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ORGANIC MATTER TURNOVER

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INTRODUCTION

Soil organic matter (SOM) is a dynamic entity. The amount (stock) of organic matter in a given soil can increase or decrease depending on numerous factors including climate, vegetation type, nutrient availability, disturbance, land use, and management practices. But even when stocks are at equilibrium, SOM is in a continual state of flux; new inputs cycle—via the process of decomposition—into and through organic matter pools of various qualities and replace materials that are either transferred to other pools or mineralized. For the functioning of a soil ecosystem, this “turnover” of SOM is probably more significant than the sizes of SOM stocks (1). An understanding of SOM turnover is crucial for quantifying C and nutrient cycles and for determining the quantitative and temporal responses of local, regional, or global C and nutrient budgets to perturbations caused by human activities or climate change (2).

DEFINITION OF SOIL ORGANIC MATTER TURNOVER

The turnover of an element (e.g., C, N, P) in a pool is generally determined by the balance between inputs (I) and outputs (O) of the element to and from the pool (Fig. 1). Turnover is most often quantified as the element's mean residence time (MRT) or its half-life ($T_{1/2}$). The MRT of an element in a pool is defined as 1) the average time the element resides in the pool at steady state or 2) the average time required to completely renew the content of the pool at steady state. The term half-life is adopted from radioisotope work, where it is defined as the time required for half of a population of elements to disintegrate. Thus, the half-life of SOM is the time required for half of the currently existing stock to decompose.

The most common model used to describe the dynamic behavior or turnover of SOM is the first-order model,

which assumes constant zero-order input with constant proportional mass loss per unit time (3, 4)

$$\frac{\partial S}{\partial t} = I - kS, \quad (1)$$

where S is the SOM stock, t is the time, k is the decomposition rate, and kS is equivalent to output O . Assuming equilibrium ($I = O$), the MRT can then be calculated as

$$\text{MRT} = \frac{1}{k} \quad (2)$$

and MRT and $T_{1/2}$ can be calculated interchangeably with the formula

$$\text{MRT} = T_{1/2} / \ln 2 \quad (3)$$

MEASURING SOIL ORGANIC MATTER TURNOVER

Most often the turnover of SOM, more specifically the turnover of SOM-C, is estimated by one of four techniques:

1. Simple first-order modeling
2. ^{13}C natural abundance technique
3. ^{14}C dating technique
4. “bomb” ^{14}C technique.

This list does not include tracer studies where a substrate (e.g., plant material) enriched in ^{13}C , ^{14}C , and/or ^{15}N is added to soil, and its fate is followed over time. Most studies of this type (see Ref. 5 for a review) use the tracers to quantify the short-term (1–5 yr) decomposition rate of freshly added material rather than the long-term turnover of whole-soil C.

Eqs. 1 and 2 form the basis for estimates of SOM turnover derived from first-order modeling; the unknown k is calculated as

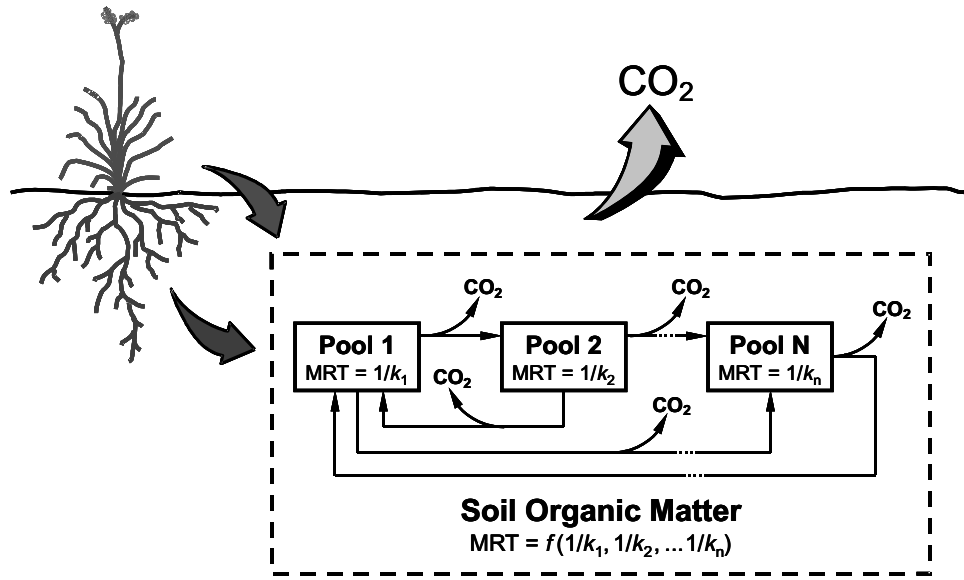


Fig. 1 The turnover of soil organic matter (SOM) is determined by the balance of inputs and outputs. Total SOM consists of many different pools that are turning over at different rates. The mean residence time (MRT) of total SOM is a function of the turnover rates of its constituent pools.

$$k = \frac{I}{S}$$

by assuming a steady state

$$\frac{\partial S}{\partial t} = 0.$$

This approach requires estimates of annual C input rates, which can be assumed to be continuous or discrete (3). The input can also be written as

$$I = hA$$

where A is the annual addition of C as fresh residue and h (the isohumification coefficient) represents the fraction that, after a rapid initial decomposition of A , remains as the actual annual input to S . An estimate of h is then necessary. A value of 0.3 is commonly used for agricultural crops, but the value can be higher for other materials such as grasses or peat (6, 7).

Another approach to estimate k by first-order modeling is “chronosequence modeling” (8). An increase (or decrease) in C across a chronosequence of change in vegetation, land use, or management practice can be fitted to a first-order model

$$S = S_e \left[1 - \left(\frac{S_e - S_0}{S_e} \right) e^{-kt} \right]$$

which is equivalent to

$$S = S_0 + (S_e - S_0)(1 - e^{-kt}) \quad (4)$$

where t is the time since the change, S_e is the C content at equilibrium, and S_0 is the initial C content before the change ($t = 0$). An average value of I can then be calculated

$$I = kS_e,$$

but in this case I represents annual inputs of new SOM (hA) rather than inputs of fresh litter or detritus. This approach is also used for chronosequences of primary succession (e.g., on glacial moraines, volcanic deposits, river terraces, dune systems), in this case $S_0 = 0$ (4).

The ^{13}C natural abundance technique relies on 1) the difference in ^{13}C natural abundance between plants with different photosynthetic pathways [Calvin cycle (C_3 plants) vs. Hatch–Slack cycle (C_4 plants)], and 2) the assumption that the ^{13}C natural abundance signature of SOM is identical to the ^{13}C natural abundance signature of the plants from which it is derived (9). Thus, where a change in vegetation type has occurred at some known point in time, the rate of loss of the C derived from the original vegetation and the incorporation of C derived from the new vegetation can be inferred from the resulting change in the ^{13}C natural abundance signature of the soil. The turnover of C derived from the original vegetation is then calculated by using the first-order decay model

$$\text{MRT} = \frac{1}{k} = \frac{t}{\ln(S_t/S_0)} \quad (5)$$

where t is the time since conversion, S_t is the C content derived from original vegetation at time t , and S_0 is the C content at $t = 0$. For further details on the technique see Refs. 9, 10.

The presence of ^{14}C with a half-life of 5570 yr in plants and the transformation of this ^{14}C into SOM with little isotopic discrimination allows the SOM to be dated, providing an estimate of the age of the SOM. The ^{14}C dating technique is applicable within a time frame of 200–40,000 yr; samples with an age less than 200 yr are designated as modern (See Ref. 11 for further details of the methodology.)

Thermonuclear bomb tests in the 1950s and 1960s caused the atmospheric ^{14}C content to increase sharply and then to fall drastically after the tests were halted. This sequence of events created an in situ tracer experiment; the incorporation of bomb-produced radiocarbon into SOM after the tests stopped allows estimates of the turnover of SOM. Further details of the technique are described in Refs. 2, 12, 13.

RANGE AND VARIATION IN ESTIMATES OF TOTAL SOIL ORGANIC MATTER TURNOVER

Comparisons of MRT values estimated by the four methods previously described (see, also, Table 1) reveal a wide range of MRTs. Although variations within each method are attributable to differences in vegetation, climate, soil type, and other factors, the largest variations in observed MRTs are method dependent. For example, MRTs estimated by simple first-order modeling and ^{13}C natural abundance are generally smaller by an order of magnitude than MRTs estimated by radiocarbon dating, because of the different time scales that the two methods measure. The ^{13}C method is generally used in medium-term observations or experiments (5–50 yr); hence, this method gives an estimate of turnover dominated by relatively recent inputs and C pools that cycle within the time frame of the experiment. In contrast, the oldest and most recalcitrant C pools dominate estimates by radiocarbon dating because of the long-term time frame (200–40,000 yr) that this method measures (11).

Table 1 Range and average mean residence times (MRTs) of total soil organic C in various ecosystem types as estimated by four different methods

Method and ecosystem	Sites and sources ^a	MRT (yr)		
		Low ^b	High ^b	Average ± SE ^c
<i>First-order modeling</i>				
Cultivated systems and recovering grassland or woodland systems	7/7	15 (14)	102 (15)	67 ± 12
<i>^{13}C natural abundance</i>				
Cultivated systems	20/10	18 (16)	165 (17)	61 ± 9
Pasture systems	12/10	17 (18)	102 (19)	38 ± 7
Forest systems	2/2	18 (20)	25 (21)	22 ± 4
<i>Radiocarbon aging^d</i>				
Cultivated systems	21/8 ^e	327 (22)	1770 (23)	880 ± 105
Grassland systems	4/3 ^f	Modern (23)	1040 (24)	— ^g
Forest systems	4/3	422 (22)	1550 (25)	1005 ± 184
<i>“Bomb” ^{14}C analysis</i>				
Cultivated systems	1/1	1863 (13)	1863 (13)	1863 ^g
Forest and grassland systems	14/12	36 (26)	1542 (27)	535 ± 134

^a First value indicates the number of sites used to calculate average MRT values; second value indicates the number of literature sources surveyed (i.e., some sources provided data for multiple sites).

^b Number in parentheses indicates reference to literature.

^c SE, standard error.

^d Values presented in MRT columns for this technique are radiocarbon ages in years B.P.

^e Includes two sites dating as “modern.”

^f Includes three sites dating as “modern.”

^g Only one value available.

FACTORS CONTROLLING SOIL ORGANIC MATTER TURNOVER

Primary production (specifically, the rate of organic matter transfer below-ground) and soil microbial activity (specifically, the rates of SOM transformation and decay) are recognized as the overall biological processes governing inputs and outputs and, hence, SOM turnover. These two processes (and the balance between them) are controlled by complex underlying biotic and abiotic interactions and feedbacks, most of which can be tied in some way to the state factor model of soil formation (4). Climate (especially temperature and precipitation) constrains both production and decomposition of SOM. Vegetation type affects production rates and the types and quality of organic inputs (e.g., below- vs. above-ground, amounts of structural tissue, C/N and lignin/N ratios), as well as the rates of water and nutrient uptake—all of which, in turn, influence decomposition rates. The types, populations, and activities of soil biota control decomposition and nutrient cycling/availability and hence influence vegetative productivity. Parent material affects SOM turnover as soil type, mineralogy, texture, and structure influence pH, water and nutrient supply, aeration, and the habitat for soil biota, among other factors. Topography modifies climate, vegetation type, and soil type on the landscape scale and exerts finer-scale effects on temperature, soil moisture, and texture. Lastly, time affects whether inputs and outputs are at equilibrium, and

temporal scale influences the relative importance of various state factor effects on production and decomposition.

Disturbance or management practices also exert considerable influence on SOM turnover via direct effects on inputs and outputs and through indirect effects on the factors controlling these fluxes. An example of management effects on MRT is illustrated in Table 2; in most cases, the MRT of whole-soil C is significantly longer under no tillage agriculture than under conventional tillage practices.

TURNOVER OF DIFFERENT SOIL ORGANIC MATTER POOLS

The previous discussion is focused on the turnover and MRT of whole-soil C; hence, it treats SOM as a single, homogeneous reservoir. But, in fact, SOM is a heterogeneous mixture consisting of plant, animal, and microbial materials in all stages of decay combined with a variety of decomposition products of different ages and levels of complexity. Thus, the turnover of these components varies continuously, and any estimate of MRT for SOM as a whole merely represents an overall average value (Fig. 1).

Although average MRTs are useful for general comparisons of sites or the effects of different management practices, they can be misleading because soils with similar average MRTs can have very different distri-

Table 2 Effect of tillage practices on mean residence time (MRT) of total soil organic C estimated by the ^{13}C natural abundance technique

Site (Ref.)	Cropping system ^a	Depth (cm)	t^b (yr)	MRT (yr)
Sidney, NE (28)	Wheat–fallow (NT)	0–20	26	73
	Wheat–fallow (CT)			44
Delhi, Ont. (29)	Corn (NT)	0–20	5	26
	Corn (CT)			14
Boigneville, France (16)	Corn (NT)	0–30	17	127
	Corn (CT)			55
Rosemount, MN (30)	Corn (NT, 200 kg N ha ⁻¹ yr ⁻¹)	0–30	11	118
	Corn (CT, 200 kg N ha ⁻¹ yr ⁻¹)			73
	Corn (NT, 0 kg N ha ⁻¹ yr ⁻¹)			54
	Corn (CT, 0 kg N ha ⁻¹ yr ⁻¹)			72
Average \pm SE ^c		NT		80 \pm 19
		CT		52 \pm 11

^a NT, no tillage; CT, conventional (moldboard plow) tillage.

^b Time period of experiment.

^c SE, standard error.

Table 3 Mean residence time (MRT) of macro- and microaggregate-associated C estimated by the ^{13}C natural abundance technique

Ecosystem (Ref.)	Aggregate size class ^a	μm	MRT (yr)
Tropical pasture (44)	M	>200	60
	m	<200	75
Temperate pasture grasses (19)	M	212–9500	140
	m	53–212	412
Soybean (45)	M	250–2000	1.3
	m	100–250	7
Corn (46)	M	>250	14
	m	50–250	61
Corn (47)	M	>250	42
	m	50–250	691
Wheat–fallow, no tillage (48)	M	250–2000	27
	m	53–250	137
Wheat–fallow, conventional tillage (48)	M	250–2000	8
	m	53–250	79
Average \pm SE ^b	M		42 \pm 18
	m		209 \pm 95

^a M, macroaggregate; m, microaggregate.

^b SE, standard error.

butions of organic matter among pools with fast, slow, and intermediate turnover rates (2, 31). Simulation models that account for variations in turnover rates for different SOM pools are now used to generate more realistic descriptions of SOM dynamics. A few models represent decomposition as a continuum, with each input cohort following a pattern of increasing resistance to decay (32), but most models are multicompartmental, with several organic matter pools (often 3–5) that are kinetically defined with differing turnover rates. For example, the CENTURY SOM model (33) divides soil C into active, slow, and passive pools, with MRTs of 1.5, 25, and about 1000 yr, respectively, and separates plant inputs into metabolic (readily decomposable; MRT of 0.1–1 yr) and structural (difficult to decompose; MRT of 1–5 yr) pools as a function of lignin:N ratio. Even though compartmental models are reasonably good at simulating changes in SOM, the compartments are conceptual in nature, and thus it has been difficult to relate them to functionally meaningful pools or experimentally verifiable fractions (34, 35).

The use of isotopic techniques to analytically determine the MRTs of physically and chemically separated SOM fractions has demonstrated the existence of various turnover rates for different pools. For example, low-density SOM (except for charcoal) invariably turns over faster than high-density, mineral-associated SOM, and hydrolyzable SOM turns over faster than nonhydrolyzable

residues (36, 37). The MRTs of primary organomineral associations generally increase with decreasing particle size, although there are exceptions (particularly among fine gradations of silt- and clay-sized particles) that have been variously related to climate, clay mineralogy, and fractionation methodology (34, 38, 39).

For a given set of biotic and abiotic conditions, the turnover of different SOM pools depends mechanistically on the quality and biochemical recalcitrance of the organic matter and its accessibility to decomposers. With other factors equal, clay soils retain more SOM with longer MRTs than do sandy soils (40). Readily decomposable materials can become chemically protected from decomposition by association with clay minerals and by sorption to humic colloids (38, 41). Clay mineralogy also plays an important role. For example, montmorillonitic clays and allophanes generally afford more protection than illites and kaolinites (42). In addition, the spatial location of SOM within the soil matrix determines its physical accessibility to decomposers. Relatively labile material may become physically protected by incorporation into soil aggregates (43) or by deposition in micropores inaccessible even to bacteria. Studies of the average MRTs of organic matter in macroaggregates vs. microaggregates show consistently slower turnovers in microaggregates (Table 3). Thus, a much higher proportion of the SOM occluded in

microaggregates consists of stabilized materials with relatively long MRTs.

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