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Review paper

The nature and dynamics of soil organic matter: Plant inputs, microbial transformations, and organic matter stabilization

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A R T I C L E I N F O

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A B S T R A C T

This review covers historical perspectives, the role of plant inputs, and the nature and dynamics of soil organic matter (SOM), often known as humus. Information on turnover of organic matter components, the role of microbial products, and modeling of SOM, and tracer research should help us to anticipate what future research may answer today's challenges. Our globe's most important natural resource is best studied relative to its chemistry, dynamics, matrix interactions, and microbial transformations. Humus has similar, worldwide characteristics, but varies with abiotic controls, soil type, vegetation inputs and composition, and the soil biota. It contains carbohydrates, proteins, lipids, phenol-aromatics, protein-derived and cyclic nitrogenous compounds, and some still unknown compounds. Protection of transformed plant residues and microbial products occurs through spatial inaccessibility-resource availability, aggregation of mineral and organic constituents, and interactions with sesquioxides, cations, silts, and clays. Tracers that became available in the mid-20th century made the study of SOM dynamics possible. Carbon dating identified resistant, often mineral-associated, materials to be thousands of years old, especially at depth in the profile. The ^{13}C associated with C_3–C_4 plant switches characterized slow turnover pools with ages ranging from dozens to hundreds of years. Added tracers, in conjunction with compound-specific product analysis and incubation, identified active pools with fast turnover rates. Physical fractionations of the intra- and inter-aggregate materials, and those associated with silt and clay, showed that all pools contain both old and young materials. Charcoal is old but not inert. The C:N ratio changes from 25 to 70:1 for plant residues to 6 to 9:1 for soil biota and microbial products associated with soil minerals. Active, slow and passive (resistant) pool concepts have been well used in biogeochemical models. The concepts discussed herein have implications for today's challenges in nutrient cycling, biogeochemistry, soil ecosystem functioning, pollution control, feeding the expanding global population and global change.

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1. Introduction

Soils play a major role in ecosystem dynamics, biotic diversity, water infiltration, erosion control, global food security, biofuels, the control of and response to global change, and the Earth's fresh water quality (Fang et al., 2005; Cheeke et al., 2013; Coleman and Wall, 2014). Decomposition must be slightly lower than plant inputs, on a long-term basis, to produce the soil organic matter (SOM) found in the world's biomes. Our present, industrial society is based on the fossil fuels produced during the Carboniferous and Permian eras. The precursors of the fossil fuels were deposited over millions of years under conditions of high plant productivity with limited decomposition due to high moisture contents and low, fungal lignase activity (Horwath, 2015). These hydrocarbons are now being returned to the atmosphere in excess amounts. Carbon dioxide, the most important plant nutrient, is the major atmospheric component of the global C cycle and a greenhouse gas. The simultaneous advent of agriculture, which occurred 10,000 yr ago on three continents, could be attributable to an increase in atmospheric CO_2 to above 200 ppmv (Sage, 1995). A level below 200 could be too low to allow for domestication of crops. Increased CO_2 levels, rising to today's 400 + ppmv, together with other components of the green revolution such as improved plant genetics and fertilization, have played a part in the three-fold increase in global grain production and associated plant residue inputs since 1950. Future levels of atmospheric CO_2, as well as predicted increased temperatures will also impact SOM dynamics (Batjes, 2014).

A great wealth of information on soil organic carbon (SOC) constituents and dynamics can be found in the literature of the mid-20th century when tracers first became available. Hopefully, this information is not lost, repeated, or disregarded in today's experiments. This review highlights some of the original work, relates it to modern concepts, and will hopefully lead to improved future research. The tables, figures and associated information in this paper are primarily based on the authors' work, but reflect the literature in general. It is not possible to cover all the literature over this extended period. The selected references of both the older and modern literature hopefully can lead interested scientists to the relevant papers.

The composition and global distribution of SOM is a valuable storehouse of information on vegetation, parent materials, climate, and disturbance (Table 1). De Deyn et al. (2008) published a review of plant, functional traits and soil C sequestration in contrasting biomes. Tropical forests constitute 12.2% of the Earth's land area with high net primary productivity (NPP) and annual C inputs of 2.03 kg C m^{-2}. Their soils, long thought to be SOM deficient, are now known to have fairly high SOC contents of 12 kg C m^{-2} or 692 PgC (10^{15} g) on a global basis when analyzed to the depth 3 m.

A useful estimate of gross SOC turnover, at an ecosystem level, can be attained by relating the SOC level to litter inputs (SOC content/annual litter input) on the assumption of steady state conditions. Tropical, forest soils, characterized by high rainfall and temperatures, trees with endotrophic mycorrhiza, lower C:N ratios and abundant soil fauna, have gross turnover times of 5.3 yr in the surface and 22 yr over the 3 m profile depth. Thus, they are major contributors to the annual CO_2 flux. The lower inputs for temperate forests with diverse trees and high litter decomposability, from broad leaved trees, result in lower SOC stocks that however can have reasonable soil ages at the surface (Mathieu et al., 2015). The higher SOC stocks in boreal forests reflect inputs from mostly coniferous trees with ectomycorrhizal fungi, lower temperatures and often wet conditions that result in high C:N ratios (Aitkenhead and McDowell, 2000). Podzolization can affect the SOC and soil organic nitrogen (SON) contents under such conditions. Croplands span the full range of mean annual, global temperatures. Disturbance, such as that caused by cultivation, usually results in decreased stocks of SOC with higher turnover times (Follett et al., 1997; Lal et al., 2015), whereas afforestation of agricultural land can lead to increased stocks (Morris et al., 2011; Mellor et al., 2013).

The deserts are affected by abiotic as well as biotic decomposition resulting in low SOC per unit area and low C:N ratios (Adair et al., 2008). Grasslands with high, beneath- to above-ground

Table 1
The global area, abiotic controls, net primary productivity, C inputs, terrestrial C, and turnover rates of soil C (adapted from Batjes, 2014; De Deyn et al., 2008; Horwath, 2015).

Biome	Area	MAP	MAT	Mean soil C	NPP	C inputs	Terrestrial C stock (PgC)	Gross SOC turnover time yr	
	% of total	(mm) yr^{-1}	°C	(kg m^{-2})	($PgCyr^{-1}$)	(kg m^{-2} yr^{-1})	Soil (0–3 m)	0–20 cm	0–300 cm
Tropical forests	12.2	1400–4500	23–28.5	12.0	20.1	2.03	692	5.3	22
Temperate forests	9.5	750–2500	9–14.5	8.7	7.4	0.85	262	9.5	26
Boreal forests	8.8	600–1800	-5–5	16.4	2.4	0.50	150	10	27
Tropical savannas	19.0	500–1350	18–28	5.4	13.7	0.48	345	6.2	30
Temperate grasslands	7.1	450–1400	−2–15	13.3	5.1	0.30	172	15.1	63
Mediterranean shrubland	3.1	400–600	15–20	7.6	1.3	0.46	124	16.7	70
Deserts	14.4	125–500	−4–25	3.4	3.2	0.08	208	25.4.	144
Tundra	7.0	250–1500	−15–5	19.6	0.5	0.10	818	52.3	165
Croplands	16.8	150–4500	−3–28.5	7.9	3.8	0.48	248	6.3	24
Wetlands g	2.2	250–4500	−2–28.5	72.3	4.3	0.17	450	150	945
Total	100			16.7	61.8	0.05	3051	NA	NA

MAP = mean annual precipitation; MAT = mean annual temperature; NPP = net annual primary productivity for the biome; NA = not applicable.