Organic carbon stock in Indian soils and their geographical distribution

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The first ever estimate of organic carbon (OC) stock in Indian soils was 24.3 Pg (1 Pg = 10^{15} g) based on 48 soil series taking into account of a few major soils. The present OC stock has been estimated as 63 Pg in the first 150 cm depth of soils. Soils with their geographical distribution through the country were used for computing soil organic carbon (SOC) stock in different depths in various physiographic regions. To sustain the quality and productivity of soils, the knowledge of OC in terms of its amount and quality in soils is essential. This has more relevance in soils of the tropical and subtropical parts of the globe, including the Indian sub-continent. SOC stock appears to be a single parameter that can help effectively in prioritizing the area for restoring soil health.

RESTORATION of soil quality through soil organic carbon (SOC) management has remained the major concern for tropical soils. To make this programme successful, the comprehensive knowledge on SOC stocks forms an essential prerequisite in future land resource management programmes. The contributions of SOC on physical, chemical and biological properties of soils in sustaining their productivity are being appreciated since the dawn of human civilization. Important factors controlling SOC levels include climate, hydrology, parent material, soil fertility, biological activity, vegetation patterns and land use[1]. SOC is sensitive to impact of human activities, viz. deforestation, biomass burning, land use changes and environmental pollution. To sustain the quality and productivity of soils, a knowledge of SOC in terms of its amount and quality is essential. The first comprehensive study of organic carbon (OC) status in Indian soils was conducted by Jenny and Raychaudhuri[2]. They studied 500 soil samples collected from different cultivated fields and forests with variable rainfall and temperature patterns. The study confirmed the effects of climate on carbon reserves in the soils. However, these authors did not make any estimate of the total carbon reserves in the soils. The first attempt in estimating OC stock was made by Gupta and Rao[3]. They reported OC stock of 24.3 Pg (1 Pg = 10^{15} g) for the soils ranging from surface to an average subsurface depth of 44 to 186 cm with the database of 48 soil series. However, this estimate was based on a hypothesis of enhancement of OC level judging by success stories of afforestation programmes on certain unproductive soils.

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In the recent past, the greenhouse effect has been of great concern, and has led to several studies on the quality, kind, distribution and behaviour of SOC[4–7]. Global warming and its effect on soils in terms of SOC management have led to several quantitative estimates for global C content in the soils[4–10].

The most prudent approach to study SOC, however, would be on an unit area basis for a specified depth interval which requires information on the spatial distribution of soil types, SOC and bulk density of soils. It would thus provide a better understanding of the terrestrial reservoir of SOC far beyond the general objectives of C sequestration in soils and the detrimental effects of global warming[4]. No efforts have yet been made to work out the OC stock in dominant physiographic regions of India. The present attempt is to elucidate the SOC stocks, their distribution over a range of soil depths and their relative contribution as influenced by physiography.

The size of total SOC stock is calculated following the method described by Batjes[6]. The first step involves calculation of OC, multiplying OC content (g/g), bulk density (mg/m^3) and thickness of horizon (m) for individual soil profiles with different thickness varying from 0 to 30, 0 to 50, 0 to 100 and 0 to 150 cm. During the soil survey programme of our country and also while establishing benchmark soils of India[11,12], the soils were studied and sampled up to a depth of 150 cm. Information in terms of OC and BD has been very helpful for the estimation of SOC stock in the first 30, 50, 100 and 150 cm depths. The total OC content determined by this process is multiplied by the area of the physiographic unit in the second step to work out the total SOC stock in Pg.

The Indian sub-continent comprises three major physiographic regions, namely Mountain and Hill Region of the Himalayas, Indo-Gangetic Plain and Peninsular Plateau, including the Coastal Plain, and a group of islands[13]. Based on stratigraphic and tectonic history and relief along with the erosional processes, Singh[14] earlier reported four physiographic macro regions, namely (i) the Northern Mountains, (ii) the Great Plains, (iii) the Peninsular Uplands, and (iv) the Indian Coasts and Islands. NATMO[15] has classified the physiography of India into five regions, viz. (i) the Northern Mountains, (ii) the Great Plains, (iii) Peninsular India, (iv) the Peninsular Plateau, (v) the Coastal Plains and Islands.

An attempt has been made to estimate the SOC stock in these physiographic regions[15]. This information will have relevance in terms of comparing the SOC stock in different physiographic regions.

The Northern Mountains extend all along the northern border of the country, with a length of 2500 km, an average width of 240 km and an area of 55.3 mha. Three major fold axes represent the Himadri (Greater Himalayas), Himachal (Lesser Himalayas) and the Siwaliks (Outer Himalayas) in this physiographic region. Mighty but older streams like the Indus, Sutlej, Kali, Kosi and Brahmaputra have cut through steep gorges to escape into the Great Plains. The main unifying factor is the parallelism of the three axes extending east-west[14].

The SOC reserves in this physiographic region based on 40 soil series range from 7.89 Pg to 18.31 Pg in the first 30 cm to 150 cm soil depth. The Northern Mountains cover 17% of the total geographical area (TGA) of the country, but contribute about 40% of the total SOC stock in the first 30 cm of the soil depth (Figure 1). A closer look at the selected soils of this region indicates a very high SOC content (Table 1). Parts of northern India (Jammu and Kashmir), and north-eastern India (Sikkim, Arunachal Pradesh) experience very cold climate along

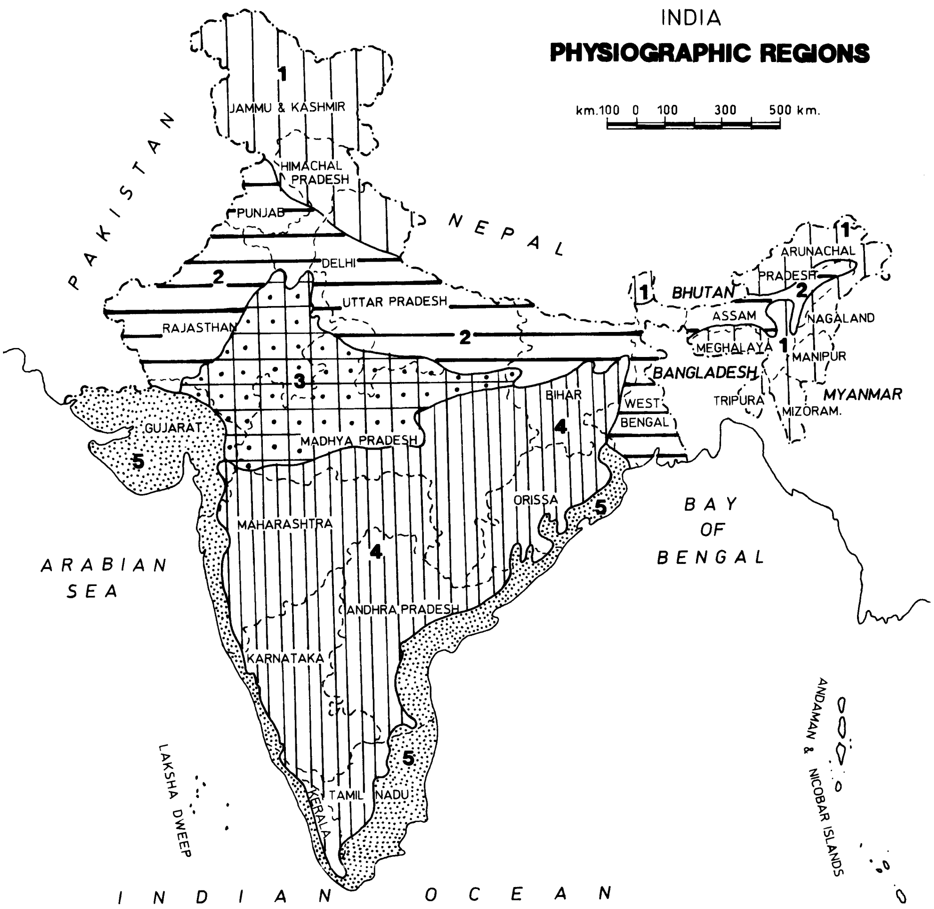

Figure 1. SOC stock in different physiographic regions of India, based on 1800 soil samples.

Symbol	Physiographic regions	SOC stock (Pg) Soil depth (cm) 0–30	0–150	Area (m ha)
1	Northern Mountains	7.89 (39)[1]	18.31	55.3 (17)[2]
2	The Great Plains	3.281 (18)	10.53	72.4 (22)
3	Peninsular India	3.64 (17)	13.34	54.7 (17)
4	Peninsular Plateau	3.62 (17)	10.11	105.7 (32)
5	Coastal Plains and the Islands	2.24 (11)	10.90	40.9 (12)
	Total	20.99 (100)	63.19	

[1]Figures in parentheses indicate per cent of total SOC stock.
[2]Figures in parentheses indicate per cent of total geographical area of the country.

with a relatively high rainfall (Table 2); such prevailing cool temperature helps storing a relatively higher SOC stock due to low rate of decomposition of soil organic matter.

The aggradational Great plains cover about 72.4 mha (Figure 1) area with the Ganga and the Brahmaputra forming the main drainage axes in the major portion. The thickness in the alluvial sediments varies considerably with its maximum in the Ganga Plains. The physiographic scenery varies greatly from arid and semi-arid landscapes of the Rajasthan Plains to the humid and per-humid landscapes of the delta and the Assam valley in the east. Topographic uniformity, except in the arid Western Rajasthan, is a common feature throughout these plains. The Brahmaputra and the Ghaghra carry more sand than silt and have formed long levees and have also raised their beds. With an average elevation of about 150 m, ranging from nearly zero m above mean sea level (Bengal delta) to nearly 300 m (Punjab and Upper Ganga Plains) near the foot-hills, the Indo-Gangetic Plains are characterized by extremely low gradients.

On the basis of about 36 soil series, the SOC stock of the Great Plains has been found to vary from 3.28 to 10.53 Pg from first 30 cm to the first 150 cm soil depths (Figure 1). Although these plains constitute 22% of the TGA of the country, the contribution of these plains to the overall SOC stock of the country is only 16%. The low SOC stock can be attributed to low SOC content of the soils. The low base status of acid soils has further affected low OC in soils (Table 1). The Haldi soils in the cooler foothills (Table 2) showing higher SOC content are exceptions.

Peninsular India covers the central uplands, Aravalli range, Eastern Rajasthan uplands, Madhya Bharat Plateau, Malwa Plateau, Vindhyan Scarpland, Vindhyan Range, Narmada valley and the Bundelkhand upland. This physiographic region covers an area of 54.7 mha (Figure 1). Most of the Satpura–Vindhyan region is overlain by the Deccan Trap in the west, with a general horizontal disposition. The Vindhyas show a somewhat folded structure, particularly in the western section. The gentle gradient of the Vindhyas to the north overlooking the trough to the

Table 1. General characteristics of a few representative soils in various physiographic regions of India (in first 30 cm depth)

Soil series*	Soil subgroup**	OC (100 g)	pH (water)	CEC cmol p^+ kg^{-1}
The Northern Mountains				
Kibber	*Typic Cryorthids*	1.4	7.8	9.0
Sukna	*Typic Haplumbrepts*	2.9	4.5	9.6
Yakimoli	*Typic Hapludalfs*	2.7	4.4	16.0
Digingru	*Typic Palendalfs*	1.9	4.5	11.0
Dialong	*Ultic Hapludalfs*	1.7	4.5	14.4
The Great Plains				
Thar	*Typic Torripsamments*	0.1	8.0	2.3
Zarifa viran	*Typic Natrustalfs*	0.3	10.3	11.5
Itwa	*Aeric Ochraqualfs*	0.3	6.6	12
Pantnagar	*Aquic Hapludolls*	2.7	6.5	19
Haldi	*Typic Hapludolls*	0.7	7.1	8
Peninsular India				
Bijapur	*Udic Ustochrepts*	0.2	6.7	6.6
Sarol	*Typic Haplusterts*	0.4	8.0	53.2
Jambha	*Typic Haplusterts*	0.5	8.5	53
Bhubaneswar	*Typic Haplustulfs*	0.6	4.7	6.2
The Peninsular Plateau				
Raichur	*Typic Pellusterts*	0.8	8.0	71.8
Nimone	*Typic Haplusterts*	0.4	8.1	56.9
Kasireddipalli	*Sodic Haplusterts*	0.7	8.8	73
Coimbatore	*Vertic Ustropepts*	0.4	8.7	39
Amgaon	*Typic Plinthustalfs*	0.6	6.1	5.8
The Coastal Plains and Islands				
Lakhpat	*Typic Natrargids*	0.2	8.7	27.0
Kalathur	*Sodic Haplusterts*	0.6	9.4	41.0
Sagar	*Typic Haplaquepts*	0.7	6.6	22.0
Thiruvananthapuram	*Oxic Dystrochrepts*	1.1	4.5	6.2
Minicoy 1	*Typic Ustipsamments*	4.2	7.9	3.3
AP Coast	*Typic Ustifluvents*	0.8	8.4	33

*Adapted from refs 7 and 13; **Also see ref. 27.

south is another distinguishing feature, while the Satpuras possess steep gradients towards the Narmada valley in the north and Tapti valley in the south.

The dominant soils in this part of India are characterized by shrink-swell minerals and are commonly known as black cotton soils. About 18 representative soils of this region were used to work out the total SOC stock. The SOC reserves are found to vary from 3.64 to 13.34 Pg in the first 30 cm and 150 cm soil depths respectively (Table 1, Figure 1). This region covers 17% of the TGA of the country and contributes similar percentage of SOC share (Figure 1). A closer look at the point data indicates poor SOC content of these soils (Table 1) which has been ascribed to overall higher atmospheric mean maximum temperature (32–40°C) and lower mean annual rainfall (500–900 mm) in this part of the country (Table 2).

Morphologically polygenetic and complex, relatively stable landscape extending from the southern margin of the Great Plains up to the coastal margins of the country covering 105.7 mha area form the spectacular Peninsular Plateau of India (Figure 1). The Peninsular landscape consists of several cycles of denudation, sedimentation and igneous activities. As many as nine cycles (Delhi, Satpura, Eastern Ghats, Dharwar, Cuddapah–Vindhyan and Cainozoic) have operated either completely or in an interrupted form[14].

Nearly 36 soil series were identified to work out the SOC stock of this physiographic region. With a few exceptions, these soils are dominantly of shrink-swell nature and are characterized by low SOC content (0.4%) (Table 1) due to high tropical temperature (Table 2). This is the reason why the Peninsular Plateau region contributes only 17% of the total SOC stock of the country in spite of occupying about one-third the area of the entire country (Figure 1).

The Indian coasts vary in their characteristics and structures. The west coast is narrow except around the Gulf of Canbary and the Gulf of Kutch. In the extreme south, however, it is somewhat wider along the south Sahyadri. The backwaters are the characteristic features of this coast. The east coast plains, in contrast, are broader due to depositional activities of the east flowing rivers

Table 2. Range in characteristics of various physiographic regions of India

Elevation (m above msl)	Temperature (°C) Maximum	Minimum	Annual	Mean annual precipitation (mm)	Vegetation
The Northern Mountains					
600–6000	14–17	– 5 to – 9 (Leh)	9–14	100–115	Dry alpine scrub
	17–18	– 10 to – 14 (Kashmir)	8–10	550–600	Dry temperate coniferous forest
	23–27	7–10 (Lower parts of Northern hills)	15–18	2000–2500	Moist temperate
The Great Plains					
300–600	41	6–8 (Upper)	25	600–800	Tropical thin forest
	31–32	16–18 (Middle)	25–26	1000–1200 1000–1500	Tropical mixed deciduous forest
	35–36	10–12 (Lower)	25–26	1300–1600	Moist deciduous
Peninsular India					
300–900	38–40	< 9 (west)	25–27	500–900	Mixed deciduous and thorn forest
	30–34	17–19 (central)	25–28	1000–1600	Mixed deciduous moist deciduous
	32	9–12 (eastern)	25–26	1400–1600	Mixed deciduous
The Peninsular Plateau					
300–1800	38–41	15–20	26–27	700–1100	Tropical dry deciduous
	31–35	20–24	25–29	700–1000	Tropical dry deciduous thorn forest
	30–38		26–29	600–1000	Tropical thorn and dry deciduous
The Coastal Plains					
0–300	East				
	30–32	25–26	27–28	900–1000	Thorn forest
	39–40	20	28–29	1000–1100	Tropical moist deciduous and littoral
	36–37	14–16	26–27	1500–2000	Littoral and swamp
	West				
	37	17	27–28	> 2000	Moist deciduous
	33–36	22–24	27–28	2000 – > 3000	Wet evergreen littoral and swamp
	Island				
	27–32	20–23	26–27	2000 – > 3000	Tropical rain forest and semi evergreen littoral and swamp

owing to the change in their base levels. Extensive deltas of the Mahanadi, Godavari, Krishna and Kaveri are the characteristic features of this coast. The two groups of Islands, i.e. the Arabian Sea Islands and Bay Islands differ significantly in origin and physical characteristics. The Arabian Sea Islands (Laccadive, Minicoy, etc.) are the foundered remnants of the old land mass and subsequent coral formations. On the other hand, the Bay Islands lie only about 220 km away from the nearest point on the main land mass and extend about 590 km with a maximum width of 58 km. The total area covered by the Coastal Plains and the Islands is 40.9 mha.

On the basis of 43 soils series, the SOC stock of this region has been worked out. The stock ranges from 2.24 to 10.90 Pg in the first 30 cm to first 150 cm depth of soils respectively (Figure 1). The soils in this region vary widely from recently formed sandy soils (Minicoy 1, AP coastal soil), beginning of the soil formation (Sagar, Thiruvananthapuram series), salt-affected shrink-swell soils (Rinawada, Kalathur series) to typical acid sulphate soils of Kerala (Ambalapuzhay series) (Table 1). This region has a wide range of climatic variations (Table 2) causing varied SOC content and other related properties in such soils (Table 1).

The Northern Mountains are holding 39% of SOC stock of the country largely due to the thick forest vegetation aided by low rate of OM decomposition and thus helping to pile up the level of SOC. The study of Dixon *et al.*[16] provided a recent estimate of carbon pools and flux of global forest ecosystems.

The Northern Mountains of our country have maximum concentration of forest ecosystem, except parts of central and western India. It can be, with a word of caution, used as the present soil carbon stock of the cooler forest systems of the country. The uncertainties in such estimates include not only a reliable estimate of the area of forests but also the amount of carbon in forest soils – the data for the latter being few. Recently Eswaran *et al.*[17] noted that about 40% of the SOC stock of the global soils reside in forest ecosystems. The present estimate is also near the 40% contribution of world soils (Figure 1).

The Indo-Gangetic Plains (IGP) cover about 60% of the total area of the Great Plains. The IGP undergo a gradual change in climate, physiography, natural vegetation and cropping systems[18]. A recent account of the total carbon stock in soils of IGP indicates that the soils under hot humid and per humid climates are deficient in SOC due to intensive agricultural practices. Carbon sequestration in these soils is, however, possible through green manuring and application of farmyard manures in view of conducive soils and climatic conditions[7]. Most part of the humid and sub-humid regions of the Great Plains punctuated by 2 to 3 cooler months and dominated by non-calcareous soils falls under the sufficient zones of SOC content. It has been reported that the soils of arid and semi-arid climates occupying more than one-third area of IGP are poor in SOC content and are thus prone to become calcareous sodic soils[19]. Proper rehabilitation programmes can make these sodic soils resilient and can thus form an important step for carbon sequestration to improve the soil quality. The total area under the entire Indian Peninsula is about 160 mha. Out of this about 30 mha is under black cotton soils. Relatively low rainfall and high summer temperature have been found to be the main reason for poor SOC content in the black cotton soils as well as other red soils occurring in the Indian Peninsula. Judging by the poor SOC stock, it becomes necessary to take new initiatives in restoring the productivity of black cotton soils in particular[19] and other soils in the Peninsular India[7] in view of global climatic changes as experienced in the current aridic environment in parts of southern and central Peninsular India[20].

Keeping in view the distribution of SOC stock in different physiographic region (Figure 1), it appears essential that SOC status in soils of various regions needs to be increased by proper carbon sequestration through afforestation and by reclaiming sodic soils[7].

In this context it is relevant to mention the SOC quality in terms of its functional pools *vis-à-vis* turnover time[20]. The quality of SOC may be judged by the content of either decomposable (labile) or resistant fractions. The labile fractions are again grouped into an active pool and are composed of microbial biomass, soluble carbohydrates and exocellular enzymes (turnover time is less than 1 year) and a recalcitrant/resistant pool. This resistant pool is composed of particulate organic matter (turnover time ranges from 8 to 50 years) and a passive pool is composed of humic acid, fulvic acid and organo-mineral complex (turnover time ranges from 400 to 2200 years)[21].

The quality of SOC according to its functional groups indicates that plants and animal residues with average turnover period of less than 1 year could be the ideal source of organic matter for the rapid sequestration of OC. Practically FYM and green manures have been found to be good sources for better accumulation in different soils and cropping systems[3,22,23].

Forest ecosystem in hills and mountain areas appears to be the most conducive soil–climatic environment for higher accumulation of SOC, thus helping in maintaining the soil quality. Such an environment exists not only in hills and mountain areas but also at places in other physiographic regions. Encroaching such areas for agricultural activity to produce more food grains will make the soil unhealthy by decomposition of OC due to increase in soil temperature as a result of reduction in vegetation cover. Soils under arid and semi–arid climates irrespective of physiographic regions are impoverished in SOC despite their ability to interact with organic matter in binding OC in terms of clay–organic complex. Sequestration of OC in soils of these climates is not possible due to high temperature and less rainfall impairing the fate of vegetative cover over the land.

In the present scenario of differing climatic parameters such as the rising of temperature and shrinking of annual rainfall in some areas of the country, it will continue to remain as a potential threat for tropical soils of the Indian sub-continent[25]. Therefore, the arid climate will continue to remain as a bane for Indian agriculture because this will cause soil degradation in terms of depletion of OC and formation of pedogenic $CaCO_3$, with the concomitant development of sodicity and/or salinity[7,20,26]. To combat such a situation, the restoration of OC balance and efforts to enlarge the soil carbon pool by appropriate management techniques and also to encourage agro-forestry should form the strategic perspectives to sustain the health of Indian soils. The most unfavourable natural endowment is the climatic adversity and this will ever demand for extra resources to support targetted yields in Indian agriculture and thus may retard the pace of the rehabilitation programme required to restore the soil productivity. Despite this fact, research on soils of arid climates sponsored through national agenda needs to be an immediate concern. In the absence of such a programme, deforestation will continue to increase the area under agriculture and obviously this may delay in achieving the desirable balance between the land and the people. Thus the soil carbon stock can act as a single most important parameter in prioritizing areas for the management of the soils in different physiographic regions of the country.

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