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Dynamics of organic matter in soils

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Summary Dynamics of C, N, S, and to some extent P are expressed by a knowledge of the size and turnover rates of plant constituents such as soluble C and N components, cellulose and hemicellulose, and lignin. Soil organic matter constituents include: the microbial biomass as determined chemically or microscopically, non-biomass active components determined by isotopic dilution, stabilized N constituents for which good techniques are not yet available, and resistant or old C and associated N determined by carbon dating. The processes involved in the nutrient transformations and transfers are reasonably well understood. The control mechanisms require further elucidation to be able to extrapolate from the laboratory to the field, and between field sites. Major control mechanisms requiring further insight include the effects of C availability on transformations of C and N. The other control for which every little is known is that of spatial compartmentalization. Compartmentalization ranges from landscape or management sequences to pedogenic layers, rhizosphere-mycorrhizal effects, clay-sesquioxide surfaces, aggregation, localized enzymes, and microbial effects such as membrane boundaries. Control mechanisms for concurrent mineralization-immobilization, the stabilization of microbial products, and the relative role of the biomass as a catalyst rather than as a source-sink for nutrients, must be understood. There is potential for combining a knowledge of microbial production and turnover with that of the roles of the soil organic active fraction as a temporary storehouse for nutrients. This, in conjunction with management techniques such as zero tillage and crop rotation, should make it possible to better utilize soil and fertilizer N, especially in areas of the world where the cost of nutrients is high relative to the value of the crop grown.

Introduction

Soil organic matter (SOM) dynamics play a major role in natural ecosystems and extensive agriculture. In intensive agricultural systems with high fertilization rates, the various organic components have the potential for acting as a temporary nutrient reservoir. The proper management of this reservoir should make it possible to increase the efficiency of use of both soil and fertilizer nutrients. The net magnitude and general microbiology of processes such as N, P, and S mineralization-immobilization are reasonably well understood. However, information is lacking concerning the actual or gross flows that occur in the concurrent processes of mineralization-immobilization. The *in situ* controls also require further investigation if they are to be utilized in a nutrient management program.

Empirical measurements of the transformations of C, N, S, and P cannot be determined for the many soil–plant type interactions involved in agricultural and non-agricultural systems. Extrapolation of the available information from the laboratory and the few field sites where detailed information is available[16,41,53] requires a better knowledge of the factors controlling the various processes[29]. Although C, N, S, P, and the minor elements are involved in SOM dynamics, because of space restrictions, the rest of this paper will stress C and N interactions.

A reasonable amount of information is now available on abiotic controls such as moisture and temperature, aeration, and composition of the plant residues[31,32,34]. Not enough information is presently available to relate the effects of soil spatial compartmentalization and C availability to SOM dynamics. Spatial compartmentalization includes effects such as catenary sequences, pedogenic layers, soil structure and aggregates, rhizosphere-mycorrhizal effects, clay or sesquioxide surfaces, localized enzymes, and microbial membrane boundaries.

C available for microbial growth, whether from resistant humic components, plant detritus, or as photosynthate translocated to symbiotic partners, plays a major role[47]. The recent advances in the identification of soil humate constituents[5,50] and advances in NMR spectroscopy[12,42] should be related to kinetic studies of SOM. The increased understanding concerning the flow of plant C to underground structures such as mycorrhizal fungi and N-fixing organisms[19,54] also is aiding in the interpretation of underground dynamics.

Organic matter dynamics relative to soil type

The type, content, and extent of aggregation of clay continues to be recognized as a major controlling factor affecting SOM dynamics[52]. Bacterial utilization of proteins in the presence of clay minerals[25] could be divided into three types. At high protein-to-clay ratios, growth was not affected by the clay. At intermediate ratios, growth rate but not the final yield was reduced, and at low protein-to-clay ratios of montmorillonite and kaolinite, the protein was unavailable for hydrolysis. Clay minerals have been shown to protect microbial metabolites produced during degradation of labelled substrates[20,29].

The strong association of minerals such as allophane with SOM components makes this a useful tool for measurement of clay–SOM interactions. Studies on the addition of ^{14}C-labelled glucose, cellulose, and proteins from algae and of labelled polysaccharides from wheat straw[26,58] showed that the allophane caused a major reduction in the

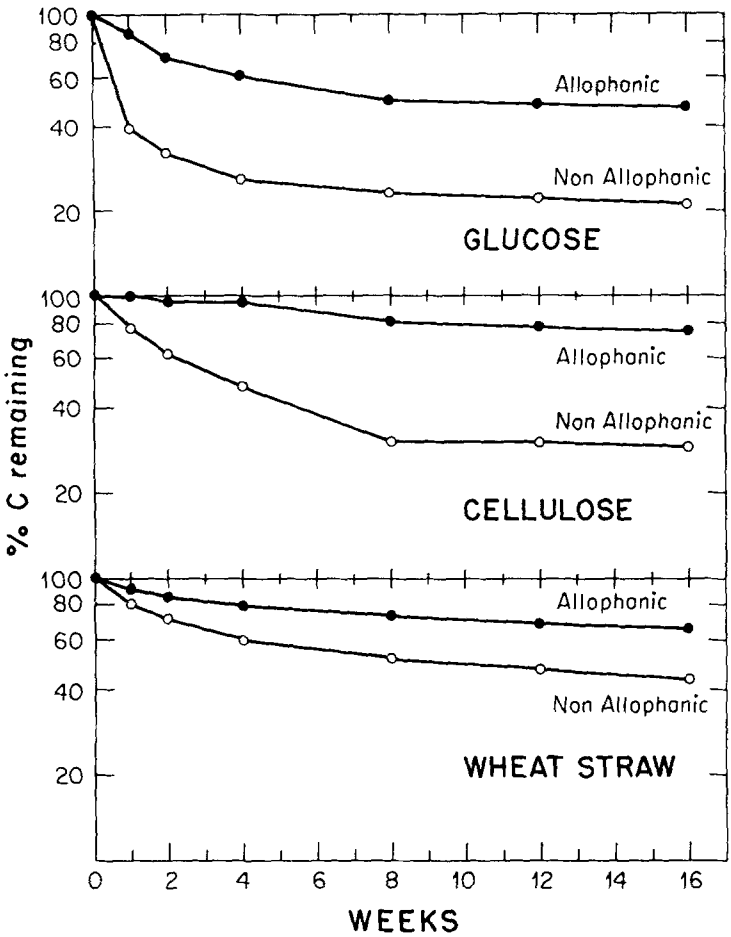

Fig. 1. Comparison of degradation of wheat straw, cellulose, and glucose in allophanic and non-allophanic soil (Zunino *et al.*[58]).

degradation rate of added carbonaceous materials (Fig. 1). The strong initial protective effects on compounds that include glucose and cellulose must lead to further investigations on the effects of possible inhibition of microbial activity during the initial degradation and in the sequential growth phases, in addition to the effects involving microbial metabolite protection. Increased efficiency of microbial growth[46] in the presence of allophanic clays have been cited. Microbial growth on simple compounds such as glucose and proteins usually shows high efficiency values in soils; these are very similar to those obtained in pure culture[8,36]. The work of Marshman and Marshall[25] also showed no effects of clays on microbial growth efficiency.

Table 1. Radiocarbon age of Melfort soil and fractions collected in 1978

Fraction	Proportion of organic C	Age, % modern	Eq. Age, years
Soils	1.00	90.6	795
Coarse silt	0.25	90.6	800
Fine silt	0.29	88.7	965
Coarse clay	0.31	85.5	1255
Fine clay	0.08	97.9	170

Not dated: Organic carbon with sand (0.03).

Work with tracers has verified that large amounts of labelled phenolic compounds are incorporated into stabilized humus, while non-aromatic materials are incorporated into the soil biomass[18]. The addition of ^{14}C labelled melanic fungal residues[24] resulted in a slow degradation rate of the materials and concentration of the cell wall materials in the humin fraction of SOM.

The stabilization by fine clays, of otherwise readily decomposable substrate, is also shown by data from C dating (Table 1). The differences in the C age between the fine clay and the coarse clay of this soil is probably associated with differences in their clay mineralogy. The protection of otherwise readily degradable substrates, including proteinaceous materials and polysaccharides[3], makes clay adsorbed materials an important contributor to the dynamics of materials with an intermediate range of turnover. The association of very old materials with coarse clays and silts must be attributable to a different type of chemical bonding with recalcitrant humates and more resistant microbial cell wall constituents[30].

The use of flotation to separate light and heavy fractions differentiates plant residues and some light aggregates[45], and is proving a useful separation technique for both forest and agricultural conditions[10,48]. Tisdall and Oades[52] have reviewed the literature on mechanisms of aggregate formation. Data on the actual effect of protection on degradation rates are, however, still hard to obtain.

The molecular weight distribution of SOM is altered during microbial attack and humification. Incubation of plant litter is said to result in a decrease in the amount of SOM in the greater than 100,000 molecular weight range; incubation of the soil alone showed the opposite effect[57]. These observations fit in with other suggestions[50] that the initial microbial breakdown of plant residues is followed by the synthesis of humic substances of high molecular weight. Ruggiero *et al.*[42] have shown with NMR spectroscopy that incorporation of non-aromatic molecules such as polysaccharides into higher molecular weight fractions is attributable to the trapping of non-humic substances

in the voids of the high molecular weight polymer. Anderson[2] had postulated that humification leads to a decrease in molecular size, *i.e.* the production of fulvic from humic acids. However, fulvic acids usually show high tracer activity and turnover rates. This anomaly was explained when Anderson and Paul[4] showed that elimination of the highly-labelled, low molecular weight extraneous materials present in what is normally known as fulvic acids, by dialysis through a 2,000 molecular weight size membrane, results in fulvic acids that are as old as humic acids in this soil.

The role of the active fraction in SOM dynamics

The suggested occurrence of an active SOM fraction[9] was quantitatively developed[14] with ^{15}N and kinetic analysis. This fraction has more recently been divided into a biomass and non-biomass active component[35]. The measurement of NO_3–N accumulated over long-term aerobic incubation of soils[49] has led to the calculation of a potentially mineralizable N pool (N_0). This has been a very useful concept for determining the effect of controlling factors such as temperature[33], moisture, and organic matter[40] on mineralization rates.

Tracer studies have indicated that recently immobilized N is incorporated into a series of soil fractions such as humic and fulvic acids and ^{14}C and ^{15}N components that can be separated by acid hydrolysis or particle size analysis. No one fractionation technique has been found to adequately separate SOM into biologically meaningful components. Paul and Juma[35], in their simulation model, found that a realistic description of N cycling in soil should consider at least four separate pools: biomass N, non-biomass active N, stabilized N, and old N (Table 2).

The chloroform-incubation technique is useful for following tracers through the biomass as well as determining its relative size and nutrient content. The determination of a K_N value representative of the proportion of biomass N mineralized after fumigation has been based on ^{15}N

Table 2. N pools and techniques used for pool size determination in a Chernozemic soil*

	% of soil N	$T_{1/2}$ yrs	Method of determination	Relative contribution of mineralization %
Biomass	4–6	0.5	Fumigation incubation	30
Active non-biomass	6–10	1.5	Isotope dilution	34
Stabilized	36	22 yrs	By difference	35
Old	50	600 yrs	Associated with old C (carbon dating)	1

* During 12 week incubation.

Table 3. Parameters for the net mineralization of glucose and straw-^{14}C during 7 years incubation of Sceptre soil in the field (Voroney[55])

Glucose-^{14}C remaining (%)	=	$29e^{-.36t}$	$+ 40e^{-.023t}$	$+ 31e^{-.0002t}$
$T_{1/2}$ (days)		2	30	3450
Straw-^{14}C remaining (%)	=	$52e^{-.036t}$	$+ 19e^{-.003t}$	$+ 29e^{-.00026t}$
$T_{1/2}$ (days)		19	230	2653

e = base of natural logarithm; t = time in days.

labelled organisms added to soils[27,28] and the chloroform treatment of an *in situ* soil population of labelled organisms. The effect of varying rates of N immobilization after fumigation of biomass with different C:N ratios was overcome by using a sliding scale of CO_2–C:NH_4^+–N produced during incubation of different soils to correct the K_N value for immobilization[56].

Table 3 shows the first-order equations for net mineralization (no correction for microbial growth) of glucose-^{14}C and straw-^{14}C remaining in soil after 7 years' field incubation in a semi-arid climate[55]. Glucose-C was utilized with a high efficiency as the first component degraded represents 29% of the added glucose-C, with a half-life of 2 days. The intermediate fraction with a half-life of 30 days accounted for 41% and represents degradation of microbial biomass and metabolites. The remaining 31% of the ^{14}-C was present in a stabilized fraction that had a half-life of 3450 days. The equation for decomposition of straw-^{14}C shows that the soluble materials, cellulose and hemicellulose[39], had a net decay rate equivalent to a half-life of 19 days. The amount of straw-^{14}C remaining in the stabilized period is similar to that of glucose-^{14}C, but the glucose-derived C is more resistant than the plant-derived ^{14}C. Some of the straw components such as lignin are probably disappearing faster than the microbial materials derived from the glucose[53].

Tracer data from a number of experiments show an interesting relationship which I shall refer to as the catch-up effect. The long-term degradation rate of materials under one set of environmental conditions appears to be primarily controlled by the particular plant composition and by the stabilization rates within a soil. Factors such as fallow vs. crop, or wet years, often tend to be evened out over extended periods. Although cropping, which drys out the soil, results in lower decomposition rates[44], this is usually counterbalanced by faster rates of decomposition during the fall or following spring under prairie conditions. The 'catch-up' effect involving the interaction of inherent decomposability and stabilization with seasonal effects had not yet been adequately incorporated into the modelling of SOM dynamics.

Interpretation of the role of the biomass and active fraction in nutrient cycling and crop management

Knowledge about the size and turnover of the components constituting the active fraction can be used in the interpretation of nutrient cycling parameters, such as (1) the role of SOM in ecosystem functioning, (2) the interpretation of soil tests for nutrient availability as a prerequisite to fertilization, (3) management to increase the efficiency of fertilizer, symbiotically fixed, and soil N, and (4) the interpretation of information on N and other nutrient dynamics relative to internal cycling and plant uptake (the priming effect).

The SOM active fraction size and turnover rate is related to agricultural practices[21,22,51], and soil vegetation type[3,13]. Adams and Laughlin[1] found biomass C and N of grassland soils to be greater than those of arable soils. Zero tillage, in which plant residues are left on the soil surface, results in an increased concentration of biomass at the surface[6,7], but the overall biomass throughout the rooting zone may not be greatly affected[23,38].

The biomass N, which is a major component of the active fraction, has an ^{15}N content similar to that of the mineral N produced upon incubation, and can play a major role as a source of mineralizable N. Marumoto *et al.*[28] found that oven-drying at 70°C approximated the $CHCl_3$ treatment in its effect in releasing P and N during subsequent incubation. It was concluded that the amount of soil biomass might be used for estimating the mobile plant nutrient pool in soil. Voroney*, in the analysis of N_0 for 100 medium textured soils in Saskatchewan found that the N_0, ranging from 50 to 300 $\mu g\, g^{-1}$ soil, equalled 3.3 times the flush of N produced during incubation after chloroforming. The K_N value for such soils is usually 0.3, indicating that N_0 approximated the size of the biomass.

The internal cycling of N through a large biomass can have major effects on the interpretation of nutrient cycling and fertilizer uptake experiments[15]. An example of the potential for altered ^{15}N effects is shown in Table 4. A nitrification inhibitor added to a soil with added ammonia or urea did not affect plant uptake (data not shown) and had no statistically significant effect on the size of the N biomass. The ^{15}N remaining in the soil after growth of a crop was increased by the presence of the inhibitor from 42% to 57% of that added, and the biomass ^{15}N was doubled. The N mineralized on incubation after crop growth was not affected. The uptake of $^{15}NH_4$ by the

* Personal communication.

Table 4. Effect of nitrification inhibitor on ^{15}N distribution biomass N and net N mineralization after growth of a wheat crop in Chernozemic soil with 0.44% total N content (Juma and Paul[17])

	^{15}N distribution %			^{14}N $\mu g\ g^{-1}$ soil	
Treatment	Plant uptake	Soil	Biomass	Biomass N	Mineralized*
N**	39	42	16	140	96
N + Inhibitor	36	57	26	168	73

* During 12-week incubation. ** N added as ammonia or urea.

microorganisms resulted in a consequent release of ^{14}N. Utilization of this ^{14}N by plants would result in apparent increased utilization of soil N. Acceptance of the significance of internal cycling will result in the recalculation of some tracer data; it should also add to the usefulness of the results in that better estimates of what actually is happening in SOM dynamics can be made.

Anaerobic incubation of soils has been found to be a useful technique for the measurement of N turnover relative to forest productivity[37]. Much of the N released during this period probably can be attributed to biomass N, *e.g.* fungal materials which decay under the anaerobic conditions.

The turnover rates of the biomass are as significant as the sizes of these components. Tropical and temperate soils have similar amounts of SOM, especially when the concentrations in lower portions of the profile are taken into account[43]. However, the former have a higher N supplying power per unit of total N[11]; this must be related to the size and turnover of the biomass and other portions of the active component of SOM.

There is the potential for better nutrient management through techniques such as zero-till intercropping with or without legumes, improved soil and fertilizer efficiency, and better management of harvested areas in forestry[21,43]. Realization of this potential will, however, require a much better application of presently available and of new information on SOM dynamics.

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