Carbon Turnover in Soil Physical Fractions

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ABSTRACT

Soil organic matter (SOM) as represented in mathematical simulation models involves several hypothetical pools of differing resistance to decay. These conceptual pools satisfy requirements of modeling, but usually have little in common with existing information on physical and chemical properties of SOM. Using our data on turnover times for soil C in fractions of natural aggregates and primary particles, we attempted to relate age of C in physical fractions with that in widely accepted theoretical pools. Soil from a field experiment with ^{14}C-labeled soybean residues was sampled periodically and separated into physical fractions. The amounts of ^{14}C associated with these fractions at different times provided data for calculation of decay rates and turnover times. The most labile fraction of SOM was plant fragments with turnover time ranging from 1 to 3 yr, which was inversely related to fragment size. Soil aggregates were found to be enriched in C compared with whole soil. This was most pronounced for coarser aggregates whose construction apparently involved the relatively labile plant fragments in some progressive state of decay. The macroaggregates with partially processed C showing turnover from 1 to 3 yr contrasted with microaggregates that included more highly humified C having a longer residence time of ≈ 7 yr. Various soil fractions differing in residence time of associated C were assembled into several groups that demonstrated consistency with conceptual pools of two widely accepted simulation models. Data from ^{13}C natural abundance studies of soil and of primary fractions were in harmony with models requiring at least two pools of stable SOM.

CARBON FLOW through the organic matter of soil is essential to the functioning of terrestrial ecosystems. Recently, this phenomenon has attracted great interest due to concerns about global warming and the prospects for using soil as a sink for C released to the atmosphere by human activity.

It is widely accepted that the term SOM designates a highly heterogeneous pool that includes numerous carbonaceous compounds. These range from easily mineralizable sugars to complex and recalcitrant products of microbial transformations. Residence times of C in these components of SOM vary from a few minutes to hundreds of years. Modeling of C flow through this extremely complex material requires its subdivision into more or less homogeneous compartments, characterized by a narrow range of residence times.

A number of models simulating C and N cycling have been proposed during the last decade. Some of these models adequately describe C and N transformations in different soil types or under different managements. The models have been developed on the presumption that SOM is represented by a changing continuum (Bosatta and Ågren, 1985; Janssen, 1984) or by a number of compartments distinguished on the basis of accessibility of organic C to microorganisms. The number of such compartments varies from one (Jenny, 1941; Woodruff, 1949) to several, sometimes up to 10 (McGill et al., 1981). Two models most often cited in literature were developed by Jenkinson and Rayner (1977) and Parton et al. (1983, 1985, 1988). These models have the same number of compartments with almost identical mineralization rates and residence times. Definition of these compartments, however, is uncertain and does not give a clear idea about physical status of organic material comprising each pool.

Physical fractionation of soil according to particle size has been used to study the stabilization and turnover of organic matter in soil. Quantitative isolation and study of organo-mineral fractions, however, usually requires a combination of degradative chemical and physical methods. Even if chemical treatments are excluded and only physical methods like sonification are used, some changes are unavoidable in structural organization of organic matter, especially that protected inside aggregate units (Aringhieri and Sequi, 1978).

Fractionation by dry or wet sieving into separate groups of aggregates is probably the least disruptive method to isolate organo-mineral complexes for study. Combining C-labeling procedures with a nondegradative fractionation offers an acceptable approach for studying the distribution of C among fractions (Anderson and Paul, 1984; Christensen, 1985, 1986; Wagner et al., 1994). A single observation of distribution of labeled material, however, gives a static picture. Studies over time, therefore, are required to evaluate flow of C between fractions and to determine its residence time in soil.

In one of our long-term experiments with field labeling, we traced the distribution of ^{14}C, originating from labeled plant residues, among different fractions of individual particles and natural aggregates during a time period of

4 yr. We present some of our results related to the residence time of C in decomposing vegetative fragments, aggregates, and mineral particles.

MATERIALS AND METHODS

Soil of Sanborn Field where the experiment was carried out is a Mexico silt loam (fine, montmorillonitic, mesic Udollic Ochraqualf) developed in thin loess deposits overlying glacial till. The surface layer contains 2.5 to 2.9% organic matter. Mean annual air temperature of the region is 13°C, with maximum monthly average in July (26°C) and minimum in January (-1.5°C). Mean annual precipitation is 973 mm, with potential evapotranspiration of 790 mm (Scrivner et al., 1972). The soil has an argillic (Bt) horizon, which causes perching and lateral flow of water above. Upper horizons (Ap and E) are very silty with the E possessing a chroma of 2, indicative of vertical eluviation of clay and oxides (Miles and Hammer, 1989).

In summer of 1985, a soybean crop [*Glycine max* (L.) Merr.] was grown on plots 2.25 by 0.75 m, replicated six times. Plants were labeled three times during intensive vegetative growth. Uniform distribution of the ^{14}C label was accomplished using temporary air-conditioned tents of clear plastic above plots. During labeling, the tents were kept airtight for at least 24 to 36 h, during which time the radioactive label was completely assimilated by the plants. Efforts were taken to keep the ^{14}CO$_2$ uniform through the canopy and, after each labeling, activity absorbed by plants was checked. A significant level of radioactivity in plants was obtained by the time of harvest (up to 18 M Bq kg^{-1} C). This level allowed C mineralization to be tracked for several years. At maturity, the crop was cut at the soil surface, chopped to provide pieces 10 to 15 cm in length, and spread on the respective plots. The next spring, residues were incorporated into the soil by hand, simulating disking. A soybean crop was grown each successive year through 1988. Each of these years the soybean residues were incorporated into soil at maturity. In 1989, the experimental plots were left fallow.

Composite soil samples were taken periodically within a depth of 0 to 10 cm. A total of five samples were taken from each plot. Sampling dates were 10 Apr. 1986, 20 Oct. 1986, 10 Aug. 1987, 26 May 1988, and 11 Nov. 1989. Samples were air dried at room temperature, gently pressed to pass a 2-mm sieve, and stored.

The soil was separated into aggregate fractions by a wet sieving technique (Kemper and Rosenau, 1986). Subsamples of 20 g each were placed on the top of a nest of the sieves operated by a machine. The sieves had openings of 1.0, 0.5, and 0.25 mm. By lowering the nest into a container of distilled water to the floor of the top sieve, the soil was wetted by capillary action for 10 min. Subsequently the sieving machine was engaged for 10 min, after which the aggregates on each sieve were collected by washing with water to yield fractions 2 to 1, 1 to 0.5, 0.5 to 0.25, and <0.25 mm. Floating pieces of crop residues were discarded. The material <0.25 mm was further fractionated by manual wet sieving to yield microaggregates 0.25 to 0.1 mm and material <0.1 mm.

Particle fractionation was completed without using a chemical dispersant, but employing ultrasonification to destroy aggregates. Particle fractions 2 to 0.2, 0.2 to 0.053, and 0.053 to 0.025 mm were separated by manual wet sieving, after which the vegetative component of each was separated by flotation. Fine silt, 25 to 2 μm, was separated from clay by sedimentation. Organic C and N and C/N ratios of aggregates were determined, and activity of ^{14}C incorporated was measured after combustion using a liquid scintillation technique.

RESULTS AND DISCUSSION

Aggregate Distribution and Stability

For all sampling dates, a little more than 50% of the soil was found in macroaggregate fractions, but <5% in the fraction 2 to 1 mm. The latter had a high C enrichment coefficient of 1.35, which defines the increase in C relative to that in whole soil, and the lowest clay content (Table 1). The main portion of macroaggregates was represented by fractions 1 to 0.5 and 0.5 to 0.25 mm. Both fractions have almost similar clay and C contents, and are only slightly enriched with C compared with the whole soil. About 11% of the soil was in the form of microaggregates (0.25–0.1 mm). This fraction had the highest clay content and is highly enriched with C and N. One-third of the soil mass was not aggregated.

Increased clay content with decreasing size of aggregates was also noted by Edwards and Bremner (1967) and Christensen (1986). Since the clay fraction contains a major portion of the organic C and N (Anderson et al., 1981; Tiessen and Stewart, 1983; Christensen, 1987) the higher clay content explains C and N accumulation in microaggregates.

The foregoing argument, however, cannot explain aberration with the macroaggregate fraction, 2 to 1 mm, which has a similar C content (22 g kg^{-1} soil) as the microaggregate fraction, 0.25 to 0.1 mm. Narrower C/N ratio (8.5) and higher clay content in microaggregates are indicative of a different kind of organic matter, which is highly processed and more stable compared with organic matter associated with fraction 2 to 1 mm. The latter has a C/N ratio of 10.2, which is probably attributable to incompletely humified organic material and suggests that active binding agents are root hairs and fungi.

Aggregate stability showed no significant variability associated with sampling position across two replicate plots as determined by Tukey's Studentized range test. Nor were there any significant differences in the quantity of soil distributed among aggregate fractions at various sampling dates during the first two yearly cycles (Aslam, 1992). The quantity of coarse aggregates was significantly higher (<10%) only in the last sampling (fall of

Table 1. Characteristics of water-stable aggregates separated from plots with decomposing labeled soybean residues.†

Size fractions	Quantity	Clay	C	C enrichment ratio‡	C/N ratio
	g kg^{-1}	%	g kg^{-1}		
Macroaggregates					
2–1 mm	48	8.70	22.25	1.36	10.23
1–0.5 mm	238	10.00	17.50	1.06	9.34
0.5–0.25 mm	249	10.72	17.25	1.05	9.04
Microaggregates					
0.25–0.1 mm	109	12.13	22.25	1.36	8.46
Mineral particles					
<0.1 mm, nonaggregated	355		12.00	0.73	7.60
Whole soil	–	9.42	16.38	1.00	8.49

† Each value is mean of 30 observations (five samples collected at different times during a period of 3 yr, from six plots).
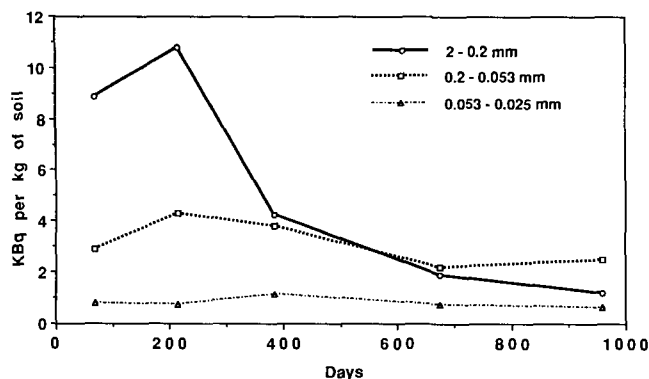‡ Carbon percentage relative to that for whole soil.

Fig. 1. Dynamics of ^{14}C activity associated with vegetative fragments during decay of ^{14}C-labeled soybean residues. Day 0 was 22 Sept. 1985.

Fig. 2. Distribution of radioactivity among aggregate fractions.

1989), but this probably was caused by small changes in residue management. Data on seasonal changes in soil aggregation are conflicting. In some studies (Strickling, 1950; Stefanson, 1971), definite seasonal trends in aggregate stability were found, with maximum in spring and reduced stability through summer. The same authors, however, did not find significant variation in some years. Carbon and N content in the fractions in our experiments was unchanged with time as well.

Dynamics of Carbon in Plant Fragments

Soybean residues left on the soil surface after harvest lost $\approx 22\%$ of the label during the fall due to mineralization. The loss occurred mainly from decomposition of leaves and hulls, which represented ≈ 40 to 50% of the aboveground biomass (Buyanovsky and Wagner, 1986). Until spring tillage, most of the plant material was in the form of large (>2.0 mm) pieces of stems lying on the ground. During spring disking, these pieces were crushed and mixed with the soil. Sampling on 30 April (215th day) showed that the amounts of ^{14}C associated with fragments 2 to 0.2 and 0.2 to 0.053 mm reached their maximum after cultivation (Fig. 1). The >2-mm fraction had disappeared almost completely by this time.

Specific activity in the coarse vegetative fragments showed a progressive decline with time, and after 3 yr was $\approx 4\%$ of initial activity and less than that in the whole soil. The activity in smaller vegetative fractions initially increased during the first year and then declined, suggesting a flow of the label from the larger pieces of residue to the small ones. Taken as a whole, the specific activity changes reflect fragmentation of plant residues with time, mineralization of C by soil organisms, and a dilution with fresh unlabeled residues.

Degradation rates and mean residence times of C in

plant fragments were computed from total activity data beginning at the point when maximum label content occurred in each fraction (Table 2). It appears that the mean residence time of C (t_{mr}) for the coarse material is ≈ 1 yr. For the fraction 0.2 to 0.053 mm, t_{mr} is 1.5 yr, and for the finest fraction is 2 yr. A small amount (1-2%) of initially labeled material was identified in these fine fractions as late as the third year of cultivation.

Carbon in Aggregates

Radioactivity recovered in aggregated soil material in the first spring after labeling was 42% of the total ^{14}C residing in the soil. Approximately one-half of ^{14}C was in unbound, coarse plant fragments, not associated with aggregates. Most of the C associated with aggregates was found in macroaggregates, which comprised 80% of the total aggregated soil material. The activity in macroaggregates demonstrated declining rate curves (Fig. 2) whereas activity in microaggregates showed a nearly linear decline. The three size fractions of macroaggregates showed significant differences in residence time for C, with smaller aggregates demonstrating the greater persistence (Table 3).

The specific activity of ^{14}C was initially highest in the 2- to 1-mm aggregate fraction and showed a rapid disappearance of the label, especially during the first year after plant labeling. The decay rate for C in coarse aggregates calculated from total activity data appeared to diminish significantly after the first year. Mean residence time for coarse aggregates during the initial period was ≈ 1 yr, a value similar to that for vegetative particles

Table 2. Degradation rates, k, and mean residence time of C, t_{mr}, in labeled plant fragments.

Plant fragments	k	t_{mr}
mm	d^{-1}	yr
2-0.2	0.0030	1
0.2-0.053	0.0018	1.5
0.053-0.025	0.0013	2

Table 3. Degradation rates, k, and mean residence time of C, t_{mr}, in aggregates.

Aggregate size	k		t_{mr}
	Initial 0.5 yr	Next 3 yr	
mm	— yr^{-1} —		yr
Macroaggregates			
2-1	1.24	0.16	0.8-4
1-0.5	0.65	0.09	1.5-10
0.5-0.25	0.36	0.11	3-10
Microaggregates			
0.25-0.1	†	0.15	7
Nonaggregated soil mineral particles	†	0.14	7

† No detectable period of rapid decay.

of this size. Apparently the aggregates are held together by thin roots and fungi binding soil particles to sizable vegetative fragments. A wider C/N ratio also supports this suggestion. Rapid destruction of these bioaggregates may be caused by death of fungal hyphae and decay of the plant fragments. Part of these aggregates, or the C they contained, later became stabilized and mean residence time was extended. Because aggregates 2 to 1 mm represent only 4 to 5% of total soil mass and <6% of C, their role in total C transfer is not very significant.

The fraction 1 to 0.5 mm represents ≈23 to 25% of the soil and contains about one-third of the total C. There are reasons to believe that at least part of these aggregates are also organized around small vegetative particles. Both 2- to 1- and 1- to 0.5-mm fractions had wide C/N ratios, and total activity of C as well as specific activity showed maximum values in the beginning of the process. Residence time of C in the 1- to 0.5-mm fraction initially was ≈1.5 yr, and later appeared to significantly increase (Table 3). For the fraction 0.5 to 0.25 mm, the calculated residence time of C is ≈3 yr or greater.

The fact that macroaggregates have a short residence time for C corroborates very well with the results of other studies which demonstrate that this fraction is sensitive to changes in soil organic matter level induced by soil management and is dependent on live binding agents (Tisdall and Oades, 1979). Rapid degradation of these bioaggregates may be caused by the death of fungal hyphae and decay of the plant tissues. Elliott (1986) showed that organic matter associated with macroaggregates is more labile and less highly processed than that in microaggregates. Christensen (1986) found significant differences in incorporation of straw C into aggregates, with the fraction <0.25 mm practically unaffected by C addition, while the 1- to 2-mm fraction showed a marked effect of straw addition.

Our calculations show that organic C in microaggregates has a residence time of ≈7 yr (Table 3). It is known from other studies that this fraction is relatively stable against physical disruption (Edwards and Bremner, 1967; Tisdall and Oades, 1979). Elliott (1986) and Gregorich et al. (1989) also showed that organic matter associated with microaggregates is more recalcitrant than that associated with whole or crushed macroaggregates.

Mineral particles not organized into aggregates (<0.1 mm) have the lowest C content (C enrichment ratio 0.73) and narrowest C/N ratio (7.6) (Table 1). In Mexico silt loam, approximately one-third of total C is associated with nonaggregated mineral particles. Carbon associated with this fraction has a mean residence time of at least 7 yr (Table 3).

Carbon Dynamics in Mineral Fractions

Soil samples examined after ultrasonification were used to determine ^{14}C associated with fine silt (25–2 μm) and clay (<2 μm). Total activity associated with these mineral particles was low and relatively constant throughout the period of study (Fig. 3). For both silt and clay particles, the maximum amount of ^{14}C and the highest specific activity were observed at 1 yr after harvest of the labeled crop. When this ^{14}C associated with silt and
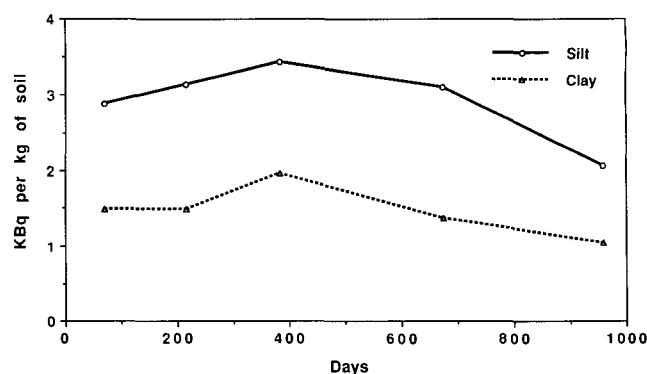

Fig. 3. Dynamics of ^{14}C activity in silt and clay fractions. For fine silt mineralization rate coefficient (k) is 0.0004 d^{-1} and mean residence time of C (t_{mr}) is ≈7 yr, for clay k is 0.0003 d^{-1} and t_{mr} is 10 yr.

clay was expressed as the relative amount of the total label, significant changes with time were observed. Relative label for the fine silt fraction progressively increased and, by 2 yr after harvest, had doubled to account for 30% of the total. Its proportion continued to increase and was 40% of total after 4.5 yr when the experiment was concluded. The proportion associated with clay particles increased only from 10 to 12% of total label during the first 2 yr.

Residence time of ^{14}C in the fine silt and clay fractions demonstrated a comparatively short cycle of 7 and 10 yr, respectively. This corroborates the suggestion of Gregorich et al. (1989) that some readily decomposable organic matter is sequestered within microaggregates made up of fine mineral particles and is protected from microbial attack. A mineralization rate coefficient, k, for fractions released by ultrasonic energy similar to that used in our study was reported as 0.096 d^{-1} for the sand-size fraction and 0.075 d^{-1} for the clay-size fraction. Our estimates of k for fine mineral particles are slower (0.0003–0.0004 d^{-1}) because they are associated with organic matter in natural aggregates in the soil, thus demonstrating that aggregates provide some protection for easily mineralizable carbonaceous compounds for the lifespan of the aggregate.

Other data collected from the same site contribute further to understanding the residence time of C associated with primary mineral particles. Balesdent et al. (1988) studied natural abundance of ^{13}C in primary mineral particles in soils of long-term plots at Sanborn Field during 97 yr of cultivation. Using data on changes with time in the relative proportions of prairie and crop C associated with silt and clay fractions reported by these authors, we calculated turnover of C associated with these mineral fractions (Table 4). A relatively rapid replacement of existing soil C by that from an introduced crop occurred during the initial 27 yr of cultivation, suggesting the major involvement of a labile SOM pool. Subsequently, when the total level of SOM was no longer declining, the rate of turnover for soil cropped either to wheat (*Triticum aestivum* L.) or timothy (*Phleum pratense* L.) was markedly slower, suggesting dynamics associated with a more recalcitrant pool of C of prairie origin. Generally, the rate constants after the initial 27

Table 4. Rate of replacement of prairie C by C originating from cultivated crops in fine mineral fractions of the soil.†

Crop	Soil fraction	Replacement rate	
		1888–1915	after 1915‡
		yr^{-1}	
Wheat	silt	0.020	0.0027
	clay	0.013	0.0010
Timothy	silt	0.017	0.0014
	clay	0.011	0.0006

† Calculated from data of Balesdent et al. (1988).
‡ A period of 23 yr under wheat, 71 yr under timothy.

yr were 10-fold slower than during the initial period. These rates of replacement correspond to mean turnover times of 50 to 90 yr for the first 27 yr of cropping and 400 to 1600 yr for the subsequent period. In both time periods, and for soil cropped either to wheat or to timothy, the turnover of C associated with fine silt (2–25 μm) was generally two times faster than that associated with clay.

Presumably, two or more different pools of organic matter are associated with soil primary particles. One pool has a short residence time, and another has a much longer duration stretching into the hundreds of years. Other reports (Jenkinson and Parry, 1989; Sørensen, 1987) agree that recently incorporated C associated with mineral particles has a much shorter residence time than that of the native nonlabeled C.

A molecular-level interpretation has been suggested by Chassin (1979) to explain the range in residence times for C in SOM. He postulated that the clay–humic complex consists of several monolayers of organic material. Each layer has a specific composition, with the one near the clay surface and the very distant external layers possessing a relatively high aliphatic component. Intermediate layers were assumed to be relatively high in aromatic components.

Experiments of Gregorich et al. (1989) with soil–water suspensions treated ultrasonically using energy levels ranging from 100 to 1500 J mL^{-1} indirectly confirmed a multilayer arrangement of organic molecules around primary mineral particles. Application of energy above 300 J mL^{-1} to the clay-size fraction in their experiments released significant quantities of organic C. These components demonstrated a much faster mineralization rate than those obtained with lower energy sonication.

It is logical to postulate association of short-duration ^{14}C (residence time <10 yr) with external layers of organic matter coatings on clay and silt particles. Internal layers, made of different components, may be more

mineralizable than the external layers, but are protected physically (on an aggregate level) and chemically (on a molecular level) from microbial attack.

Soil Physical Fractions and Organic Matter Pools

We have arranged various size fractions of soil material using, as a criterion, residence time of C. Such a classification initially suggests that there are no distinctive pool boundaries, because the transition from one fraction to another is smooth. We compared aggregate fractions separated in our study with theoretical pools of SOM in Jenkinson and Rayner (1977) and Parton et al. (1988) models (Table 5).

Pools I and II with rapid turnover in Jenkinson's and Parton's models are represented by plant materials that are (I) decomposable or metabolic and (II) resistant or structural. The first, metabolic pool is represented by easily available cell constituents. It cannot be separated by physical methods, and is characterized mainly by quality (C/N ratio). Thus, a parallel between Parton's metabolic pool and vegetative fraction 2 to 0.2 mm is rather relative and serves only to emphasize the association of this pool with primary vegetative particles. The available form of C disappears in early stages of residue degradation and, in accord with the models, has a turnover time of <0.5 yr. In a related study, we found that residence time of C is 26 d in hemicellulose and 53 d in cellulose (Broder, 1985). As these fragments become reduced in size, the available C was exhausted by soil organisms. Further fragmentation resulted in increasingly smaller pieces of residue. With this decrease in size there was an increase in resistance of the fragments to degradation. Macroaggregates (2–1 mm), organized around plant fragments, have approximately the same life span as vegetative fragments 0.2 to 0.053 mm, and represent a transient C pool.

Pool III, representing soil biomass or active soil C, demonstrates a turnover time of 2.44 (Jenkinson) or 1.5 to 10 yr (Parton). The ^{14}C label in several physical fractions including macroaggregates 1 to 0.5 and 0.5 to 0.25 mm, microaggregates, and nonaggregated soil all fit this category. Approximately 20 to 30% of the total soil C is involved in this important pool representing processed carbonaceous material in a continuous stage of transformation. Entering this pool are products of destruction of larger aggregates exposing their inner components to microbial attacks from which they may have been previously physically protected. Formation of new aggregates probably also takes place here by means of fresh products of microbial transformation.

Table 5. Comparison of mean residence times of C in theoretical pools of soil organic matter and in soil physical fractions.

Pool	Jenkinson and Rayner (1977)	Parton et al. (1988)	Physical fraction in this study
I	Decomposable plant material 0.24 yr	Metabolic plant residues 0.5 yr	Vegetative fragments 2–0.2 mm 0.5–1 yr
II	Resistant plant material 3.33 yr	Structural plant residues 3.0 yr	Vegetative fragments >0.053 mm 1–2 yr
			Vegetative fragments 0.053–0.025 mm 2–3 yr
			Macroaggregates 2–1 mm 1–4 yr
III	Soil biomass 2.44 yr	Active soil C 1.5–10 yr	Aggregates 1–0.5 mm 2–10 yr
			Aggregates 0.5–0.1 mm 3–10 yr
			Nonaggregated soil 7 yr
IV	Physically stabilized 72 yr	Slow soil C 25–50 yr	Fine silt (internal) ≈400 yr
V	Chemically stabilized 2857 yr	Passive soil C 1000–1500 yr	Fine clay (internal) ≈1000 yr

It is assumed that the quality of this active SOM is the same in all members of this pool, although residence time of labeled C in nonaggregated soil is somewhat shorter than that in durable aggregates. Nonaggregated soil, i.e., primary mineral particles that are not bound together in aggregates, is assumed to represent either products of destruction of aggregates, or parts of future units. The fresh organic films associated with their surfaces during this transitional phase are not protected from microbial attack. As soon as they became organized into aggregates, turnover time of C increased.

The two most stable pools of SOM, characterized as physically (IV) or chemically (V) protected C pools, are certainly the most puzzling as to their physical configuration in the soil. Our work with ^{14}C does not contribute significantly to understanding this characteristic of SOM because artificial labeling with ^{14}C yields short-term results not appropriate for tracing changes in the label concentration during prolonged periods. Some researchers have preferred not to differentiate these two pools and rather characterize them both as a stable SOM with mean age of 853 yr (Hsie, 1992) or having turnover time extending 1000 yr (Balesdent et al., 1988).

There are, however, indisputable differences in behavior of C associated with clay and silt fractions (Table 4) as characterized by Balesdent et al. (1988). As was reported above, a mean residence time for C in the silt fraction is ≈400 yr and that for clay is ≈1000 yr.

The calculated turnover times for C in both silt and clay are well fitted with the characteristic of so-called physically and chemically stabilized SOM. This stabilized character supports our postulate that SOM in association with silt and clay differs in resistance to decay due to its attachment to one of these two classes of mineral particles. Each is associated with a particular kind of bonding. Physically stabilized or slowly transformed soil C is in association with fine silt particles, presumably in internal layers of a multilayer film. Fine clay particles are also surrounded with multilayer films of organic matter. The montmorillonitic character of the Mexico soil clay minerals (Miles and Hammer, 1989), and availability of polyvalent cations, Fe^{3+} and Al^{3+}, due to specific redoxymorphic features of this soil, favor strong bonding of humic substances with clay particles (Stevenson, 1982). The forces binding organic molecules to colloidal particles should be much stronger than those holding films onto silt particles. About 50% of total SOM is associated with this resilient pool.

CONCLUSION

In modeling, SOM is usually divided into several compartments with specific ranges of degradation rates and residence times for C. In reality, SOM is a sequence of pools, sometimes with overlapping C residence times.

Fractions with the shortest residence time are undecomposed vegetative particles. Their rates of degradation appear to be inversely proportional to size. Residence times for C in these fractions vary from 1 yr for large plant fragments to 2 yr for very small particles, presumably of higher lignin content. This is the most transient part of

organic material in soil and is totally dependent on the periodic supply of residues by crops or the native vegetation. Short-term accumulation of C is most likely to occur in this pool. From the compartment, rapid loss of SOM occurs when native lands are first brought under cultivation (Buyanovsky et al., 1987).

Most similar to the plant fragment fraction are coarse macroaggregates with a short life span. It is suggested that they are organized around plant residue particles. High C contents and wide C/N ratios support this concept. In smaller fractions of macroaggregates the content of clay is higher and the C/N ratio is narrower, suggesting a less rapid turnover of C. Characteristics of small aggregates indicate that their organic matter is relatively complex, and includes C with residence times extending to 10 or so years.

About one-half of total SOM C is represented by very resilient materials associated with primary mineral particles. This C is protected from microbial attack, primarily by structural organization of these primary particles into aggregates, and, secondly, by chemical structure of organic matter as it bonds with mineral particles.

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