ORGANIC CARBON IN SOILS OF THE WORLD

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Abstract

The C stored in soils is nearly three times that in the aboveground biomass and approximately double that in the atmosphere. Reliable estimates have been difficult to obtain due to a lack of global data on kinds of soils and the amount of C in each soil. With new data bases, our study is able to provide more reliable data than previous estimates. Globally, 1576 Pg of C is stored in soils, with ≈ 506 Pg (32%) of this in soils of the tropics. It is also estimated that ≈40% of the C in soils of the tropics is in forest soils. Other studies have shown that deforestation can result in 20 to 50% loss of this stored C, largely through erosion.

The equilibrium of C on earth is a function of three reservoirs, the oceans, atmosphere, and terrestrial systems. These three reservoirs are in a dynamic equilibrium, each interacting and exchanging C with the other. A fourth reservoir, the geological reservoir, is estimated to have 65.5×10^6 Pg (Kempe, 1979) and is a permanent sink. A small fraction (≈4000 Pg) of the geological sink is present as fossil fuels from which C release takes place as a result of mining activities of man. The relative amounts of C stored in each of these reservoirs is given in Table 1.

Recent concerns about the "greenhouse effect" and damage to the ozone layer have resulted in more concerted studies on the quantities, kinds, distributions, and behavior of C in the different systems (Johnson and Kerns, 1991). Although the purpose of many of these studies is related to impacts of potential global climate change, the contributions have applications in all fields ranging from energy sources to agriculture. A very important product of such studies would be in the area of mitigating the effects of global climate change, that has a direct relationship to agriculture and specifically to organic matter management in soils (Johnson and Kerns, 1991). A better understanding of the terrestrial reservoir has benefits far beyond the current objectives of C sequestration in soils and the detrimental effects of greenhouse gases.

Estimates of global C content in soils have been made; some of the more recent are those of Bohn (1976, 1982), Buringh (1984), and Kimble et al (1990). The problems of making accurate global estimates result from: (i) very high spatial variability in C content of soils; (ii) unreliable estimates of area occupied by kinds of soils; (iii) unavailability of reliable data, particularly bulk density, to compute volumetric composition; and (iv) the confounding effect of vegetation and land use changes.

Every study has shown considerable variability in the range of organic C in classes of soils. Employing the coefficient of variation as an expression of the variability, Table 2 shows the reliability of most generalizations. In order to obtain global estimates, such variability must be understood and accepted.

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Materials and Methods

The most reliable estimate of global soil distribution is the FAO–UNESCO (1971–1981) Soil Map of the World. Unfortunately this map is not accompanied by appropriate attribute files providing properties for the map units. The study of Bohn (1982) was made using estimates of soil areas based on this map and C content of soils from a sparsely distributed set of pedons.

During the last 2 yr, the staff of World Soil Resources of the USDA Soil Conservation Service (WSR–SCS) has attempted to collate data from national sources. This is a continuing process. The current data set has ≈1000 pedons from 45 countries (mostly in the tropics) and an additional 15 000 pedons from the USA. In collaboration with other agencies, WSR-SCS, is in the process of developing a map showing major soil regions of the world (Eswaran et al, 1993). The map is digitized, and initial area estimates for the different map units of soils are available. The WSR-SCS has also developed a data base on C in soils of the world, using the WSR-SCS data base and published information. Based on this global data base on organic C, each map unit on the Major Soil Regions of the World map is assigned a value for the organic C content to a 1-m depth. If the map unit has representative pedons, the average value is employed for the map unit. If the map unit has no pedons, a "best value" is assigned based on the soil classification and the soil moisture and temperature regime of the area. This assigned value is multiplied by the area of the map unit to obtain the total C content for the unit. Because the data for CO_3–C are incomplete, this information is not estimated in the current study. The region between the Tropics of Cancer and Capricorn is considered the tropics, and similar estimates were also made for soils in this zone.

Results and Discussion

The organic C content for each of the suborders of soils as defined in Soil Survey Staff (1975) is provided in Table 3. The total mass of organic C stored in the soils of the world is 1576 Pg, of which ≈32% (or 506 Pg) is found in the tropics (Table 4). The global estimate is close to the estimate made by Buringh (1984) and deviates from those of Kimble et al. (1990) and Bohn (1982). Histosols were not included in the study of Kimble et al. (1990) and, additionally, they made their estimates by using unpublished area data of soils estimated by the SCS in the 1950s.

Lack of suitable data, in terms of measured organic C and bulk density, is still a problem with respect to arriving at reliable estimates. This is particularly the case with Histosols, for which bulk density measurements are frequently lacking. The amount of C in Histosols is a gross underestimation because only a 1-m depth is considered; in many cases, the actual depth of the organic soil is much greater than 1 m. Litter layer, a significant component in the cooler regions of the world and under forest canopy, is also not considered in the current estimate. Carbonate–C, which is present in significant amounts in soils of the arid and semiarid parts of the world, will greatly increase the total C content in soils. Reliable data

Table 1. Global reserves of C (Post et al., 1990; Johnson and Kerns, 1991.

Reservoir	Carbon
Terrestrial	
Vegetation biomass	
Soils	
Atmosphere	
Oceans	
Geologic (fossil fuel)	
Total	

Table 2. Estimates of organic carbon (OC) in different soils and error associated with estimate.

Author, soils	Mean OC	Pedons	Coefficient of variation
	kg m^{-2}	no.	%
Alexander et al. (1989), Alaska			
Shallow Entisols	16.9	7	28
Deep Entisols	32.4	7	34
Shallow Spodosols	17.4	26	42
Deep Spodosols	29.8	95	35
Cryofolists	14.2	4	30
Kimble et al. (1990), global			
Tropical Oxisols	9.7	71	42
Tropical Ultisols	8.3	53	70
Temperate Mollisols	9.1	522	46
Temperate Alfisols	5.5	354	62
Aridisols	4.2	98	60

is also not available for the former Soviet territories, Mongolia, and China.

Estimates of total area of tropical forests range from 10 to 30 million km^2 (Bouwman, 1990) due to differences in criteria used to define this ecosystem. An acceptable value is ≈15.4 million km^2 (Post et al., 1982). Table 5 provides estimates for the C stored in soils with an udic or aquic soil moisture regime in the tropics. These soils have the potential to support tropical rain forest vegetation and have an area of ≈17.5 million km^2 (estimate from the Major Soil Regions of the World map).

In the tropics, most Histosols are still under forest, though most Andisols, Oxisols, and Ultisols have been or are being deforested for agriculture. Of the 206 Pg (Table 5) of organic C stored in the potential forest soils (areas with udic or aquic soil moisture regimes), ≈184 Pg is estimated (Post et al., 1982) to be stored in the present-day tropical forest soils. The difference of 10% is attributed to losses due to conversion of forest lands to mainly agriculture. With increased deforestation, these losses can be expected to increase.

Post et al. (1990) estimated that 574 Pg of C are stored in the aboveground vegetation of the world's terrestrial ecosystems, and Brown and Lugo (1984) indicated that ≈102 Pg is stored in the biomass of tropical forests. The latter is ≈55% of the amount in forest soils, based on the estimated soil C content of Post et al. (1990). Based on this study, the amount stored in the biomass of tropical forests is only ≈20% of that stored in tropical soils as a whole.

Large areas of forest land in the tropics have been and are being cleared for agriculture and other purposes. Shifting cultivation and slash and burn agriculture are still practiced in many countries of the tropics and, with

Table 3. Organic C mass in soils of the world.

	Organic C				
	This study				
Suborder–order	Global	Tropical	Buringh (1984)	Kimble (1990)	Bohn (1982)
	Pg				
Folists	1	0			
Fibrists	207	0			
Hemists	72	23			
Saprists	77	77			
Total Histosols	357	100	41.5		377
Aquands	1	0			
Cryands	18	6			
Torrands	1	0			
Xerands	3	0			
Vitrands	1	0			
Ustands	16	15			
Udands	38	26			
Total Andisols	78	47		55.3	
Aquods	5	0			
Ferrods	0	0			
Humods	49	1			
Orthods	17	1			
Total Spodosols	71	2	50.7		
Aquox	1	1			
Torrox	0	0			
Ustox	47	47			
Perox	7	7			
Udox	64	64			
Total Oxisols	119	119	123.0	157.0	
Aquerts	0	0			
Xererts	2	0			
Torrerts	4	3			
Uderts	3	0			
Usterts	10	8			
Total Vertisols	19	11	22.2	146.5	
Salids	5	1			
Gypsids	3	1			
Calcids	17	6			
Durids	0	0			
Argids	38	7			
Cambids	47	14			
Total Aridisols	110	29	33.0	144.0	
Aquults	7	6			
Humults	3	1			
Udults	43	29			
Ustults	50	49			
Xerults	2	0			
Total Ultisols	105	85	112.9	65.5	
Albolls	2	0			
Aquolls	1	0			
Rendolls	0	0			
Xerolls	14	0			
Borolls	22	0			
Ustolls	12	1			
Udolls	21	1			
Total Mollisols	72	2	156.9	146.5	
Aqualfs	7	2			
Boralfs	37	0			
Ustalfs	31	24			
Xeralfs	10	0			
Udalfs	42	4			
Total Alfisols	127	30	254.8	130.0	
Aquepts	54	24			
Plaggepts	0	0			
Tropepts	36	36			
Ochrepts	252	0			
Umbrepts	10	0			
Total Inceptisols	352	60	206.6	194.6	
Aquents	8	0			
Arents	0	0			
Psamments	15	9			
Fluvents	16	6			
Orthents	109	4			
Total Entisols	148	19	144.6	144.8	
Rocky land	13	0			
Shifting sand	5	2			
Total misc. land	18	2	281.0		
Grand total	1576	506	1427.2	1184.2	2200

Table 4. Organic C mass in soils of the world.

Order	Area†		ORGANIC C		
	Global	Tropical	Global	Tropical	Tropical
			Pg		
Histosols	1 745	286	357	100	
Andisols	2 552	1 683	78	47	
Spodosols	4 878	40	71	2	
Oxisols	11 772	11 512	119	119	
Vertisols	3 287	2 189	19	11	
Aridisols	31 743	9 117	110	29	
Ultisols	11 330	9 018	105	85	
Mollisols	5 480	234	72	2	
Alfisols	18 283	6 411	127	30	
Inceptisols	21 580	4 565	352	60	
Entisols	14 921	3 256	148	19	
Misc. land	7 644	1 358	18	2	
Total	135 215	49 669	1576	506	

† Most recent estimates by USDA Soil Conservation Service (Eswaran et al., 1993).

Table 5. Organic C in tropical forest soils (those soils that are under forest or can support a forest).

Order	Organic C		
	Tropical soils	forest soils	Forest soils
	Pg		
Histosols	100	100	
Andisols	47	25	
Spodosols	2	0	
Oxisols	119	43	
Vertisols	11	1	
Aridisols	29	0	
Ultisols	85	30	
Mollisols	2	0	
Alfisols	30	4	
Inceptisols	60	2	
Entisols	19	1	
Misc. land	2	0	
Total	506	206	

minimal or no soil conservation practices, soil erosion is rampant. Deforestation can result in a 20 to 50% loss of this stored C in the tropics (Brown and Lugo, 1984), much of the loss resulting from erosion of the organic-rich surface horizons. Replenishing this is a slow process not easily achieved. Soil conservation, apart from its other benefits' also assists in maintaining this reservoir of soil C.

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