Soil organic carbon pool in Indian forests

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Abstract

A database of published measurements (with depth) of soil organic carbon (C) containing information on location, soil type, texture, measured/estimated bulk density and forest type in Indian forests was prepared. It was used for estimating soil organic C densities for various forest types for two-depth classes (0–50 and 0–100 cm). The mean soil organic C density estimates for top 50 cm based on 175 observations ranged from 37.5 t/ha in tropical dry deciduous forest to 92.1 t/ha in littoral and swamp forest. The mean soil organic C density estimates based on 136 observations ranged from 70 t/ha in tropical dry deciduous forest to 162 t/ha in montane temperate forest for top 1 m soil depth. The estimated soil organic C densities were combined with remote sensing based recent forest area inventory (64.20 Mha) by Forest Survey of India [The State of Forest Report, Forest Survey of India (FSI), Ministry of Environment and Forest, Govt. of India, Dehradun, 80 pp.] to arrive at estimates of soil organic C pool by major forest types of India. The total soil organic C pools in Indian forests have been estimated as 4.13 PgC[1] in top 50 cm and 6.81 PgC in top 1 m soil depth. These estimates may be taken valid for 1980–1982 period on which the remote sensing based forest area assessment was made by FSI. The historic loss in forest soil organic C pool (1880–1981) in top 1 m soil depth has been estimated as 4.13 PgC. The estimated soil organic C densities by forest types can form input in models for estimating net C release from forests by deforestation as well as in estimation of historic loss in soil organic C pool in Indian forests.

Keywords: Soil organic C density; Bulk density; Forest type; Remote sensing; Forest area; Soil organic C pool

1. Introduction

Soil organic carbon (SOC) holds a very important role in global C cycle, as it is the largest terrestrial C pool. Soil can be a source (CO_2, CH_4 and N_2O) or sink (CO_2 and CH_4) of green house gases depending on land use and management (Lal, 1999). Nearly all models of global climate change predict a loss of carbon from soils as a result of global warming (Schimel et al., 1994; Mc Guire et al., 1995). However, restoration of eroded and degraded soils and intensification of agriculture can lead to C sequestration in soils (Lal, 1999).

Although soil organic C is the largest terrestrial C reservoir but its mass is least certain (Bolin et al., 1979). Estimates of storage of organic C in soils on a global scale vary between 700 and 3000 PgC (Bouwman, 1990). These estimates are based on a number of approaches, such as soil groups (Bohn, 1976; Buringh, 1984), vegetation groups (Ajtay et al., 1979; Bolin et al., 1979), FAO/UNESCO soil map (Sombroek et al., 1993), Holdridge life zone classes (Post et al., 1982) and modeling of plant production and decomposition (Meentemeyer et al., 1981). Estimates of total global soil organic C are converging on about 1500 PgC in top 1 m soil (Adams et al., 1990; Eswaran et al., 1993). This is two times the amount of 750 PgC in atmosphere as CO_2; while estimates referring to top 2 m suggest that another 900 PgC could occur at a depth of 1–2 m (Batjes, 1996). IPCC (2000) estimated the total soil C pool in top 1 m as 2011 PgC. Lal (1999) gave a conservative estimate of soil C pool as 2300 PgC, which is about 4.1 times the biotic pool, and about three times the atmospheric C pool.

Jenny and Raychaudhuri (1960) studied organic C status in Indian soils and reported the effects of climate on carbon reserves in virgin and cultivated soils. Using ecosystem areas from different sources and representative global average C densities from Ajtay et al. (1979) and Schlesinger (1983), the Indian soil organic C pool size of 23.4–27.1 and 24.4–26.5 PgC; respectively, was estimated by Dadhwal and Nayak (1993). Gupta and Rao (1994) estimated the organic C stock of 24.3 PgC using the database of 48 soil series for few major soils ranging from surface to an average subsurface depth of 44–186 cm. Velayuthum et al. (2000) have estimated soil organic C stock in different soil orders and different agro-ecological regions (Sehgal et al., 1992). For top 1 m depth they have estimated soil organic C stock as 47.5 PgC, which is double the previous estimates of Dadhwal and Nayak (1993) and Gupta and Rao (1994).

Approximately 40% of global soil C inventory resides in forest ecosystems (Hudson et al., 1994) and dynamics of forest soil organic C has significant implications to global C budget. Indian estimates of forest soil organic C are in the range 5.3–6.7 PgC (Dadhwal et al., 1998; Ravindranath et al., 1997), however most of these estimates are based on average global or regional soil C densities of various forest types. Using the average soil C densities given by Ajtay et al. (1979), the total soil organic C pool in Indian forests was estimated as 6.4–6.7 and 5.9–6.2 PgC for the period 1950–1951 and 1985–1986, respectively, by Dadhwal et al. (1998). Ravindranath et al. (1997) had estimated forest soil organic C as 5.4 PgC for the year 1986 using remote sensing based area under forest type and organic C content of different forest types from literature. Using FAO (1993) forest area (only 52 Mha) and soil pool estimated for tropical and subtropical forests by Palm et al. (1986), forest soil organic C pool of 4.9 and 4.6 PgC was estimated for 1980 and 1990, respectively, by Dadhwal et al. (1998). While there are recent studies on Indian forest phytomass C pool (Ravindranath et al., 1997; Chhabra et al., in press) and litterfall (Dadhwal et al., 1997) but soil organic C pool estimates by forest types based on Indian datasets, which are necessary for computing soil C cycle changes due to deforestation in India, have not been studied/reported. The present study aims to estimate soil organic C pool in top 50 cm and 1 m soil depth for recent and earlier period using soil organic C densities based on data for different forest types in India.

2. Methodology

India lies to the North of the equator between 8°4′ and 37°6′N latitude and 68°7′ and 97°25′E longitude. The total geographic area of the country is 328.8 Mha and as per the latest remote sensing based estimate by Forest Survey of India, forests cover 63.73 Mha area (FSI, 1999).

A database of published information on location, forest type, soil type, depth of profile, organic C percent, soil texture (sand and clay percent) and soil bulk density was prepared from the published Indian studies. Where organic matter (percent) was reported, a fraction of 0.5 was taken as soil organic C percent (Ajtay et al., 1979). In case the soil bulk density was not reported it was estimated from soil texture characteristics using the following equation developed by Adams (1973).

$$\rho = \frac{100}{(X/\rho_0) + (100 - X/\rho_m)}$$

where ρ is the soil bulk density (g/cm^3), X the percent by weight of organic matter, ρ_0 the average bulk density of organic matter (0.224 g/cm^3), and ρ_m the bulk density of mineral (g/cm^3).

The mineral matter bulk density (g/cm^3) was calculated using percentage of sand and clay from the texture triangle of Rawls (1983). A comparison between observed and calculated bulk density values from 33 soil depth/class cases, showed that the above procedure gave an RMSE of only 6%.

The size of total soil organic C stock was calculated using the method described by Batjes (1996). In the first step soil organic C density (t/ha) was computed by multiplying organic C percent, soil bulk density (g/cc) and thickness of the horizon (cm), for individual soil profile. The soil organic C density estimates were then added for top 50 cm and 1 m horizon depths in the second step. The data was then grouped according to forest types of Champion and Seth (1968). As adequate samples were not available for all the 16 major forest types recognized by Champion and Seth, all the classes were not treated separately. Tropical wet evergreen and tropical semi-evergreen were grouped under tropical evergreen forest. Alpine, sub-alpine, moist temperate, wet temperate and dry temperate were grouped as montane temperate forest. Tropical thorn forest was included under tropical dry deciduous forest, while subtropical dry evergreen forest was included in tropical dry evergreen forest. Subtropical broad-leaved hill forest and subtropical pine forest was grouped as subtropical montane forest. The Indian forests were classified into seven major types, namely, tropical evergreen, montane temperate, tropical moist deciduous, tropical dry deciduous, littoral and swamp, tropical dry evergreen, Subtropical montane.

The soil organic C pool in top 50 cm and 1 m soil depth for each of the seven major forest categories were estimated as product of the forest area under each category and mean soil organic C density estimates. The uncertainty in these estimates is expressed as ±standard error over mean estimates. As sufficient observations for dry evergreen and subtropical montane forests were not available, the soil organic C densities in top 50 cm and 1 m for tropical dry deciduous and tropical moist deciduous forest, respectively, were used for arriving at soil organic C pool estimates at respective depths. The forest area under each forest type category was taken from FSI inventory (FSI, 1987). This is based on satellite data acquired between 1980 and 1982. Although, more recent estimate of 63.73 Mha total forest area has been provided by FSI (FSI, 1999), but these do not report area under forest types of Champion and Seth (1968) and the total difference between these estimates is only 0.35 Mha at national level.

3. Results and discussion

The database of 175 and 136 observations for top 50 cm and top 1 m soil depth, respectively, was broadly categorized under seven major forest types. Champion and Seth (1968) classification of forest types has been adopted as it well recognized and areal extent compatible to it were also available. In India, tropical moist deciduous forests are the most dominant type occupying ~37%, whereas tropical dry evergreen forests cover only 0.2% of the total 64.2 Mha forest area of the country. The range of estimated soil organic C densities in top 50 cm and 1 m soil depth for different forest types of India at different locations with information of soil type and soil texture is summarized in Table 1. The soil profiles of tropical moist deciduous forests studied for the two soil depth classes have widespread locations in six states of Kerala, Madhya Pradesh, Mizoram, Tamil Nadu, Uttar Pradesh and West Bengal and union territory of Andaman and Nicobar Islands. The estimated soil organic C densities for 64 and 58 profiles of tropical moist deciduous forests are in the range 8.9–177 and 14.5–327.6 t/ha in top 50 cm and 1 m soil depth, respectively. The soil organic C density estimates of tropical dry deciduous forest varied from 7.7 to 85.6 t/ha in top 50 cm for 35 soil profiles and 18.5–147.7 t/ha in top 1 m soil depth for 17 soil profiles. The estimated soil organic C densities for Montane temperate forests distributed in states of Himachal Pradesh, Megahlaya, Uttar Pradesh and West Bengal were in the range 12.1–184.3 t/ha in top 50 cm and 24.1–525.7 t/ha in top 1 m soil depth. The 15 soil profiles studied for littoral and swamp forests in states of West Bengal and Kerala were confined to only top 50 cm soil depth. The estimated mean soil organic C densities and soil organic C pools for two depth classes (0–50 and 0–100 cm) in major forest types of India are summarized in Table 2. The estimated mean soil organic C densities were in the range of 37.5 t/ha in tropical dry deciduous forest to 92.1 t/ha in littoral and swamp forest for top 50 cm soil depth, while 69.9 t/ha in tropical dry deciduous forest to 161.9 t/ha in Montane temperate forests for top 1 m soil depth. The soil organic C pools in different forest types were calculated using estimated mean soil organic C densities and forest area. The soil organic C pool estimates for top 50 cm soil layer were in the range

Table 1
Summary of location, soil texture, soil taxonomic class and estimated soil organic C density (0–50, 0–100 cm) for different forest types of India used in this study

State[a]	Location (coordinates)	Soil texture	Soil taxonomic names	Soil OC density (t/ha)				Reference
				Top 50 cm		Top 1 m		
				N[b]	Range	N	Range	
Tropical evergreen forest								
MZ	Mizo hills (22°0′–24°15′N, 92°20′–93°29′ E)	Sandy loam, clay loam	Typic Hapludults, Umbric Dystrochrepts	3	24.6–60.9	3	33.8–103.6	Singh and Datta (1983)
DNH	–[c]	–	Vertisols Paleustollic Udic Chromusterts, Alfisols Udic Haplustalf, Entisols Lithic Ustorthents	6	31.6–94.6	3	53.8–68.8	Biswas (1985)
KE	Ariappa FD	–	–	4	94.4–97.7	4	152.1–164.2	Balagopalan and Jose (1986)
TN	Gudalur FD	Loamy sand	Fluventic Dystrochrepts	2	149.9–187.0	2	265.2–297.7	Prasad et al. (1986)
ANI	–	–	Psamment, Fluvent, Aquent, Aquept, Orthent, Ochrept, Ustalf	8	53.4–218.4	8	76.51–411.4	Ganeshmurthy et al. (1989)
J&K	Kashmir valley (33°22′–34°27′N, 74°30′–75°35′E)	–	Mollisols, Typic Hapludoll, Lithic Hapludoll, Typic Arfiudolls	5	38.9–181.7	2	98.0–152.0	Verma et al. (1990)
MZ	(22°0′–24°15′N, 92°20′–93°29′E)	Sandy loam, clay loam, clay	Typic Hapludults, Umbric Dystrochrepts	4	56.4–92.8	4	82.1–134.1	Singh et al. (1991)
Assam	Jorhat	Sandy loam	–	2	86.7–151.2	2	115.9–268.7	Singh et al. (1995)
ANI	Little Andaman (6–14°N)	–	–	1	123.0	1	169.7	Narayan et al. (1998)
J&K	Baramulla (34°00′N, 74°10′E)	Loamy skeletal	Lithic Udorthents	1	44.4	–	–	Mahapatra et al. (2000)
Montane temperate forest								
HP	Badaghat FD	Loamy sand, loam, sandy loam, silt loam	–	6	12.1–26.5	4	24.1–42.8	Chaudhri et al. (1977)
UP	Chakrata FD	–	–	5	38.6–106.3	5	57.1–176.5	Banerjee and Badola (1980)
WB	Darjeeling	–	–	–	–	9	158.3–525.7	Singh et al. (1987)
ME	E.Khasi hill (26°27′N, 90°91′45″E)	–	Humic Hapludult, Typic Udorthent, Typic Dystrochrepts, Typic Haplumbrept	5	42.2–184.3	5	67.0–222.4	Nair et al. (1989)
HP	Shimla	Loam, silty loam, silty clay	–	6	26.2–112.8	6	44.8–174.6	Gupta and Singh (1990)
UP	Mussorie FD (30°15′30″–30°27′2″N, 78°03′40″–78°18′20″E)	Silty loam, loam, silty clay loam	Typic Arguidoll, Typic Argiustolls	3	96.7–159.5	3	140.3–261.4	Raina et al. (1999)

Tropical moist deciduous forest								
MP	S&N Raipur	Loamy sand, clay loam sand, sandy loam		9	38.0–87.3	9	57.2–112.2	Yadav and Sharma (1968)
KE	Nilambur FD	–	–	6	51.4–123.9	6	71.7–186.6	Jose and Koshy (1972)
UP	–	–	–	2	53.0–157.2	2	82.8–164.2	Rajamannar and Krishnamoorthy (1978)
UP	N.Kheri (28°0′–28°30′N, 80°16′–80°35′E)	Sandy loam	Hyperthermic Typic Haplumbrept	1	46.2	1	65.9	Banerjee et al. (1981)
UP	Kheri FD	–	–	3	8.9–46.8	3	14.5–66.6	Singh et al. (1982)
UP	Dun valley	Silty loam–silty clay	–	3	51.6–65.1	3	87.1–105.1	Singhal et al. (1982)
WB	Birbhum	Loamy sand, sandy loam, sandy clay, clay loam	Ultisol Typic Haplustall, Entisol Hyperthermic Paralithic Ustorthent, Alfisol Haplustalf	2	18.6–21.5	–	–	Das and Roy (1982)
MZ	–	Sandy loam, clay loam	Typic Hapludults, Umbric Dystrochrepts	1	79.1	1	104.3	Singh and Datta (1983)
TN	Coimbatore FD (10°15′–11°0′N, 76°42′–76°51′E)	–	–	3	44.9–96.1	3	75.6–191.2	Prasad et al. (1985)
UP	Dehradun (30°11′30″–30°32′30″N, 77°34′30″–78°10′30″E)	–	Thermic Udic Haplustoll, Loamy Skeletal Thermic Udic Haplustoll, Fine Loamy Thermic Udic Haplustoll, Sandy Skeletal Thermic Udorthents	4	72.2–165.7	4	92.3–213.6	Samra et al. (1985b)
TN	Gudalur FD (11°25′–11°35′N, 76°15′–76°35′E)	Loamy sand	Ultic Tropudalf	1	176.1	1	327.6	Prasad et al. (1986)
MP	Shahdol FD (22°38′–24°17′N, 88°32′–82°12′E)	–	Sandy Skeletal Mixed Hyperthermic Lithic Ustochrepts, Fine Loamy Mixed Hyperthermic Udic/Vertic Haplustoll	5	79.4–116.7	2	113.5–171.6	Totey et al. (1986a)
MP	N. Shahdol FD	–	Haplustalf/Haplustoll	2	95.6–103.8	2	136.3–167.5	Totey et al. (1986b)
	S. Shahdol FD	–		1	52.0	–	–	
UP	Dun valley	–	Silty Loam Mixed Hyperthermic Udic Haplustalfs	3	41.2–48.9	3	59.3–68.1	Narain et al. (1990)

Table 1 (*Continued*)

State[a]	Location (coordinates)	Soil texture	Soil taxonomic names	Soil OC density (t/ha)				Reference
				Top 50 cm		Top 1 m		
				N[b]	Range	*N*	Range	
UP	S. Kheri (28°0′–28°30′N, 80°16′–80°35′E)	Sandy loam	Fluventic Haplumbrept Sandy Hyperthermic, Entic Haplumbrept Sandy Hyperthermic, Typic Haplumbrept Sandy Hyperthermic, Typic Haplaquolls Sandy Hyperthermic, Aquic Haplustolls Fine Silty Hyperthermic, Udic Haplustolls Sandy Hyperthermic, Aquic Argiustoll Loamy Hyperthermic, Udic Haplustalfs Loamy Hyperthermic	8	27.3–130.7	8	33.1–161.8	Banerjee et al. (1990)
UP	Kheri Pilibhit (28°0′–29°5′N, 79°15′–18°35′E)	–	Loamy Sand Typic Ustipsamment Sandy Hyperthermic, Loamy Sand Entic Haplumbrept Sandy Hyperthermic, Loam Eutric Ustochrepts, Sandy Hyper Loam Mollic Arguistalfs Loamy Hyperthermic	4	40.9–92.5	4	62.2–150.5	Banerjee and Sharma (1990)
MH	Chandrapur (19°27′–20°44′N, 78°48′–80°0′E)	Loamy skeletal clay	Lithic Ustorthents, Rhodic Paleustalfs, Typic Paleustalfs	2	32.1–61.8	2	72.9–99.4	Srivastava et al. (1991)
MZ	22°0′–24°15′N, 92°20′–93°29′E	Sandy clay loam	Umbric Dystrochrepts	1	120.9	1	147.0	Singh et al. (1991)
ANI	S. Andaman	–	–	1	59.6	1	103.1	Mongia and Bandyopadhyay (1992)
UP	Mussorie FD (30°15′30″–30°27′2″N, 78°03′40″–78°18′20″E)	Silty loam–loam	Typic Dystrochrepts, Ruptic Alfic Eutrochrepts	2	139.2–177	2	206.3–298.1	Raina et al. (1999)

Tropical dry deciduous forest								
UP	Haldwani	–	–	4	39.7–85.6	4	61.9–133.3	Samra (1982)
UP	Bijnor (29°4′–29°12′N, 78°01–78°41′E)	Loamy sand, sandy loam, silt loam, loam, sand	Typic Haplumbrept, Typic Ustochrepts, Typic Arguistoll, Udic Haplustalf	5	17.6–84.1	4	26.6–147.7	Samra et al. (1985a,b)
UP	Indo Gangetic Plains	Silty clay loam, sandy clay loam, loam sand, loam sand	–	5	7.7–29.8	5	18.5–49.8	Singh et al. (1990)
WB	Mednipore	Loamy sand, sandy loam	–	8	8.8–34.1	2	42.9–51.7	Nath et al. (1990)
WB	Midnapore-	Typic Halaquept	–	11	26.1–55.7	–	–	Nath et al. (1991)
MP	Betul, Chhindwara (20°15′–22°30′N, 77°22′30″–81°30′E)	–	Typic Ustochrepts, Typic Haplustalf	2	63.4–68.3	2	113.4–128.1	Tamgadge et al. (2000)
Littoral and swamp forest								
WB	Sunderban	–	–	6	37.7–67.4			Bandyopadhya (1986)
KE	Konkan coast	Sandy loam –loam	–	9	93.3–153.9			Powar and Mehta (1999)

[a] ANI: Andaman and Nicobar Islands, DNH: Dadar Nagar Haveli, HP: Himachal Pradesh, J&K: Jammu and Kashmir, KE: Kerala, ME: Meghalaya, MG: Meghalaya, MP: Madhya Pradesh, MZ: Mizoram, TN: Tamil Nadu, UP: Uttar Pradesh, WB: West Bengal. FD: forest division.

[b] Number of observations.

[c] Information not available.

Table 2
Soil organic C density and pool estimates (1980–1982) in different forest types of India (using FSI, 1987 data) (PgC = 10^{15} gC)

Forest type[a]	Area (Mha)	Soil C density (t/ha), mean (±S.E.)[b]			Soil C pool (PgC), mean (±S.E.)		
		N	Top 50 cm	Top 1 m	N	Top 50 cm	Top 1 m
T-evergreen	7.77	36	90.7 (±7.7)	138.9 (±15.1)	29	0.70 (±0.06)	1.08 (±0.12)
Montane temperate	6.43	25	73.4 (±10.4)	161.9 (±19.2)	32	0.47 (±0.07)	1.04 (±0.12)
T-moist deciduous	23.68	64	73.2 (±5.0)	111.6 (±8.0)	58	1.73 (±0.12)	2.64 (±0.19)
T-dry deciduous	20.01	35	37.5 (±3.4)	69.9 (±10.1)	17	0.75 (±0.07)	1.39 (±0.20)
Littoral and swamp	0.40	15	92.1 (±9.4)			0.04 (±0.003)	–
T-dry evergreen[c]	0.14					0.005 (±0.005)	0.009 (±0.001)
ST-montane[d]	5.77					0.42 (±0.03)	0.64 (±0.05)
Total	64.20	175			136	4.13 (±0.35)	6.81 (±0.7)

[a] T: Tropical, ST: subtropical.
[b] Standard error in parentheses.
[c] Mean soil C density of T-dry deciduous used.
[d] Mean soil C density of T-moist deciduous used.

0.005–1.73 PgC, while for top 1 m soil depth the estimates varied from 0.009 to 2.64 PgC in tropical dry evergreen and tropical moist deciduous forests, respectively. The total soil organic C pools have been estimated as 4.13 and 6.81 PgC in top 50 cm and 1 m soil depths, respectively. Tropical moist deciduous forests, which are the dominant forest types of India, contribute 38.7% to the total forest soil organic C pool (top 1 m soil depth). Humid tropical climate with alternate wet and dry periods coupled with high mean annual precipitation favor accumulation of considerably high organic matter in such forest soils. Tropical evergreen and Montane temperate forests that occupy only 7.7 and 6.4 Mha forest area contribute ~15% to the total soil organic C pool of 6.81 PgC in top 1 m soil depth. These estimates may be taken valid for 1980–1982 period on which the FSI assessment for RS based forest area (FSI, 1987) is based.

The ambient organic C content of the soil is determined by various factors. The soil organic C content may depend upon physiography or location of the study soil profile. The organic matter has a significant positive correlation ($r = 0.77$) with altitude (Banerjee et al., 1998). Nath and Deori (1976) observed an increase in organic matter content from 1.03 to 9.78% in soils of Andhra Pradesh as the altitude increased from 180 to 1800 m. The increase in organic matter with altitude was also observed by Chakravorty and Chakravarti (1980) in the eastern Himalayan soils, Minhas and Bora (1982) in soil profiles of Himachal Pradesh, and Singh and Datta (1983) in hill soil profiles of Mizoram.

The estimated soil C densities and soil C pools in the present study are based on available dataset of observations for different forest types. These need to be improved with additional observations as subtropical Montane and tropical dry evergreen forests could not be adequately covered. The present estimate of 6.81 PgC in top 1 m forest soil depth can be compared favorably with previous Indian estimates of 5.9–6.2 PgC for 1985–1986 (Dadhwal et al., 1998) and 5.4 PgC for 1986 (Ravindranath et al., 1997). The estimated mean soil C densities in top 1 m soil depth are in the range 69.9–161.9 t/ha, which is comparable with 115.0 t/ha (coefficient of variation: 29%) estimated by spatial modeling approach (Brown et al., 1993) for Indian forests. The soil organic C pool estimates of this study may be associated with some uncertainties. Approximately 8–10% standard error was estimated for soil organic C pool estimates in two depth classes. The total soil organic C pools in Indian forests were estimated as 4.13 (±0.35) and 6.81 (±0.68), in top 50 cm and 1 m soil depth. The lack of bulk density observations in the published studies is another source of uncertainty in these estimates. A comparison between observed and calculated bulk density values from 33 soil depth/class cases, reported RMSE of only 6%. As soil C density is correlated with forest densities, this could also add to uncertainty in these estimates. Of the total 64.20 Mha forest area (FSI, 1987), 36.14 Mha area was under dense forests (crown density 40% and over), and 27.66 Mha under open forests (crown density 10 to less than 40%). The database could cover a range of observations of different forest densities. These estimates are based on forest types. A number of additional factors such as forest density and altitude has been shown to significantly influence the soil organic C density. However, the published information is not sufficient to include these factors in estimates. Thus preparation of different layers in GIS (Geographic Information System) incorporating many factors such as climate, soil type, elevation and forest density, etc. that influence soil organic C density, and remote sensing based forest area can help in improving the soil C pool assessments.

The kind of land use also strongly influences the amount of organic C in soil. The loss of soil organic C by conversion of natural vegetation to cultivated use is well known. Various land uses result in rapid declines in soil organic matter (Post and Mann, 1990). The clearing of forests and their conversion into agricultural lands reduces the soil C content, mainly through reduced production of detritus, increased erosion rates and decomposition of soil organic matter by oxidation (Sombroek et al., 1993). Ghosh et al. (1981) reported that organic matter content in different soil series of 'tarai' region of Uttar Pradesh was invariably higher under forest vegetation as compared to adjacent cultivated fields under maize–wheat cropping. Tomar et al. (1986) reported that an Ustifluvent of Morni hills (Haryana) under forest contained 1.65-fold more organic matter than an adjacent field under maize–wheat cultivation. The conversion of closed forests to open forests may also reduce the soil organic C content. Jose and Koshy (1972) had reported that such change might decrease soil organic C density by about 42 and 38% in top 50 cm and top 1 m soil depth, respectively, in tropical moist deciduous forests of Nilambur Forest division, Kerala.

This study can also be used to set an upper limit of soil organic C contribution to net C release due to deforestation in India. Using the current proportion of various forest type categories and state-wise forest area estimates of 1880 given by Richards and Flint (1994), the projected forest area by type for each state was computed. The soil organic C pool in top 50 cm and 1 m soil depth was then estimated as 6.38 and 10.51 PgC, respectively, (Table 3). The historic loss in forest soil organic C pool (1880–1981) in top 1 m soil depth has been estimated as 4.13 PgC. Difference in the total C through time reflect both changes in C stocks and changes in forest area, but it may not be equivalent to losses of terrestrial C from forest soils to the atmosphere. Some of the soil C originally in forests, might have become soil C in cropland due to changes in land use over the century. Post and Kwon (2000) had reported that when natural vegetation is converted to cultivated crops, there may be reduction by ~30% of the original amount in top 1 m soil layer. Tomar et al. (1986) had reported that there might be ~40% decrease in soil organic C content in conversion of forestlands to croplands. About 25% of soil organic C held in forest soils is released to the atmosphere as a result of cultivation (Davidson and Ackerman, 1993). The decline in soil organic matter content is partly due to a lower fraction of non-soluble material in the more readily decomposed crop residues and tillage which in addition to mixing and stirring of soil, breaks up aggregates and exposes organo-mineral surfaces, otherwise inaccessible to decomposers (Post and Kwon, 2000). Taking an average 35% loss of forest soil organic C in conversion to agriculture, of the total 4.13 PgC soil organic C loss over the 100 years, ~1.4 PgC might be released to the atmosphere from the forest soils in India. This soil C release is in contrast to 4.5 PgC emissions due to phytomass C pool decrease (Flint and Richards, 1994) in the similar period and 3.45 PgC emissions from fossil fuel use

Table 3
Soil organic C pool estimates (1880) in different forest types of India (using Richards and Flint, 1994 data)

Forest type	Area (Mha)	Soil C pool (PgC), mean (±S.E.)	
		Top 50 cm	Top 1 m
T-evergreen	9.74	0.88 (±0.07)	1.35 (±0.14)
Montane temperate	8.02	0.59 (±0.08)	1.29 (±0.15)
T-moist deciduous	41.35	3.03 (±0.21)	4.61 (±0.33)
T-dry deciduous	35.51	1.33 (±0.12)	2.48 (±0.36)
Littoral and swamp	0.63	0.06 (±0.06)	
T-dry evergreen[a]	1.64	0.06 (±0.005)	0.11 (±0.02)
ST-montane[a]	5.78	0.42 (±0.029)	0.64 (±0.05)
Total	102.68	6.38 (±0.53)	10.51 (±1.05)

[a] Using mean soil organic C density estimates of 1980–1982.

and industrial activities (Dadhwal et al., 1996) over the 20th century in India. The historic soil organic C loss may provide a reference point for the potential of C sequestration in soils (Lal, 1999). In general, 60–75% of the soil organic C lost can be re-sequestered over a 25–50-year period through adoption of judicious land use and recommended agricultural practices (IPCC, 1995).

4. Conclusion

The estimated mean soil organic C densities were in the range of 37.5 t/ha in tropical dry deciduous forest to 92.1 t/ha in littoral and swamp forest for top 50 cm soil depth, while 69.9 t/ha in tropical dry deciduous forest to 161.9 t/ha in Montane temperate forests for top 1 m soil depth. Moist deciduous forests being the dominant forest type in India covering 23.6 Mha forest area (FSI, 1987) have high soil organic C pools of 1.73 and 2.64 PgC in top 50 cm and 1 m soil depths representing 42 and 38.7% of total soil organic C pool, respectively. The total soil organic C pools in Indian forests have been estimated as 4.13 PgC (top 50 cm) and 6.81 PgC (top 1 m soil depths). These estimates may be taken valid for 1980–1982 period on which the remote sensing based forest area assessment was made by FSI (FSI, 1987). The soil organic C content may be influenced by various interacting factors of physiography, changes in land use, soil type etc. The earlier soil organic C estimates by Gupta and Rao (1994) and Velayuthum et al. (2000) give an idea of recent soil organic C by soil type, but cannot be used for past soil organic C pool assessment. The historic loss in forest soil organic C pool (1880–1981) in top 1 m soil depth has been estimated as 4.13 PgC, of which $\sim$1.4 PgC might have been released to the atmosphere from the forest soils in India. This soil C release is in contrast to 4.5 PgC emissions due to phytomass C pool decrease and 3.45 PgC emissions from fossil fuel use and industrial activities over the 20th century in India. The study presents recent and historic soil organic C pool estimates by forest types and historic net soil organic C loss to the atmosphere. These estimates may form inputs in models for computation of net C release resulting from deforestation in Indian forests. Further, these Indian forest soil C estimates are significant as soils provide an option for rising greenhouse gas CO_2 mitigation by potential soil C sequestration.

Acknowledgements

This research was carried out under ISRO-DOS Geosphere Biosphere Programme. AC acknowledges the grant of Junior Research Fellowship by Space Applications Centre.

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