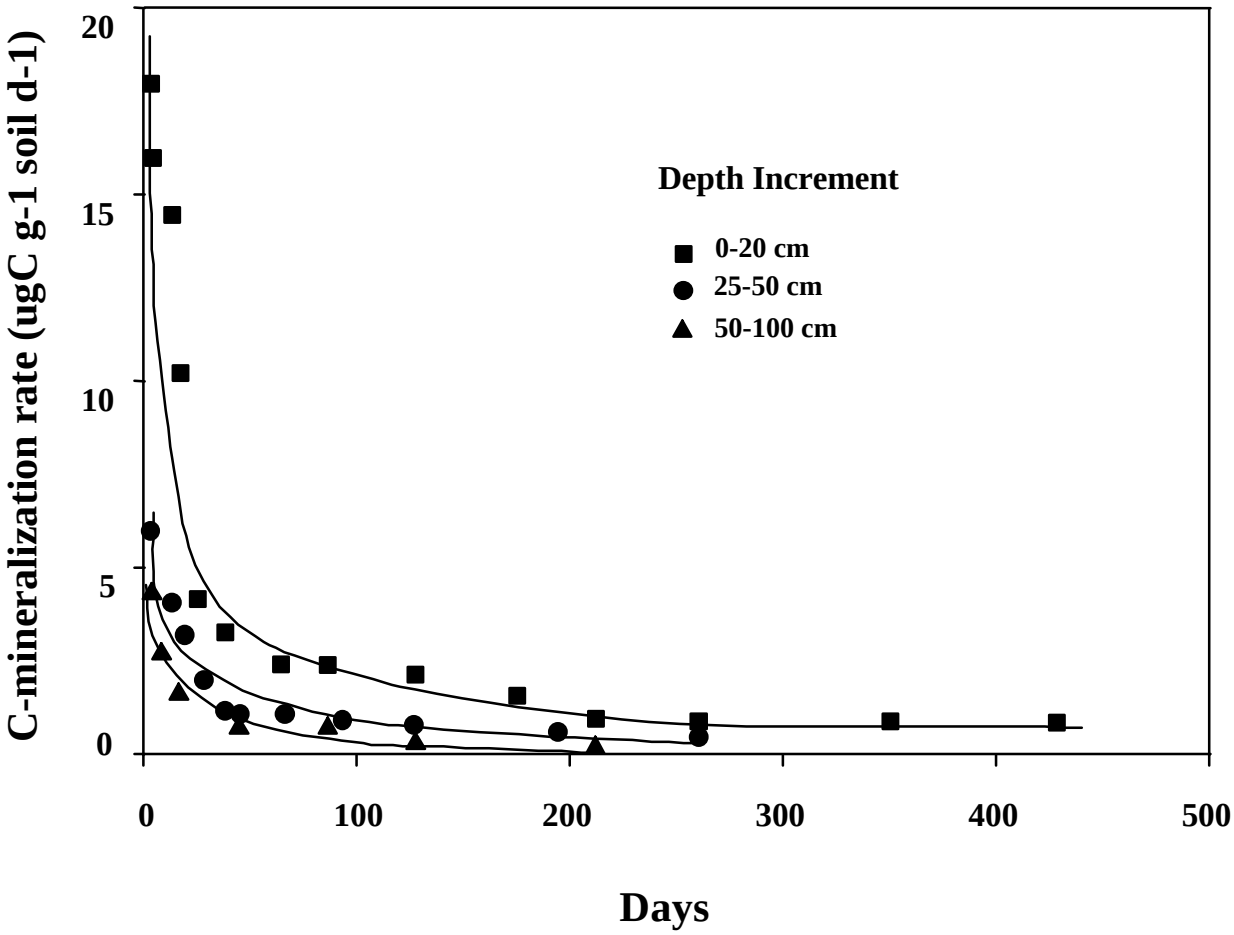
	C Distribution %	^{13}C ‰	C from Corn %
LF	4.04	-19.7	69
MOM* + Sand	7.38	-21.1	59
Silt	17.18	-23.5	28
Clay	30.29	-23.1	32
Whole Soil		-23.1	33

* Macroorganic matter

Table 4 The role of aggregates in soil organic carbon dynamics

Aggregates mm	C Distribution %	^{13}C ‰	C from Corn %
0.10 - 0.25	0.33	-24.2	21
0.25 - 0.50	0.40	-24.0	22
0.50 - 1.00	1.11	-23.7	26
1.00 - 2.00	2.81	-23.6	26
2.00 - 4.00	7.82	-23.6	26
4.00 - 6.30	56.9	-23.0	34

Figure 1 CO_2 Evolution from the three depths of the Michigan Corn Belt soil


C-mineralization rate (ugC g-1 soil d-1)
20
15
10
5
0
0
100
200
300
400
500
Days
Depth Increment
0-20 cm
25-50 cm
50-100 cm