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Carbon Turnover Kinetics with Depth in a French Loamy Soil

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ABSTRACT

Soil C dynamics below the plow layer have been little studied, in spite of proven large C stocks and suspected large C stabilization potential. The objective of the present study was to determine C-turnover kinetics throughout the 1-m profile of a cultivated loam soil of the Paris basin, France. The soil ^{13}C signature was determined to depths of 1.05 m in 32 replicated plots having received from 0 to 10 yr of maize after wheat. Above- and below-ground maize-residue biomass inputs were estimated throughout the 10-yr period. After 10 yr, maize-derived soil organic carbon (SOC) constituted about 10, 5, and 2% of the total SOC at 15-, 50-, and 100-cm depths, respectively. About one-third of recently deposited maize-derived SOM present in the 1-m soil profile was retrieved below the Ap horizon. The ratios of maize-derived soil C to the cumulative maize above- and below-ground inputs over the 10-yr period averaged 17% across the soil profile. This ratio was lower in the Ap horizon (i.e., 13%) than in deeper soil horizons. Circumstantial evidences suggest that the distribution profile of recently deposited maize-derived C was influenced by fine root activities, bioturbation, and dissolved organic carbon (DOC) transport, the latter being substantiated by a high correlation (r^2 = 0.86) between SOC contents and amorphous Fe + Al contents. In conclusion, our study stresses the need to take into account the full 1-m soil profile in C sequestration studies.

Carbon sequestration in soils has attracted considerable attention in recent years as a tool to mitigate the increase in atmospheric CO_2 concentration driven by human activities (Lal, 2004; Franzluebbers, 2005). This interest in soil C sequestration derives notably from the vastness of the 1-m-depth soil C reservoir, which doubles that of the atmosphere (Lal, 2004). Therefore, even proportionally modest increases in soil C sequestration could translate into substantial sequestration of atmospheric CO_2. Such accretion of soil C contents could theoretically be obtained through changes in land use or modifications of agricultural management practices such as tillage (Franzluebbers, 2005). Nevertheless, while the first meter of soil is acknowledged as containing vast amounts of C, the immense majority of process studies aimed at understanding the mechanisms of C sequestration in soils have been conducted in the top 30-cm or in even shallower surface layers.

Total C stocks in subsurface soil layers of agricultural soils generally surpass those contained in the plow layer or layer of equivalent depth in no-till systems (Deen and Kataki, 2003; Wu et al., 2003; Sisti et al., 2004). This suggests that at least half of the soil C has mostly escaped the scrutiny of process studies aimed at assessing land management impacts on C sequestration. Wu et al. (2003) estimated that 23% of cultivation-induced C losses from Chinese soils originated from soil layers subjacent to the plow layer. Two years of contrasted crop vs. bare fallow treatments in Michigan resulted in significant differences in soil C concentration in the Bt horizon but not in the Ap horizon (Rasse et al., 1999). These studies suggest that the large amounts of C contained in deeper horizons can turn over fairly rapidly according to accretion kinetics that are potentially different from the ones prevailing in the much-studied surface layer.

Soil organic matter (SOM) in deeper soil layers is both different in nature and exposed to contrasting environmental conditions as compared to that of the surface layer. Deeper soil layers receive a high proportion of root C contributions. Large root populations are found below the plow layer in maize systems (Rasse and Smucker, 1998). For deep-rooting crops such as alfalfa (*Medicago sativa* L.), fine root populations in sub-plow layers largely exceed those present in the surface horizon (Rasse et al., 2000). A recent estimate suggests that root-litter C has an average mean residence time in soils 2.4 times that of shoot-litter C (Rasse et al., 2005). In addition to direct root inputs, deeper horizons are enriched in SOM that is transported as dissolved organic matter (DOM) (Michalzik et al., 2003).

Environmental conditions prevailing in the deep soil profile have been suggested detrimental to the decomposition of organic matter (Gill et al., 1999; Gill and Burke, 2002). Microbial and fungal activities are reduced in deeper vs. surface soil layers (Taylor et al., 2002) and subsurface microbial communities are distinct from those present in the surface layer (Fierer et al., 2003b). Organic matter was found less decomposable (Ajwa et al., 1998) and more associated with minerals (Eusterhues et al., 2003) in deeper layers. Furthermore the degree of N and P limitation to C mineralization increased with depth (Fierer et al., 2003a). All these elements suggest that estimated kinetics of SOM turnover in deeper soils cannot be extrapolated from surface layer studies.

The specificities of SOM dynamics in deeper soil layers are potentially of critical importance when evaluating the impact of management practices. For example, numerous studies that focused exclusively on the plow layer soil concluded that C storage is substantially increased by no-till vs. conventional-till practices (Doran, 1980; Franzluebbers et al., 1994; Clapp et al., 2000; West and Post, 2002; Chan

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Abbreviations: DCB, dithionite-citrate-bicarbonate; DM, dry matter; DOC, dissolved organic carbon; DOM, dissolved organic matter; F, fraction of maize-derived SOM; MP, maize plant; MS, maize soil; SOC, soil organic carbon; SOM, soil organic matter; WP, wheat plant; WS, wheat soil.

et al., 2002; Sainju et al., 2002; Franzluebbers, 2005). When subsurface layers are included in the analysis, the effect of no-tillage on C sequestration can remain positive (Olson et al., 2005) or no longer be detectable (Deen and Kataki, 2003). This highlights the importance of determining the kinetics of new C accretion and turnover rate throughout the multiple layers of rooting-depth soil. The objective of the present study was to determine the kinetics of new C accretion throughout the 1-m profile of a cultivated loam soil under wheat to maize transition through annual monitoring of the ^{13}C signature of the SOM over a 10-yr transition sequence.

MATERIALS AND METHODS

Site Description

The wheat-maize succession experiment was conducted at the "Les Closeaux" INRA field experiment in the "Parc du Château de Versailles," France. The soil is classified as a Eutric Cambisol and a Eutrochrept according to the FAO and USDA classifications, respectively.

Thirty-two research plots of 15 by 6.4 m each were installed in 1992 on a wheat field that had been cultivated for at least 50 yr, mainly in cereals, but had never received any C4 plant. For each growing season from 1993 through 2001, three (four in 1993) randomly-selected plots were sown to maize (*Zea mays* L.), and the other ones were cropped with winter wheat (*Triticum aestivum* L.). Four control plots remained under wheat. The experimental plots were sampled in April 2003, when the experimental design had generated a simultaneous and random distribution of plots having received 0 yr of maize after wheat (i.e., the four control plots) and from 2 to 10 yr of maize after wheat, with three replicates from 2 to 9 yr and 4 replicates for the 10th year. Plots are managed according to standard agricultural practices for similar field crops in the Paris basin. Under either wheat or maize cropping, crop residues were returned to the soil after harvest and all plots were moldboard plowed to a depth of 30 cm in October of each year. Corn was manually harvested, and ears were hand shucked in the field, so that only grains and cobs were exported; all other plant organs were returned as residue to the soil surface during the subsequent machine-cutting of the stems.

Soil Samples

Soil properties were determined at the onset of the experiment in 1992. Particle-size distribution obtained after soil dispersion using chemical dispersants, pH in water, cation exchange capacity (CEC) at pH 7, and abundance of exchangeable cations (Ca^{2+}, Mg^{+}, Na^{+}, K^{+}) were determined using standard methods (Baize, 1988).

Plots were sampled on 16 Apr. 2003 to a depth of 105 cm with a hydraulic probe equipped with a 2-cm-diam. sampling core. Four cores were extracted from each plot. All cores were divided in 15-cm depth increments and the four subsamples per plot were pooled together. Soils were air-dried and sieved at 2 mm. Carbonates were absent from the 105-cm soil profile, as is later presented in the results section. This indicates that soil samples did not require carbonate removal before organic C and $\delta^{13}C$ determination. Twenty-gram subsamples of the 2-mm fraction were ground to pass a 200-μm sieve. Soil samples were analyzed for C and N contents and $\delta^{13}C$ isotope ratios were measured on the same analysis by automated measurement of quantity and ^{13}C content of CO_2 evolved from a CHN auto-analyzer (CHN NA 1500, Carlo Erba Instruments, Milan, Italy) coupled with an isotopic ratio mass spectrometer (VG Sira 10) (Girardin and Mariotti, 1991). The laboratory reference is calibrated against the international standard Vienna Pee Dee Belemnite (VPDB). Results were expressed as $\delta^{13}C$, the isotopic ratio ($^{13}C/^{12}C$) relative to the standard.

Ammonium oxalate-extractable Fe and Al (Fe_o and Al_o) and dithionite-citrate-bicarbonate-soluble Fe and Al (Fe_d and Al_d) were quantified on the 2-mm ground soil samples from the April 2003 sampling and were estimated according to Holmgren (1967). The Fe_o and Al_o were estimated by extraction with 0.2-*M* acid NH4-oxalate solution at pH 3.0 for 4 h in the dark (Blakemore et al., 1987), followed by centrifugation at 1500 g for 30 min. Extracted Fe and Al contents were determined by inductively coupled plasma with an ICP–AES 61E, Thermo Jarrell Ash Polyscan (Thermo Electron, Barcelona, Spain). These extractions methods were chosen because they were reported as giving the best correlations with SOM sorption properties in forest soils (Kaiser et al., 1996). Here we tested this relationship for agricultural soils.

Bulk density measurements were conducted on undisturbed samples collected every 15 cm in one soil pit opened in the research plots in April 2005. Samples were taken directly from one face of the pit with a tube corer (8-cm diam. by 10-cm height) inserted perpendicularly to the soil profile. Three replicates were taken from each of the 15-cm layers. Samples were then oven-dried at 105°C for 76 h before being weighed. Visual description of the soil profile was conducted on the open pits.

Biomass Estimates

Corn plant biomass and yields were estimated in September 2003 by a census of the total number of corn plants in each plot combined with destructive analyses conducted on 12 randomly selected corn plants per plot. Stalks of selected plants were cut 20 cm above-ground in agreement with machine cutting of the stems. Selected shoots were separated into male flowers, stems, leaves, and ears. The latter included grains and cobs, but not the husks, which were pooled together with the leaves and were consistent with harvest methods. Ear shanks were pooled together with the stems. The proportion of stem base to total stem was estimated separately on four random groups of three plants each. This proportion (i.e., 11.5%) was used to correct the measured stem biomass to account for all stem material returned to plots at harvest. All plant organs were weighted, and subsamples were dried at 60°C. Subsamples were consistently weighted just after they had cooled down (i.e., about 2 h after removal from the forced-air dryer) so that potential hygroscopic adsorption of water from the air moisture was consistent among samples.

Plant biomass returned to plots at harvest had to be estimated for years previous to 2003 for lack of consistent measurements throughout the 10-yr period. Plant biomass inputs were estimated from grain yield data and the ratio of grains to other plant organs as measured in 2003. For 8 out of 11 yr, grain yield data were obtained from direct measurements in the research plots. For 1996, 2001, and 2002, data from similarly managed fields within the research station were used. These data were corrected for the 8-yr average yield deviation between the Closeaux research plots and the surrounding experimental maize fields. Root biomasses were estimated in 2003 at the time of harvest (i.e., on 12 September). Undisturbed soil samples were collected in four of the maize research plots with an 8-cm-diam. auger specific to root sampling (SDEC, Reignac sur Indre, France) to a maximum depth of 90 cm by successive increments of about 15 cm. Precise sample depths were recorded. Three soil cores were collected in each of the four plots for a representative sampling of the row, the inter-row and the region in between. Soil samples were kept frozen until the day of root extraction. Roots were washed free of soils by adding 200% water by volume and shaking at 150 rpm for 30 min. The slurry was sieved at 500 μm. Main visible roots were hand-picked from the sieve. The remaining organic material was separated from the mineral particles by flotation in water and the remaining roots were hand-picked from the organic debris. Roots were dried at 40°C because this material needed to be used for subsequent molecular analyses not presented in this study. We estimated the amount of fine root biomass lost through the 500-μm sieve by sieving the slurry at 50 μm, decanting, and hand-picking roots under a binocular magnifying glass. This extremely tedious operation could only be conducted on 5 samples because of time constraints. The data suggested that roots lost in the 50- to 500-μm slurry represent 3 and 10% of root biomass retained on the 500-μm sieve for the 0- to 15- and 15- to 30-cm depths, respectively. For deeper horizons, this value was approximately 20%. Root biomasses were corrected accordingly. Root biomass inputs to soils for growing seasons previous to 2003 were estimated similarly to other plant organs and were based on recorded grain yields and the 2003 measured grain yields/root biomass ratio in the different soil layers. All plant organs were ground to pass a 200-μm sieve and analyzed for total C and N using a NA 1500 CHN auto-analyzer (Carlo Erba Instruments, Milan, Italy).

Mathematical and Statistical Analyses

Percentages C and N were converted into total amounts present per soil layer (g m^{-2}) through multiplication with the measured soil bulk densities. The $\delta^{13}C$ values were converted into proportions *F* of maize-derived soil organic carbon (SOC) through the formula of Balesdent and Mariotti (1996):

$$F = \frac{SOC_{MSnew}}{SOC_{MS}} = \frac{\delta_{MS} - \delta_{WS}}{\delta_{MP} - \delta_{WP}} \qquad [1]$$

The subscripts MS and WS stand for soil of maize and wheat plots, respectively. The subscripts MP and WP stand for maize and wheat plant input, respectively, and MSnew stands for the recent contribution of maize-derived organic matter to soils of the maize plots. The δ_{MS} and δ_{WS} were determined for each 15-cm soil layer in the present study. The $\delta^{13}C$ values of maize and wheat tissues had previously been determined at the site, as reported by Dignac et al. (2005). For maize, these values were −12.8, −12.5, and −11.8‰, in leaves, stems, and roots, respectively. For wheat these values were −28.5, −27.6, and −28.4‰, in leaves, stems, and roots, respectively. Weight-averaged isotopic signatures were computed for each soil horizon according to the estimated distribution of maize inputs into the soil profile. This implies that below the Ap horizon all C contributions were assumed to come from roots. Although this hypothesis is probably not entirely correct, as we will later discuss in this article, it seemed better than assuming a uniform contribution of leaf, stem, and root C throughout the 105-cm soil profile. Estimated C incorporation rates are not strongly affected by the slight uncertainty on the exact ^{13}C signature of the maize plant in deeper horizons because the amplitude of the ^{13}C signal is large between maize and wheat tissues as compared to among-organ variations within each species.

Linear regressions were computed with SigmaPlot 9.0 (Systat Software, Point Richmond, CA).

RESULTS

General Profile Description

The soil profile was characterized by smooth texture transitions from silt loam in the upper 60-cm soil profile to loam at greater depth (Table 1). Rock fragments were virtually absent from the soil profile (Table 2). Bulk density was 1.50 Mg m^{-3} in the upper 15 cm of soil and varied little with depth. Bulk density of the 0- to 15-cm soil layer in an adjacent field was 1.51 Mg m^{-3} (data not shown) which suggests that bulk density displays little spatial variability in this soil and that our single-profile measurements at the Closeaux were sufficient for the purpose of this study. The pH varied from 6.8 in the plow layer to 8.0 at a meter depth, and the exchange complex was well saturated in bases, mostly with Ca^{2+} (Table 1). Extractable Fe forms were present in much higher concentrations than extractable Al forms. Oxalate-extractable Fe concentration decreased with soil depth, whereas dithionate-citrate-bicarbonate (DCB)-extracted Fe concentrations were more uniform throughout the 105-cm soil profile. In spite of prevailing high pH conditions, calcium carbonate was present nowhere in the upper 105-cm soil profile at concentrations above our detection limit of 2 g $CaCO_3$ kg^{-1} (Table 1) which confirmed negative results from simple acid-reaction tests (Table 2).

Munsell color identification suggested that substantial amounts of SOM were present in the B_1 horizon, immediately subjacent to the plow layer (Table 2). The Ap and B_1 horizons harbored substantial earthworm activities which appeared virtually absent at greater depths (Table 2). Substantial root populations were observed throughout the soil profile (Table 2).

Plant Inputs

Maize grain yields at the Closeaux experimental plots averaged an 8480 kg DM ha^{-1} between 1993 and 2003 (Fig. 1). The highest yield was recorded in 1997 with 10 110 kg DM ha^{-1}, and the lowest in 2001 with 6410 kg DM ha^{-1}. In 2003, which is our reference year for allometric relationships, the measured yield was 8985 kg DM ha^{-1} (Table 3). Therefore, 2003 appears quite representative of the 10-yr period, with a measured yield only slightly higher than the 10-yr average.

In 2003, above-ground maize biomass was 9045 kg DM ha^{-1} (Table 3). This value implies that the 2003 harvest index was 0.50 when considering stubble in total biomass and 0.53 when excluding stubble from above-ground biomass as is most often the case. Our measured harvest index corresponds typically to literature values. In a compilation of several studies, Prince et al. (2000) report that maize harvest index varies between 0.46 and 0.58 and that 0.53 is the preferred value for the purpose of developing allometric relationships. Maize plant inputs totaled an estimated 5020 g C m^{-2} from 1993 through 2002 (Table 3). About 60% of this total was in the form of leaves and stems, which were incorporated to the Ap horizon during plowing operations. The remaining 40% was the root contributions throughout the 90-cm soil profile.

Table 1. Soil properties of the "Closeaux" experimental research plots. Standard deviations are in parentheses. Values for texture, pH water, cation exchange capacity (CEC), and exchangeable base cations are linearly interpolated from 0- to 30-cm, 30- to 40-cm, 40- to 60-cm, 60- to 80-cm, and 80- to 100-cm depths from 1992 auger sampling (n = 4). Bulk density (D_b) from a 2005 profile sampling every 15 cm (n = 3). CaCO3 and oxalate and dithionite-citrate-bicarbonate (DCB) extracted Fe, Al from a 2003 auger sampling every 15 cm (n = 4).

	Texture												Oxides hydroxides				
	Clay	Silt		Sand					Exchangeable base cations				Oxalate		DCB		
Depth	0–2 μm	2–20 μm	20–50 μm	50–200 μm	200–2000 μm	D_b	pH	CEC	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	Fe	Al	Fe	Al	$CaCO_3$
cm	g kg^{-1}					Mg m^{-3}		cmol$_c$ kg^{-1}					g kg^{-1}				
0–15	174 (8)	208 (7)	322 (30)	242 (25)	52 (2)	1.50 (0.07)	6.8 (0.2)	12.0 (0.3)	11.2 (0.3)	0.88 (0.05)	0.05 (0.01)	0.51 (0.11)	2.40 (0.15)	0.61 (0.05)	5.98 (0.45)	0.85 (0.10)	<2
15–30	174 (8)	208 (7)	322 (30)	242 (25)	52 (2)	1.47 (0.01)	6.8 (0.2)	12.0 (0.3)	11.2 (0.3)	0.88 (0.05)	0.05 (0.01)	0.51 (0.11)	2.44 (0.14)	0.61 (0.06)	6.42 (0.14)	0.86 (0.09)	<2
30–45	167 (8)	196 (7)	318 (27)	259 (14)	58 (15)	1.49 (0.03)	7.3 (0.2)	9.8 (0.6)	10.5 (0.8)	0.72 (0.06)	0.05 (0.01)	0.23 (0.03)	2.20 (0.25)	0.60 (0.07)	6.27 (0.63)	0.85 (0.13)	<2
45–60	169 (12)	189 (12)	315 (15)	264 (21)	60 (12)	1.52 (0.03)	7.6 (0.2)	9.4 (0.6)	10.6 (0.9)	0.68 (0.06)	0.06 (0.01)	0.21 (0.01)	1.67 (0.41)	0.58 (0.09)	5.52 (0.68)	0.80 (0.11)	<2
60–75	195 (14)	185 (17)	290 (12)	267 (22)	62 (13)	1.61 (0.01)	7.8 (0.2)	10.5 (0.8)	11.9 (1.3)	0.84 (0.09)	0.07 (0.01)	0.24 (0.02)	1.50 (0.23)	0.61 (0.08)	4.79 (1.74)	0.72 (0.25)	<2
75–90	203 (20)	181 (21)	281 (21)	268 (33)	64 (20)	1.60 (0.02)	8.0 (0.1)	10.9 (1.1)	12.6 (1.7)	0.99 (0.15)	0.08 (0.01)	0.24 (0.02)	1.41 (0.25)	0.73 (0.05)	6.06 (0.49)	0.95 (0.10)	<2
90–105	207 (23)	179 (23)	277 (26)	269 (39)	65 (24)	1.61 (0.01)	8.0 (0.1)	11.1 (1.2)	13.0 (2.0)	1.07 (0.18)	0.08 (0.01)	0.25 (0.02)	1.77 (0.59)	0.77 (0.15)	6.79 (1.65)	0.97 (0.09)	<2

Root C contributions in the top 15 cm more than doubled those in the 15- to 30-cm soil layer. Below the Ap horizon, the root profile appeared quite uniform, with only 35% more roots in the 30- to 45-cm layer than in the 75- to 90-cm layer. The biomass shoot/root ratio was 5.7 (Table 3) which is extremely close to the 5.5 value provided by Bolinder et al. (1999) in a review of eight different studies on maize plants. This further confirms that 2003 was a normal year with respect to allometric relationships for maize plants and could be used as a standard for the other years.

Soil Carbon and Nitrogen Content and $\delta^{13}C$ Signature

The duration of maize cropping after wheat did not modify the total C content of any of the seven 15-cm-thick soil layers (Fig. 2), indicating that the SOM remained at apparent steady state in spite of the cropping transition. Indeed, no significant correlation was observed for any soil layer between C concentration and duration of maize cropping (data not shown). Total organic C stocks were about equal in the plow layer than in the subjacent 30- to 105-cm soil profile (Fig. 2). The vertical distribution of organic N concentration and C/N ratio closely mimicked that of C (Fig. 2).

The soil $\delta^{13}C$ signature under wheat was nearly uniform throughout the depth of the soil profile, from −26.1‰ in the upper soil layer to −25.9‰ at 1-m depth (Fig. 3). The highest shift in the soil $\delta^{13}C$ value in response to maize cultivation was observed in the Ap horizon which reached −24.5‰ after 10 yr of treatment. Within the Ap horizon, the 15- to 30-cm layer appears to have accumulated maize-derived SOC at a slightly higher rate than the uppermost 15-cm soil layer. The lowest isotopic shift was observed in the 90- to 105-cm soil layer which reached −25.3‰ after 10 yr of treatment. When converted into percentage SOC through Eq. [1], these data indicate that after 10 yr of maize cultivation, maize-derived SOC constituted about 10, 5, and 2% of the total SOC at 15-, 50-, and 100-cm depths, respectively (Fig. 4). In other words, assuming linear kinetics, the rate of SOC turnover approximated 1.0, 0.5 and 0.2% yr^{-1} at 15-, 50-, and 100-cm depths, respectively. Highly significant correlations between the proportion of maize-derived SOC and the duration of maize cultivation were observed in each layer of the top 90 cm of soil (Fig. 4).

Thirty-seven percent of the maize-derived recently deposited organic matter was retrieved below the plow layer (i.e., 312 g C m^{-2} out of a total of 850 g C m^{-2}) (Table 4). This deeper C was mostly retrieved in the layer immediately subjacent to the plow layer which accumulated an estimated 203 g C m^{-2}. The 75- to 90-cm layer accumulated only 24 g C m^{-2}, or about 10% of plow-layer accumulation on a comparable layer thickness.

Apparent humification ratios of maize-residue C into medium-term stabilized SOC averaged 17% across the soil profile (Table 4). This humification ratio was lower in the Ap horizon (i.e., 13%) than in deeper soil layers (Table 4). The highest value (i.e., 71%) was observed in

Table 2. Visual description of the Closeaux soil profile.

Horizon	Depth	Munsell color	RF†	Structure‡	Acid reaction	Roots	Earthworms
	cm	moist	%				
Ap	0–28	10 YR 4/3	<1 gr	sbk	negative	many fine	many
B_1	28–44	10 YR 4/4	<1 gr	sbk	negative	many fine	many
B_2	44–82	10 YR 5/4	<1 gr	sbk	negative	common fine	–
BC	82–100	10 YR 5/4: 6/4	<1 gr	sbk	negative	common fine	–

† RF, rock fragments; gr, gravel.
‡ sbk, subangular blocky.

the soil layer immediately subjacent to the plow layer. At depths of 45 to 60 cm and 60 to 75 cm, the apparent humification ratio decreased to 26 and 17%, respectively. The apparent humification ratio at the bottom of the soil profile was equal to that of the plow layer, or 13%.

Across three soil depths (i.e., 15- to 30-cm, 30- to 45-cm, and 45- to 60-cm, and 14 research plots) the distribution of total C was highly correlated (r^2 = 0.86, n = 42) to the distribution of oxalate-extractable Fe and Al contents (Fig. 5). Remarkably, strong correlations also existed within single horizons, especially at depths of 30 to 45 cm (r^2 = 0.68, n = 14) and 45 to 60 cm (r^2 = 0.68, n = 14). These data suggest that both the horizontal and vertical distributions of total C were strongly influenced by the distribution of the amorphous forms of Fe and Al, as measured through oxalate extraction. These high correlations with SOC were not observed for DCB-extracted Fe + Al contents, with r^2 of 0.00, 0.05, and 0.26 at 15- to 30-cm, 30- to 45-cm and 45- to 60-cm depths, respectively (data not shown). This suggests that amorphous more than crystalline forms of Fe and Al were responsible for DOC sorption.

DISCUSSION

The present study demonstrates that SOM turnover happens at a faster rate in the upper than in the lower horizons. This decrease in SOM turnover rate with depth in maize-planted soils has also been observed by Flessa et al. (2000). Nevertheless, these authors reported fairly low turnover rates (i.e., about 13 and 5% over a 37-yr period) in the plow and sub-plow layers, respectively. The authors indicate that shoot removal at harvest might account for this apparently low SOC turnover rate. Our estimated value of about 10% SOC turnover in the plow layer after 10 yr of maize crop is more in line with other literature estimates for surface horizons. Incorporation of maize-derived SOC into soils previously under C3 plants was reported to reach about 10% after 13 yr in Minnesota (Clapp et al., 2000) and 29% after 17 yr in moldboard-plowed loam soils in France (Balesdent et al., 1990). Between 18 and 29% of new C from C3 crops had accumulated 27 yr after converting a C4 prairie to arable land in Missouri (Balesdent et al., 1988).

The humification ratio estimated for the Ap horizon (i.e., 13%) appears consistent with other literature estimates. Compiling several studies, Bolinder et al. (1999) estimated that the humification ratio of maize residues averages 12.2% for shoots and 19.6% for roots. In a ryegrass incubation study, Broadbent and Nakashima (1974) estimated these values to be 12% for shoots and 16% for roots. Based on the data from an experiment located within a few kilometers of the Closeaux site and on a similar soil type (Balesdent and Balabane, 1996), we computed a maize-residue humification ratio of 10% for shoots and 19% for roots (including 50% exudation), averaging 14% for the entire plant.

The ratio of C concentrations in soil layers immediately above and below the estimated depth of the plow pan was 0.79 in our experiment (Fig. 2 values corrected for small depth variations in bulk density). This estimate somewhat depends on our ability to precisely split soil cores at plow-pan depth as we analyzed the entire

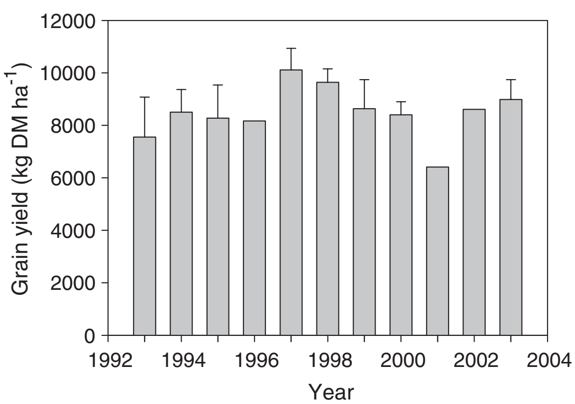

Fig. 1. Maize grain yields between 1993 and 2003. Yields were measured at the Closeaux sites except for 1996, 2001, and 2002 when data were only collected as a single-value average across the INRA-Versailles experimental station where the Closeaux plots are located.

Table 3. Measured maize dry biomass (DB) in 2003 and estimated cumulative C input from maize plant residues over the 1993 through 2003 period. Standard deviations of the mean are in parentheses with n = 28 for above-ground organs and n = 4 for roots, except for the deepest layer where n = 1.

	Maize DB	Maize C inputs§
	kg DM ha^{-1}	g C m^{-2}
Grains	8980 (± 760)	–
Cobs	1490 (± 130)	–
Leaves†	3911 (± 422)	1531
Stems‡	3644 (± 390)	1510
Roots 0–15 cm	1198 (± 312)	756
Roots 15–30 cm	556 (± 261)	351
Roots 30–45 cm	455 (± 182)	287
Roots 45–60 cm	326 (± 162)	206
Roots 60–75 cm	303 (± 175)	191
Roots 75–90 cm	298	188

† Including husks.
‡ Total stems, from ground level to top of male flowers. The 20-cm-high stubble represented 26% of this total.
§ C concentrations of leaves, stems, and extracted roots were 42, 44, and 34%, respectively. The C contribution of roots was considered twice that of biomass to account for root exudates, according to Barber (1979).

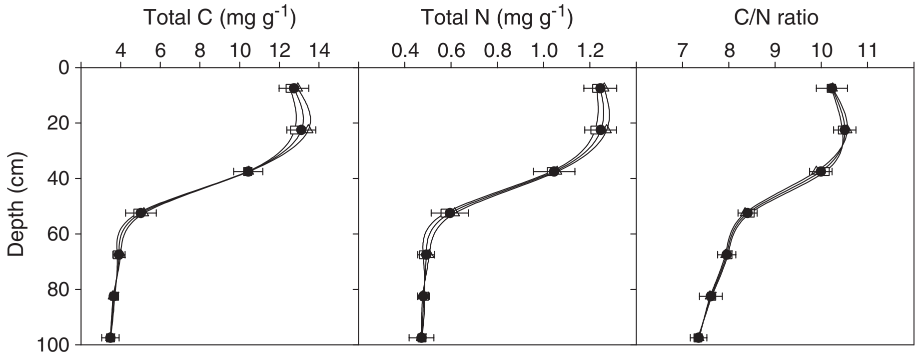

Fig. 2. Distribution of total C, total N, and C/N ratio with soil depth at the Closeaux experimental plots. Date represent 10-yr averages (*n* = 10, filled circles) with standard deviations, averages for 0 to 5 yr of maize (*n* = 5, empty squares), and 6 to 10 yr of maize (*n* = 5, empty triangles).

soil column in the present study. Analyses of a limited number of profile-type subsamples conducted in 1992 suggested this value to be 0.6 (data not shown). This discrepancy highlights the importance of C accumulation around plow-pan level as suggested by the present data, and advocates for a sampling method that leaves no soil out of the analyses. We tried to estimate a similar value from literature data available on tilled cultivated loam soils. High ratios from 0.8 to 0.98 were derived from several studies conducted in the Netherlands (Pulleman and Marinissen, 2004), Colorado (Paul et al., 1997), and Illinois (Yang and Wander, 1999). Other studies yielded a lower ratio than that obtained at the Closeaux: about 0.55 across chisel and moldboard treatments both in Ohio (Puget and Lal, 2005) and Ontario loam soils (Deen and Kataki, 2003), and an average of 0.42 across five U.S. Midwest loams under inversion tillage (Collins et al., 1999). Therefore, the presence of substantial C amounts in soil layers subjacent to the plow layer appears frequent in cultivated loam soils.

Here we report a high apparent stabilization ratio of maize residues into SOM in the 30- to 45-cm layer, but also in the 45- to 60-cm layer (Table 4). This ratio is only an estimate because it combines multiple data sources and notably above- and below-ground plant input estimates that essentially represents 1 yr of measurements, even if yields were available throughout the experiment. It also combines potential imprecision on sampling depths of both the hydraulic probe and the root auger, neither of them being as precise as open-pit profile sampling. The very low variability of C content data for the 30- to 45-cm layer (Fig. 2) suggests that sporadic contamination was not a problem. In addition, the visual description of the profile also indicated the presence of substantial amounts of SOM and biological activities in the soil layer immediately subjacent to the plow layer (Table 2).

The specific accumulation of recently deposited SOM in sub-plow layers could be due to: (1) reduced mineralization, (2) higher than expected root contributions, and (3) transfer of organic matter from the overlying Ap horizon. The latter is potentially mediated by leaching of dissolved organic C (DOC), water transport of particulate organic C, and macrofaunal activities. Here, we will briefly consider the likelihood of the different processes.

Reduced mineralization in the 30- to 45-cm and 45- to 60-cm soil layers is unlikely because no soil biophysical characteristic stands out to support this hypothesis. The adsorption capacity of the soil matrix for protecting SOM from degradation did not appear remarkably high in the 30- to 60-cm layers as compared to that of the Ap horizon in terms neither of CEC, texture, or oxides-hydroxides (Table 1).

Root activities could potentially explain the large amounts of recently deposited C detected below the Ap horizon. A recent estimate suggests that root C has an average mean residence time in soils 2.4 times that of shoot-litter C (Rasse et al., 2005). The correlation between estimated root C inputs and maize-derived soil C (raw data in Table 4) is high ($r = 0.96$, $P < 0.01$, data not shown). Nevertheless, such a high correlation is expected as the two variables co-vary with depth, and does not truly explain the lower humification ratio in the Ap horizon. Fine root activities, which were not quantified in the present study, might be a better indicator of C input and stabilization. Here we considered that C contribution from rhizodeposition was equal to that of root biomass, as suggested by Barber (1979). Although this value might be about correct on average, the more active fine roots are likely to contribute more to turnover and rhizodeposition processes than the larger roots mostly present in the surface horizon. Rhizodeposition might contribute substantial amounts of C to sub-plow layers. Recent studies suggest that rhizodeposition is of much larger magnitude than previously thought (Molina et al., 2001; Wilts et al., 2004). About a quarter of N uptake is subsequently released through rhizodeposition processes (Molina et al., 2005). It is therefore possible that fine root activities were particularly intense in the 30- to 60-cm-depth soil layer, and contribute to enrich this layer in recently deposited SOM. However, the reduced humification ratio within the deepest soil layer suggests that fine root activities do not explain the entire profile of recently deposited C.

Transfer of SOM from the Ap horizon to the subjacent 30- to 45-cm soil layer might have occurred over a short distance. Soil inversion by moldboard plowing tends to concentrate plant residues at the bottom of the plow layer (Allmaras et al., 1996). This residue C needs only transport over a few cm to substantially affect the C

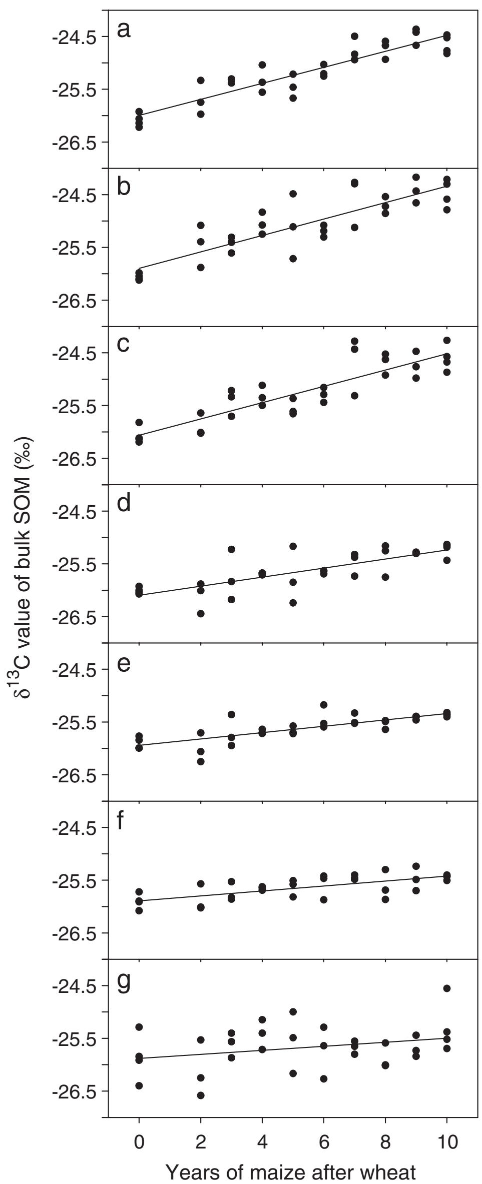

Fig. 3. Distribution of the soil $\delta^{13}C$ signature (‰) as a function of depth in the profile and the duration of maize cropping following wheat: (a) 0 to 15 cm, (b) 15 to 30 cm, (c) 30 to 45 cm, (d) 45 to 60 cm, (e) 60 to 75 cm, (f) 75 to 90 cm, and (g) 90 to 105 cm. All 224 data points represented.

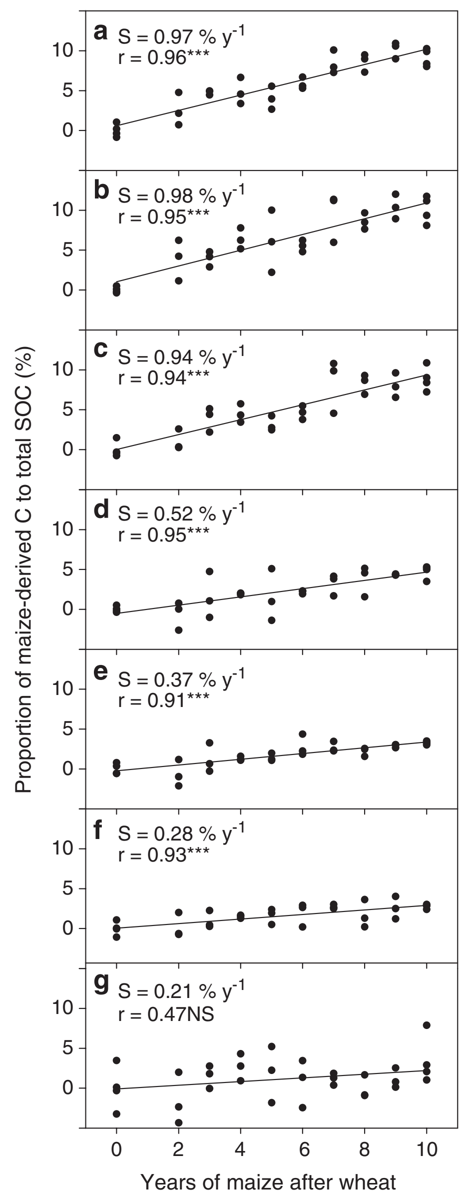

Fig. 4. Distribution of the resulting proportion of new maize soil organic carbon (SOC) (%) as a function of depth in the profile and the duration of maize cropping following wheat: (a) 0 to 15 cm, (b) 15 to 30 cm, (c) 30 to 45 cm, (d) 45 to 60 cm, (e) 60 to 75 cm, (f) 75 to 90 cm, and (g) 90 to 105 cm. All 224 data points represented. *, significant at $P \leq 0.001$; NS, not significant; S, slope.**

content of the 30- to 45-cm layer. Recent studies suggest that particulate transport of organic matter can be substantial within agricultural soils (Wu et al., 2004). In addition, substantial earthworm populations appeared active throughout the upper 45-cm soil profile, while deeper horizons appeared nearly devoid of such activities (Table 2). Modeling analyses have suggested that diffusion-type soil mixing processes, such as earthworm activities, explain more of the C depth-distribution profile than does convective transport of DOC through drainage waters (Elzein and Balesdent, 1995).

Pronounced correlations between soil C and Fe + Al contents (Fig. 5) suggest that DOC might play an important role in shaping the SOC profile of this soil. Indeed, transport of DOC and accumulation in sesquioxide-rich layers is a major soil formation process in acid forest soils. In two northern European spruce forests, Michalzik et al. (2003) estimated that DOC transport from upper soil horizons supplies from 73 to 89% of the mineral soil C. In a temperate forest, estimated DOC contribution to deeper soil profile C was 25% (Neff and Asner, 2001).

Could the DOC transport mechanism be substantial enough in the well-buffered agricultural soils of the Closeaux to explain the transfer of recently deposited C throughout the soil profile? The apparent humification ratio for the entire soil profile was 17% (Table 4). If we make the hypothesis that the humification ratio was actually constant across soil layers and that differences in C contents are attributable to DOC transport

Table 4. Comparison between the total input of maize-residue C during 10 yr of cropping and the total amount of maize-derived soil organic carbon (SOC) retrieved through δ^{13}C analyses at the end of the 10-yr period. Data are presented for each 15-cm layer to the maximum depth of root sampling (i.e., 90 cm) except for the 0- to 30-cm Ap horizon where soil was mixed annually by plowing.

Soil layer	Maize input†	Maize SOC	SOC/input ratio
cm	g C m^{-2}		%
0–30	4149	538	13
30–45	287	203	71
45–60	206	53	26
60–75	191	32	17
75–90	188	24	13
Total	5021	850	17

† Above-ground residues were assumed uniformly distributed through the 30-cm plow layer.

mechanisms only, then it implies that 172 g stable C m^{-2} were transferred from the Ap horizon to deeper soil layers over the 10-yr period. This value of 17.2 g stable C m^{-2} yr^{-1} is likely an underestimate because it rests on the hypothesis that all transported DOC consists of stable C, while in practice a substantial proportion of the DOC transported in the upper soil horizon is labile (Qualls and Haines, 1992; Marschner and Bredow, 2002). Estimated water drainage below the maize root zone at the Versailles experimental station averaged 250 mm yr^{-1} over the 1997 through 2001 period (Delattre, 2002). This value of 17.2 g stable C m^{-2} transported by 250 mm water translates into an average concentration of 69 mg C L^{-1}. The actual required concentration is likely to be substantially higher as not all transported DOC is stable. To this amount must be added the DOC concentration from the old SOM of C3 plant origin. This value of at least 69 mg C L^{-1} required to satisfy the DOC transport hypothesis appears high as compared to literature estimates. Two recent incubation studies of maize residues in C3 soil reported that the average DOC concentration of water draining from the Ap horizon ranged between 2 and 5 mg C L^{-1} (Flessa et al., 2000; John et al., 2004). In addition, these authors report that only between one-third and one-fourth of the DOC was of recent maize-residue origin. The DOC concentration in Ap horizons under field crops in southern Sweden was reported to range from 3 to 19 mg C L^{-1} (Karltun et al., 2005). This

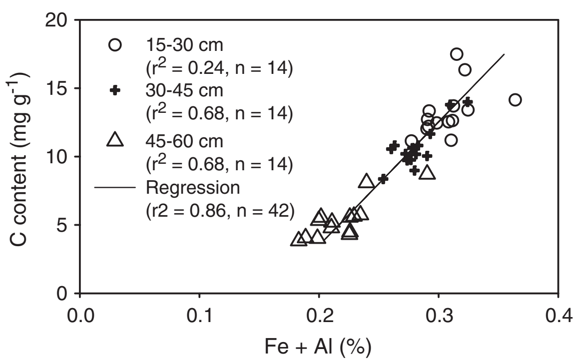

Fig. 5. Relationship between total C and oxalate-extractable Fe + Al content in the 15- to 30-cm, 30- to 45-cm and 45- to 60-cm soil layers at the Closeaux. Linear regression represented for all 42 samples (3 depths and *n* = 14 per depth).

suggests that convective transport of DOC through drainage waters escaping the Ap horizon is not a sufficient mechanism to explain the distribution of the recently-deposited maize-derived C in our system.

In conclusion, our study demonstrates that SOM turnover rate decreases with soil depth in cultivated loamy soils. No single mechanism explained the vertical distribution profile of recently deposited maize-derived C in our system. Circumstantial evidences suggest that fine root activities, bioturbation, and DOC transport all played an important role in shaping the distribution profile of recently-deposited maize-derived C. Our study also stresses the need to take into account the full 1-m soil profile in C sequestration studies, as the sub-plow-layer portion contained about half of the total C stocks and stabilized more than one-third of recent plant-residue C inputs.

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