Spatial variability in distribution of organic carbon stocks in the soils of North East India

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Northeastern region (NER) of India has wide variation in physiography and climatic conditions. Because of its strategic settings in the phyto-biomass-rich landscape of the Eastern Himalaya, the soils are rich in organic carbon. However, sporadic information on field-scale observations is available on soil organic carbon (SOC) content at regional level. Information on status and spatial variability of SOC and its complex interaction with land-use systems is scanty. Therefore, an attempt was made to estimate spatial variability in SOC inventories for surface soils across six states of NER (viz. Assam, Manipur, Meghalaya, Nagaland, Sikkim and Tripura covering a geographical area of 15.61 m ha) in Geographical Information System (GIS) environment. Results revealed that the soils were very high in SOC content – 98.54% area had >1% and 14.4% area had > 2.5% SOC content. Similarly, 76.5% area had SOC density of 20–40 Mg/ha and 8% area had very high SOC density of 40–60 Mg/ha. A total of 339.8 Tg (1 Tg = 10^{12} g) SOC stocks was estimated on an area of 10.10 m ha surface soils representing all major land-use systems, with a major share (>50%) coming from forest soils. Complex interaction of geographic location, rainfall, soil texture and land-use practices significantly influenced spatial variation in SOC content, density and stock. The SOC content as percentage of total geographical area was highest in Sikkim followed by Nagaland, Manipur, Meghalaya, Assam and Tripura.

Keywords: Land-use systems, phyto-biomass, soil organic carbon, spatial variability.

SOIL organic carbon (SOC) is one of the most important indicators of soil fertility, productivity and quality. Decline in SOC creates an array of negative effects on land productivity[1–3]. Hence maintaining and improving its level is a pre-requisite to ensure soil quality, crop productivity and sustainability of agricultural ecosystems[4]. Since soil contains a significant part of the global carbon stock (3.5%)[5], there is growing interest in assessing the role of soil as a sink for carbon under different land-use management practices, including forest ecosystems[1,2,6–8]. Increase in SOC content by 0.01% can substantially reduce the adverse consequences of annual increase in atmospheric carbon dioxide concentration[9].

The Northeastern region (NER) of India, by virtue of its geographic location and richness in biodiversity, well supported by complementary climatic factors, more particularly high rainfall for luxuriant phyto-biomass (both above and below ground) in the form of forests and allied sources of vegetation, has a unique place in the country[10]. The region experiences hot summer and cold winter. The temperature varies from as low as 0°C in the Himalayan range (Sikkim) to 35°C in some parts of Tripura. The region falls under high rainfall areas, with Cherapunjee Plateau (Meghalaya) receiving over 11,000 mm during monsoon season (June–September). The region is characterized by steep to very steep slopes in Meghalaya, Manipur, Nagaland and Sikkim, and gentle slopes in the Assam valley. The topography, climate and vegetation have played a great role in the formation of a variety of soils in the region. These could be broadly put under Red and Yellow, Brown Hill, Old and Recent Alluvial and Terai soils[11].

Phyto-biomass is one of the most important renewable sources that enriches the soil with organic carbon. However, expanding crop lands to meet the food requirement always comes at the cost of reduced carbon stocks in natural vegetation and soils[2,3]; similar is the situation in NER. There is burning of phyto-biomass of more than 8.5 million tonnes (mt) annually at the rate of 10 Mg/ha from shifting cultivation alone[12].

The magnitude of variation in SOC content and stock (increase/decrease) depends on the type of land-use, degree of land-use change and post-conversion land management[2,13]. Since the NER is highly variable in climatic conditions (tropical to alpine climate), topography, rainfall pattern, vegetation, land use and cultural diversity and ethnicity, the SOC content is expected to be highly variable across the entire region. However, limited field-scale observations are available on the spatial distribution of SOC content at the regional level[14,15]. Lack of any spatial information on land-use pattern vis-à-vis soil fertility indicators like SOC of NER makes it difficult to

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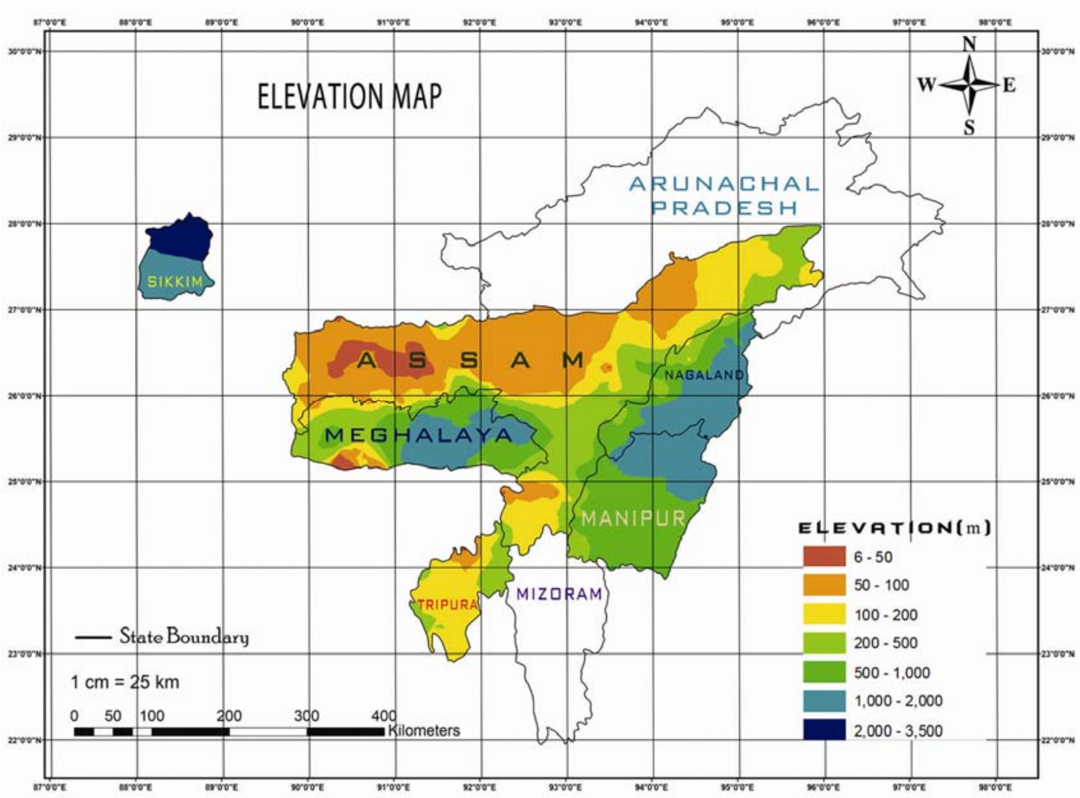

Figure 1. Study area representing geographical location, including relative elevation (m).

implement any large-scale or location-specific sustainable agricultural development programme.

With the advent of geospatial tools like satellite remote sensing and geographic information system (GIS), it is now possible to integrate them with traditional point-based observations to generate land-use–land-cover map from multi-temporal data and spatial databases on natural resources, including soil carbon inventories at the regional scale. The outcome of the findings would give a new dimension at the regional level land-use planning, agricultural area diversification and future projection studies. It would also be helpful in devising location-specific mitigation and adaptation strategies related to carbon sequestration and climate-resilient agriculture. Therefore, an attempt was made to develop the SOC map of six states of NER with the help of point data from field experimentation and secondary sources and study the SOC variability pattern with respect to land use, physiography and climate.

Materials and methods

Study area

The study area includes six states of NER, viz. Assam, Meghalaya, Manipur, Nagaland, Tripura and Sikkim having a geographical area (GA) of 15.61 m ha (nearly 4.8% area of the country; Figure 1) with a population of more than 43 million[16]. About 35% of the area in the region is occupied by the plains, except Assam where it is about 84.4% of GA. The region has a distinct land-use pattern as compared to the rest of the country. Nearly 15.3% of GA is under cultivation; forest cover in the region varies from 35.28% (Assam) to 90.68% (Mizoram)[17]. Area under shifting cultivation is 3.36% (0.877 m ha)[18]. The land-use pattern and distribution in the six states of NER is presented in Table 1 and Figure 2.

Data source

For collection of soil samples, a grid of 15 km × 15 km was prepared in ArcGIS and then overlaid on the land-use map of the study area (Figure 2) derived from multi-temporal LISS-III satellite image (23.5 m spatial resolution) of Indian Remote Sensing Satellite (IRPS-P6)[19]. A total of 694 grids, each with an area of 225 km^2 (15 km × 15 km) covered the total geographical area (TGA) of the study area (15.61 m ha). Out of 694 grids, 457 grids mostly representing major land-use systems spread across the six studied NE states (10.1 m ha areas) were selected for collection of soil samples. From each of these grids, geo-referenced composite surface (0–15 cm) soil samples were collected. Data were also collected from 285 additional geo-referenced locations of the six states studied

Table 1. Land-use–land-cover statistics of NER derived from multi-temporal remote sensing data of IRS-P6-LISS-III sensor (2004–2005)[19]

State	Assam	Manipur	Meghalaya	Nagaland	Sikkim	Tripura	Total
Geographical area (m ha)	7.79	2.22	2.24	1.65	0.7	1.02	15.61
Land use (% of geographical area)							
Built-up	22.53	32.57	45.62	39.56	1.16	10.97	27.32
Crop land	32.16	7.54	6.46	11.28	9.64	12.86	20.51
Dense forest	16.03	28.87	25.11	27.25	26.31	51.73	23.15
Open forest	4.72	11.53	1.51	0.35	10.30	11.11	5.44
Plantation crops	5.05	0.19	2.44	0.10	0.12	4.92	3.24
Shifting cultivation*	0.31	2.77	3.33	9.14	0.00	2.42	2.15
Snow-covered area	0.00	0.00	0.00	0.00	36.73	0.00	1.64
Grassland	3.41	0.00	0.00	0.04	6.80	0.00	2.01
Wasteland	4.58	14.63	13.99	11.13	8.13	4.91	8.22
Water bodies	11.23	1.91	1.54	1.15	0.81	1.09	6.32

*Current + abandoned; Source: Ref. 19.

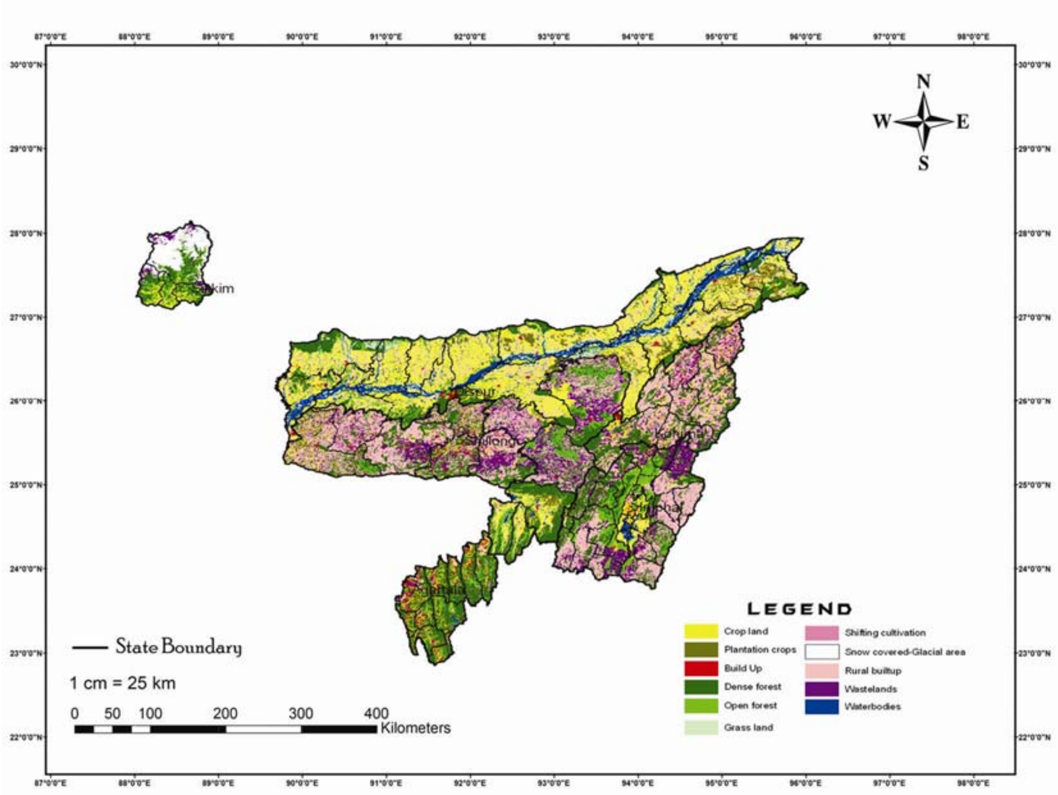

Figure 2. Land-use–land-cover map of NER derived from LISS-III (2005–06) data[19].

on surface soil texture (sand, silt and clay contents) and SOC status of surface layer from different secondary sources like published soil database generated through soil resource mapping of India by the National Bureau of Soil Survey and Land Use Planning (NBSS and LUP), Nagpur[20–24], peer-reviewed research articles and reports published by research institutions located in NER[12,14,15,25].

All together (including secondary data on 285 locations), 742 observations (sample size) representing major land uses, namely forests–dense and open (254), agriculture (crop land–168), shifting cultivation (65), plantation and horticultural crops (87), grassland (75) and wasteland (93) were considered for spatial mapping of SOC inventories of NER. State-wise sample numbers representing the major land uses are presented in Table 2. The collected 457 soil samples were air-dried, crushed and ground to pass through a 0.5 mm sieve and then analysed for SOC following wet digestion method[26].

Soils are mostly acidic in reaction and acid soils below pH 5.5 occupy more than 60% of the studied area[11]. Presence of toxic concentrations of Al^{3+} and to a lesser extent Mn^{2+}, deficiency of bases (Ca, Mg, K) due to extensive leaching and their poor retention power in clay complex, high P-fixation capacity of soil caused by highly active Al^{3+} and Fe^{3+} surfaces are some of the major constraints in achieving optimum crop productivity[11,27]. Soil textural class was determined by hydrometer method[28]. Average percentage of sand content varied from 26.9 in Nagaland to 47.3 in Meghalaya, whereas silt content (%) varied from 28.4 in Tripura to 40.6 in Sikkim. Similarly, clay content (%) varied from 18.8 in Sikkim to 32.6 in Nagaland (Table 2). Model-estimated average bulk density (BD) values computed from soil texture (silt and clay) and SOC-dependent pedo transfer function (PTF) developed by Kaur *et al.*[29] reflected a variation from as low as 0.88 (±0.16) in Sikkim to as high as 1.31 g/cm^3 (±0.18) in Tripura (Table 2).

Computation of SOC stock

Several PTFs have been developed for estimation of BD based on SOC only[30,31], whereas few are based on both SOC and textural data[32,33]. We estimated soil BD (Table 2) using PTF developed by Kaur *et al.*[29], which was based on both SOC and soil texture. The algorithm is as follows

$$\text{BD (g/cm}^3) = \exp\{0.313 - 0.191\ (\%\ \text{SOC}) + 0.021\ (\%\ \text{clay})^2 - 0.00432\ (\%\ \text{silt})\}.$$

SOC densities were estimated from the SOC contents, estimated BD values and the corresponding soil depth by using the following equation

$$\text{SOC density (Mg/ha)} = \text{SOC (g/g)} \times \text{BD (g/cm}^3) \times \text{soil depth (cm)}.$$

For estimation of SOC stocks under various land-use systems in each state, average SOC density values (Mg/ha) estimated by Choudhury *et al.*[34] under major land-use systems of NER were used. Remote sensing-based area (ha) from satellite data of LISS-III sensor[19] estimated under major land-use systems (Table 1) and the corresponding SOC density of each land-use system were used to calculate SOC stocks in Tg (1 Tg = 10^{12} g = 10^3 Mg) by the following equation

$$\text{SOC stock (Tg)} = \frac{\text{SOC density (Mg/ha)} \times \text{area under each land use (ha)}}{10^6}.$$

For estimation of SOC stocks, only major land-use systems representing agriculture (settled and shifting cultivation), forests (dense and open), plantation and horticulture, grassland and wasteland covering 10.10 m ha of the total area of 15.61 m ha area were considered. Built-up area and water bodies across the six NE states and snow-covered area of Sikkim were not included in stock estimation.

To prepare spatial inventory of SOC, a point layer on SOC observation was generated in GIS environment (ArcGIS 9.3 software) using data on 742 geo-referenced sampling locations. By interpolation of this point layer using kriging, the SOC map was generated and classified into five groups representing SOC content (%), namely 0.50–1.0, 1.0–1.5, 1.5–2.5, 2.5–3.5 and 3.5–5.5. The state-wise area statistics was also generated from the SOC map. Similarly, spatial map of SOC density (Mg/ha) was prepared having six classes of SOC density (Mg/ha), namely 10–20, 20–30, 30–40, 40–50, 50–60 and 60–80 and the corresponding area in each state under the six classes was also calculated.

Statistical analysis

Statistical analysis was performed with SAS Version 9.2 (SAS Institute Inc., Cary, NC, USA). The PROC GLM procedure of SAS was used to conduct analysis of variance (ANOVA) to determine the statistical significance of treatment (six studied NE states) effects on SOC content and density across the study area. Each state was considered as one treatment and means of treatments (6) were compared with Duncan's Multiple Range Test (DMRT) at 0.05 probability level of significance. Statistical significant differences in SOC content and SOC density among the six studied states were also graphically represented by a diffogram using PROC GLM SAS (SAS Institute, Version 9.2).

Table 2. Descriptive statistics about baseline and estimated soil properties across the study area

State	No. of samples	Sand (%)	Silt (%)	Clay (%)	BD* (g/cm^3)
Assam	224	40.7	34.6	24.7	1.24 ± 0.19
Manipur	104	33.2	36.5	30.3	1.03 ± 0.20
Meghalaya	123	47.3	28.9	21.0	1.09 ± 0.19
Nagaland	92	26.9	40.5	32.6	1.01 ± 0.22
Sikkim	71	41.4	40.6	18.8	0.88 ± 0.16
Tripura	128	44.8	28.4	26.8	1.31 ± 0.18

*Estimated BD values.

Results

GIS mapping of spatial distribution of SOC content, density and stock

SOC content: Spatial distribution of SOC content at the surface layer covering both arable and non-arable lands varied considerably across the study area (Figure 3). Of the TGA of 15.61 m ha covering the six states of NER, 98.54% of the area had SOC content of more than 1%,

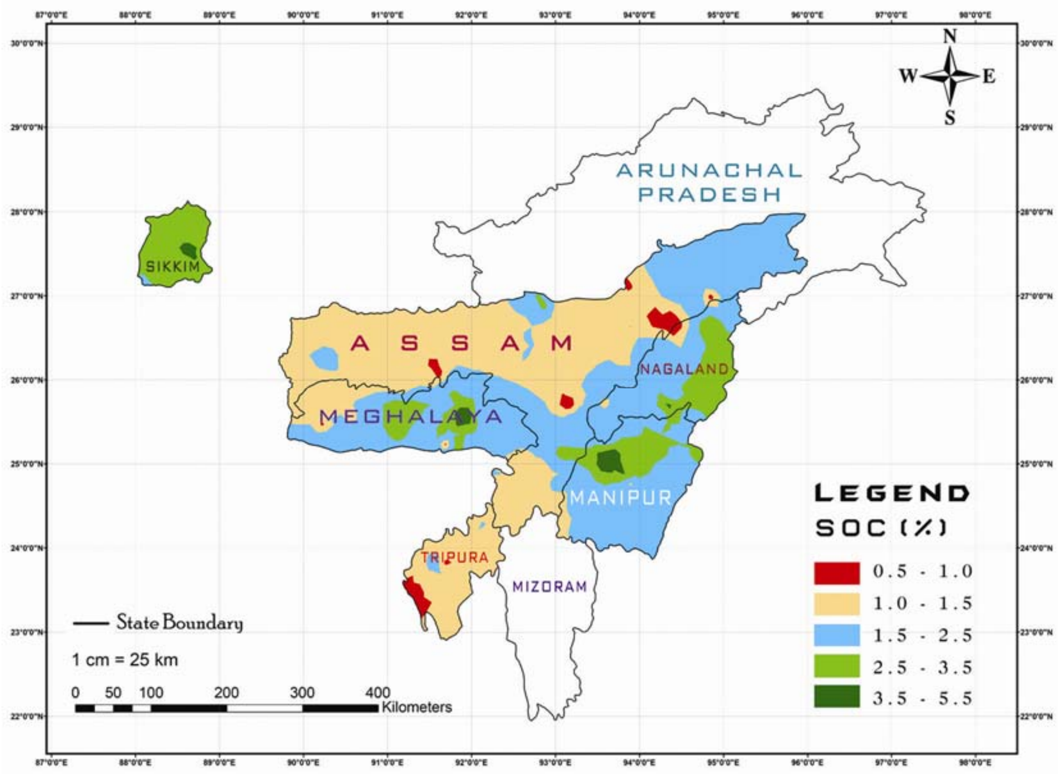

Figure 3. Spatial distribution map of SOC content across NER.

Table 3. Area under different classes of SOC (%) content in NER

State	Geographical area (m ha)	SOC content (%)				
		0.5–1.0	1.0–1.5	1.5–2.5	2.5–3.5	3.5–5.5
Assam	7.790	0.136 (1.74%)*	4.894 (62.83%)	2.695 (34.59%)	0.065 (0.84%)	0
Manipur	2.218	0	0.065 (2.93%)	1.589 (71.63%)	0.484 (21.80%)	0.081 (3.64%)
Meghalaya	2.238	0.002 (0.07%)	0.445 (19.90%)	1.407 (62.86%)	0.344 (15.39%)	0.04 (1.78%)
Nagaland	1.649	0.013 (0.81%)	0.069 (4.18%)	1.015 (61.56%)	0.549 (33.32%)	0.002 (0.14%)
Sikkim	0.699	0	0	0.012 (1.70%)	0.656 (93.88%)	0.031 (4.42%)
Tripura	1.017	0.077 (7.55%)	0.905 (89.03%)	0.035 (3.42%)	0	0
Total	15.611	0.228 (1.46%)	6.378 (40.85%)	6.753 (43.25%)	2.098 (13.44%)	0.154 (1.00%)

*Figures in parenthesis are values in percentage of total geographical area in the respective states.

whereas 57.68% of the area had SOC content more than 1.5% (Table 3). Similarly, 43.25% of the area had SOC content 1.5–2.5%, and this class was dominant in three states, namely Manipur (71.63% of TGA), Meghalaya (62.86% of TGA) and Nagaland (61.56% of TGA). Very high organic carbon content (3.5–5.5%) was recorded in small areas in Sikkim (4.42%), Manipur (3.64%), Meghalaya (1.78%) and Nagaland (0.14%). In Sikkim, most of the area (>93% of TGA) had SOC content of 2.5–3.5%, whereas in Nagaland and Manipur, it was 33.33% and 21.8% respectively. In the 1.5–2.5% range, the highest percentage of area was estimated for Manipur (71.63) followed by Meghalaya (62.86) and Nagaland (61.56). Among the NE states, Tripura had highest area (>89%) under relatively low SOC content (1.0–1.5%) followed by Assam (62.83%) and Meghalaya (19.9%). SOC content of <1% was recorded in small areas of Tripura (7.55%), Assam (1.74%) and Nagaland (0.81%; Table 3).

On the basis of percentage, SOC content (≥1.5%) was highest in Sikkim (100% area) followed by Manipur (97.07%), Nagaland (95.02%), Meghalaya (80.03%), Assam (34.59%) and Tripura (3.42%; Table 3).

SOC density: The SOC density of surface layer was estimated from the soil depth, BD and the corresponding SOC content for the six states of NER. On spatial interpolation (using kriging in GIS environment), wide variability among and within each state was observed

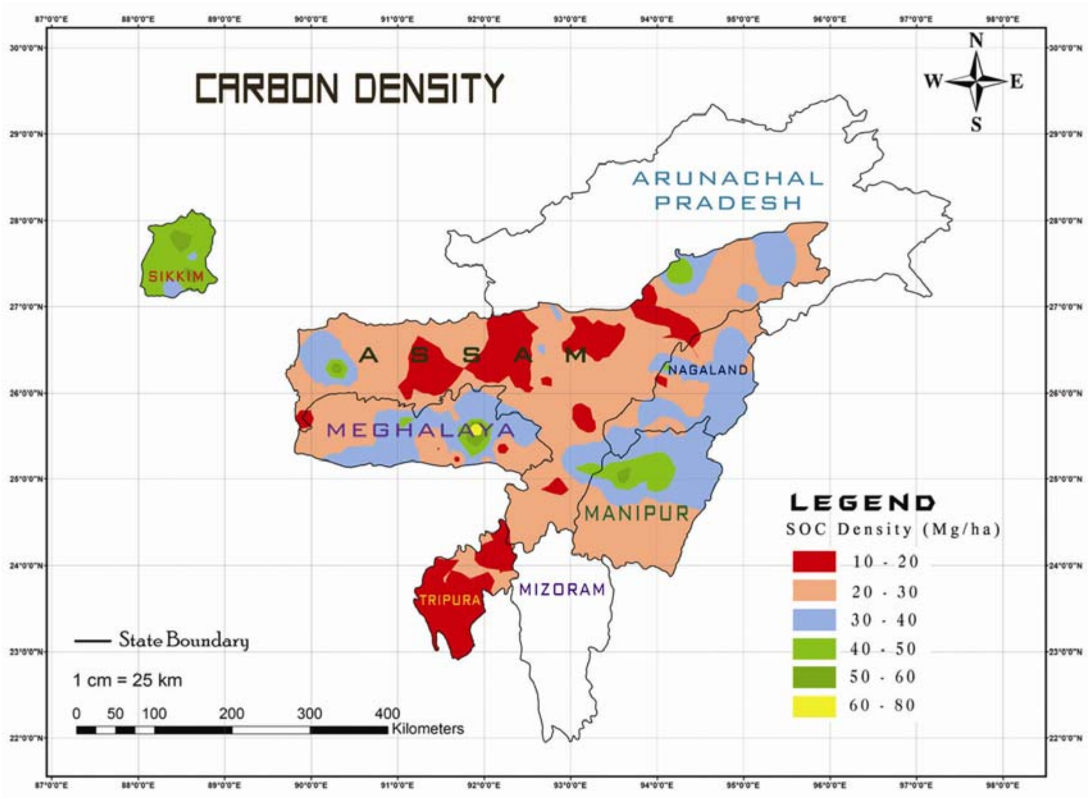

Figure 4. Spatial distribution map of SOC density across NER.

Table 4. Spatial distribution of different classes of SOC density across NER

State	Geographical area (m ha)	SOC density (Mg/ha) in percentage of total geographical area					
		10–20	20–30	30–40	40–50	50–60	60–80
Assam	7.790	19.40	65.31	13.26	1.86	0.17	Nil
Manipur	2.218	Nil	49.39	36.51	13.03	1.07	Nil
Meghalaya	2.238	1.42	49.51	42.56	4.06	1.72	0.73
Nagaland	1.649	1.71	40.43	57.51	0.35	Nil	Nil
Sikkim	0.699	Nil	Nil	7.17	81.98	10.86	Nil
Tripura	1.017	81.80	18.20	Nil	Nil	Nil	Nil
Total	15.611	15.39	52.16	24.30	7.07	0.97	0.13

(Figure 4). Average SOC density varied from 10 to 60 Mg/ha, with more than half of the area having SOC density of 20–30 Mg/ha (Table 4). Nearly 24.30% of the area had SOC density of 30–40 Mg/ha and only 8.0% of the area recorded SOC density of 40–60 Mg/ha. Among the six states, Sikkim had maximum area (81.98%) under high SOC density (40–50 Mg/ha) followed by Manipur (13.03%) and Nagaland (4.06%). Similarly, Sikkim was the only state having considerable area (>10%) under very high SOC density (50–60 Mg/ha).

In Nagaland, 57.5% of the area was under SOC density of 30–40 Mg/ha and 40.4% of the area was in the range 20–30 Mg/ha. SOC density in nearly half of the area in Meghalaya (49.51%) was 20–30 Mg/ha, while in 42.56% of the area, SOC density was 30–40 Mg/ha. Similarly, in Manipur, 49.39% of the area registered 20–30 Mg/ha and in 36.5% of the area, SOC density was 30–40 Mg/ha. Among the NE states, Tripura recorded highest percentage of area (81.8) under relatively low SOC density (10–20 Mg/ha). Assam also registered one-fifth of its TGA under low SOC density (10–20 Mg/ha), while in two-thirds of the area (65.3%), SOC density was 20–30 Mg/ha (Table 4).

SOC stock: Of the TGA of 15.61 m ha covering the six NE states, surface SOC stocks were estimated for 64.71% of the area (10.10 m ha; Table 5) representing only major land-use systems, excluding the area under settlements (rural and urban), water bodies and snow-covered areas of Sikkim. As percentage of area under settlement and water

Table 5. SOC stock (Tg) under major land-use systems in NER

State	% of GA[a]	Total SOC stock (Tg)							
		Crop land	Dense forest	Open forest	PC[b]	SC[c]	Wasteland	Grassland	Total stock
Assam	66.2	77.0	48.5	13.0	12.6	0.8	8.2	12.5	172.6
Manipur	65.5	5.1	24.9	9.0	0.1	2.0	7.5	–	48.6
Meghalaya	52.8	4.4	21.9	1.2	1.8	2.4	7.2	–	38.8
Nagaland	59.3	5.7	17.5	0.2	0.1	4.8	4.2	0.0	32.5
Sikkim	61.3	2.1	7.2	2.5	0.0	–	1.3	2.2	15.3
Tripura	87.9	4.0	20.5	4.0	1.6	0.8	1.1	–	32.0
Total	64.7	98.3	140.4	30.0	16.2	10.7	29.5	14.7	339.8
SOC density[d] (mg/ha)	–	30.7	38.8	35.3	32.1	31.8	23.0	47.0	–

[a]Percentage of geographical area considered for stock estimation; [b]PC, Plantation crops; [c]SC, Shifting cultivation; [d]Source: Choudhury *et al.*[34].

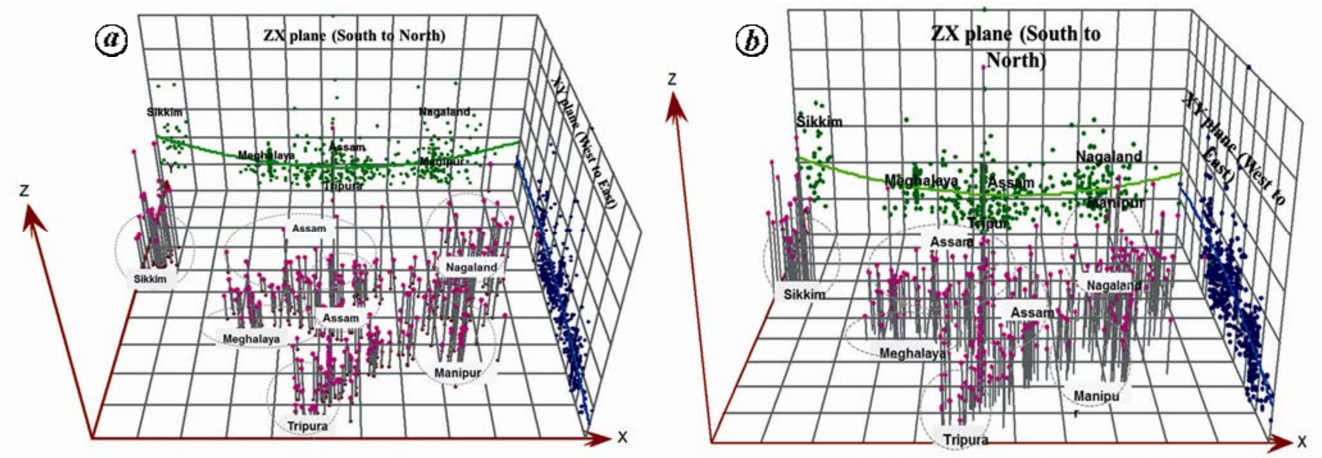

Figure 5. Spatial distribution of (***a***) SOC content (%) and (***b***) SOC density (Mg/ha) in 3D views (in *XY*, *YZ* and *ZX* planes) across NER. Height of grey colour sticks represents variation in absolute amount of SOC content and density whereas pink and green colour dots indicate spatial distribution of input data of SOC content and density from west to east (Sikkim to Nagaland) and south to north (Assam to Tripura).

bodies was lowest in Tripura and highest in Meghalaya, GA considered for SOC stock estimation was highest in Tripura (87.9%) and lowest in Meghalaya (52.84%). Total SOC stock of 339.82 Tg was estimated from an area of 10.1 m ha surface soils of the study area in NER (Table 5).

Trend analysis of SOC content and its representation in the *XY*, *YZ* and *ZX* planes using geo-statistical tools in ArcGIS software also reflected a distinct pattern in the distribution of SOC content and density across the NE region (Figure 5). Height of grey colour sticks indicates variation in SOC content and the estimated SOC density (without any extrapolation), while pink colour dots indicate the distribution from west (Sikkim) to east (Nagaland) and north (Assam) to south (Tripura). As we go from west (Sikkim) to east (Manipur and Nagaland) via Assam and Meghalaya, height of the sticks decreases gradually and then increases. The same has also been reflected by green dots in the *ZX* plane: SOC content and density decrease from Sikkim (West) to Meghalaya, Assam, Tripura and then again increase towards Manipur and Nagaland (East). Similarly, when we move from north (Sikkim) to south direction (Tripura) via Meghalaya and Assam, height of the sticks again decreases (Figure 5), indicating the decreasing trend in SOC content and carbon density.

Considering TGA of each state, diffogram studies also reflected significant differences in average SOC content and density among the six NE states (Figure 6). Sikkim registered significantly higher average SOC content (2.99%) and density (42.33 Mg/ha) compared to other states. Nagaland, Manipur and Meghalaya recorded statistically comparable (non-significant) state-level average SOC content (2.07–2.37%) and density (31.0–33.4 Mg/ha). Assam and Tripura recorded significantly lower average SOC content (1.23–1.31%) and density (22.3–22.9 Mg/ha) compared to the other four NE states.

Discussion

Among the many reasons for the variation in SOC density across NER (including within each state), deviation in SOC content seems to be the foremost factor since it reflected a strong positive correlation ($r = +0.72$ to $+0.79$) with SOC density. Variation in SOC content is controlled

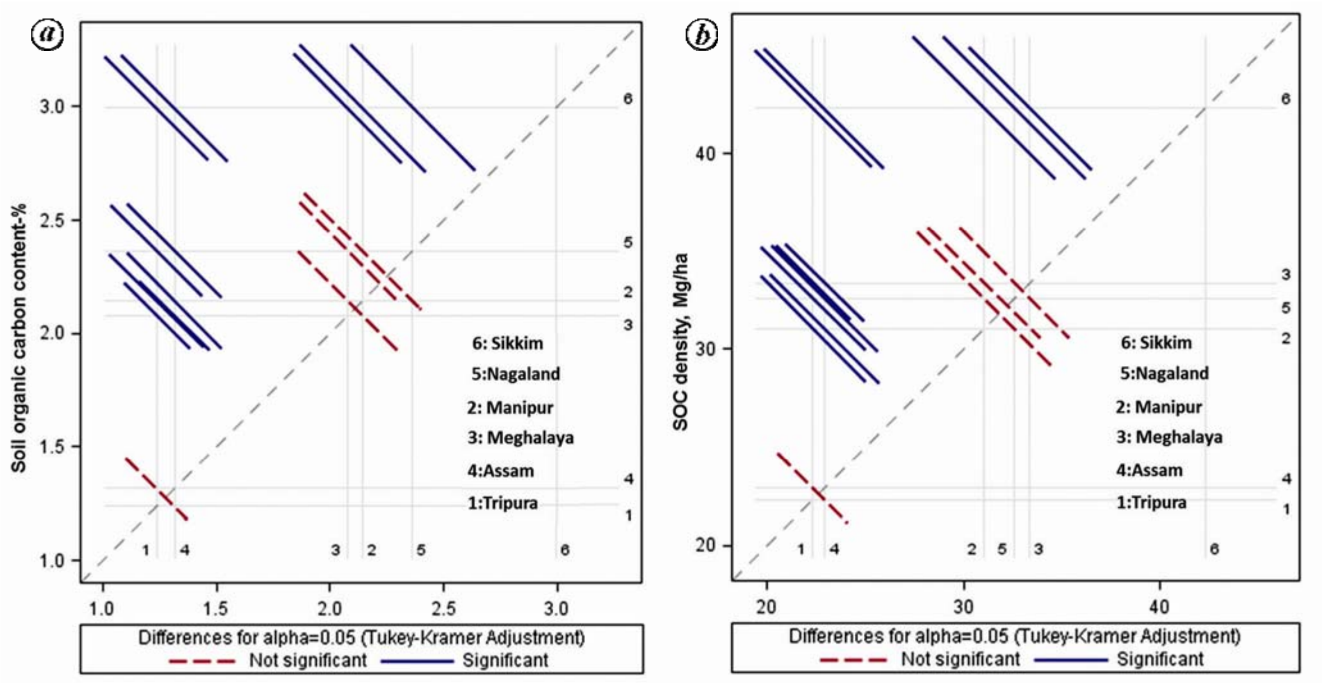

Figure 6. Diffograms showing significant differences among the six NE states of India in (***a***) SOC content and (***b***) SOC density. Faint horizontal and vertical lines represent the six states of NER. The bold lines passing through the squares diagonally represent non-significant or significant differences between the two corresponding states.

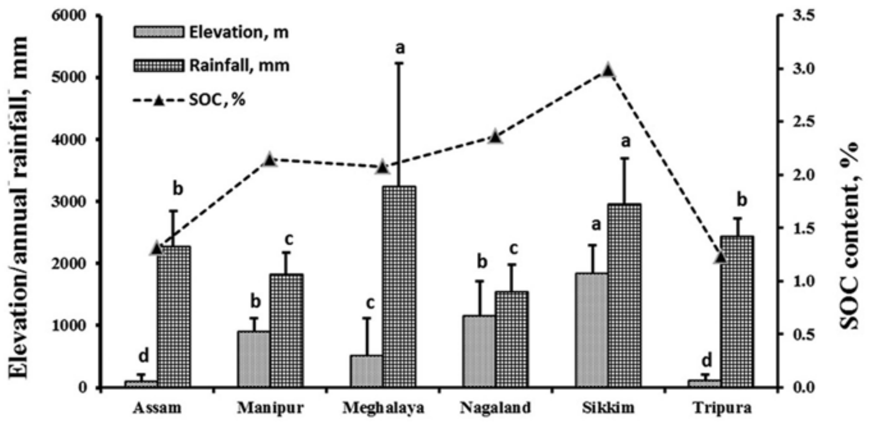

Figure 7. Mean altitudinal, annual rainfall and SOC content variation of sampling site across the six NE states of India. Symbols are treatment means and bars are standard deviations. Common letters (a–d) represent means that are statistically non-significant at 5% level of significance.

by land-use change and post-management practices that play a major role[1–3,7,13]. The significant influence of land-use practices on surface SOC content across NER was also recorded by Choudhury *et al.*[34], who reported that surface soils under grassland and dense forests contain very high SOC (>2.5%) compared to settled agriculture, including lowland paddy (1.45–1.69%) and shifting cultivation (1.70%). Therefore, significant variation in area under major land use and land cover in NER might be one of the reasons for considerable spatial variation in SOC content (Tables 2–5 and Figure 6). Another important observation made in the present study is the strong positive influence of altitudinal variation on SOC content ($r = +0.612$). With the increase in elevation of sampling sites from mean sea level, SOC content also consistently increased (Figures 5 and 7). This was even reflected in the state average altitude versus SOC content: sampling location in Sikkim had highest mean altitude (1835 m) followed by Nagaland (1143 m), Manipur (888 m) and Meghalaya (503 m), whereas Tripura and Assam were at the lowest altitude of 96–108 m (Figure 7). Distribution of SOC content also followed a similar trend, i.e. highest in

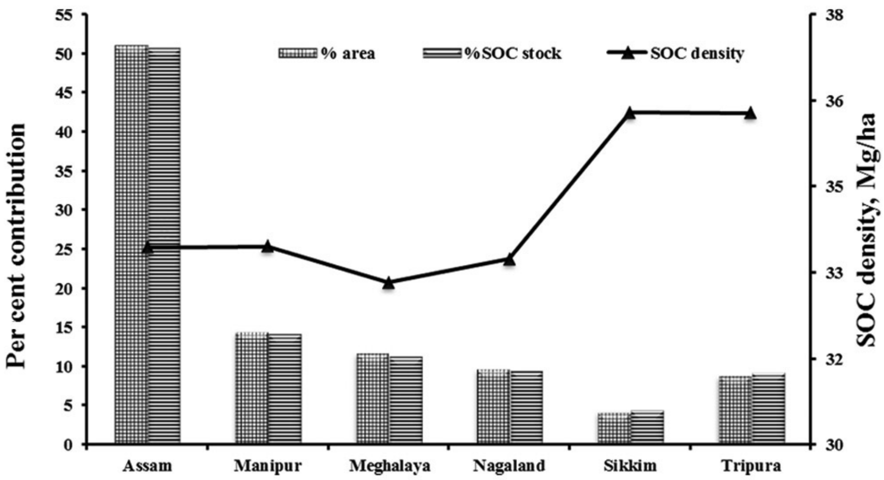

Figure 8. Per cent contribution by the NE states to the total area of estimation and total SOC stocks of the region.

Sikkim followed by Nagaland, Manipur and Meghalaya and lowest in Assam and Tripura (Figure 7). With the increase in altitude from mean sea level, the temperature decreases at the rate of 1°C for every 166 m increase in altitude[35]. Sikkim is located at a higher altitude (Figures 1 and 7), therefore, low temperature might have favoured the accumulation of higher SOC content. Along with altitudinal variation, temperature of a place depends on its latitude. Generally, temperature of places away from the equator (on higher latitudes) decreases with their distances from the equator[34]. Sikkim (northern most part of NER) is situated in the higher latitudes (27°06′15″N to 28°07′27″N), which is 4°N to Tripura, the southernmost state of NER, which is located at lower latitude (22°54′22″N to 24°32′5″N). Due to geographical location in higher latitudes and altitudes (Figures 1 and 5), average temperature in Sikkim during both winter and summer is substantially low (6.5°C and 20°C respectively) compared to Tripura (20°C and 29.5°C)[36]. Variation in temperature might have influenced SOC content, mostly due to secondary effect on SOC oxidation, decomposition and mineralization/accumulation rates. This might be one of the reasons for higher SOC content (2.99%) in Sikkim compared to considerably low SOC content (1.23%) in Tripura (Figure 7).

In the present study, annual rainfall reflected a weak positive correlation ($r = +0.15$) with SOC content and did not depict any definite trend in the state-level annual average rainfall with SOC content across the six states of NER (Figure 7). This might be partly due to variation in spatio-temporal distribution within each state of NER rather than the total annual average rainfall only. Another possible reason could be due to the occurrence of higher amount of annual rainfall in all the six states. Even the lowest amount (1540 mm) of rainfall received in Nagaland is sufficient to support most water-intensive vegetation, including agricultural crops. This might have nullified the effect of rainfall on phyto-biomass production and thus the SOC inventories.

Differences in total SOC stocks among the six states were mostly due to the variation in GA considered for stock estimation (Table 5). Assam alone contributed more than half (51%) of the area followed by Manipur (14.38%), Meghalaya (11.71%), Nagaland (9.74%), Tripura (8.85%) and Sikkim (4.24%; Table 5). Similarly, Assam alone contributed 50.8% of the total SOC stocks followed by Manipur (14.31%), Meghalaya (11.42%) and Nagaland (9.56%). Tripura and Sikkim were the lowest contributors and were the only two states with higher per cent contribution of SOC stocks per unit area: 9.52% stocks against 8.85% area and 4.51% stocks against 4.24% area respectively (Figure 8). This might be due to the presence of reasonable amount of GA under the two most effective land-use systems, viz. dense forest and grassland which have the potential to sequester soil carbon from 38.8 to 47.0 Mg/ha (Table 5 and Figure 9)[34].

In the study area, dense forest was dominant in per cent contribution to TGA (35.78% of 10.10 m ha) and SOC stocks (41.30% of 339.8 Tg; Table 5 and Figure 9). This was followed by crop land/agriculture (low and uplands) which contributed 28.9% SOC stock against an area of 31.7%. Among the remaining land uses, open forest contributed 8.82% of total SOC stocks, while shifting cultivation contributed marginal SOC stocks (3.14%) to the total amount of 339.8 Tg. Among the land uses, forests (dense and open) and grassland contributed relatively higher amount of SOC stocks against their respective per cent share in total acreage: 50.14% stock against an area of 44.19% and 4.34% stock against an area of 3.10% of 10.10 m ha (Figure 9). Several studies across the world affirmed the significant role of land-use and land-cover changes on soil carbon inventories[1–3,6–8,13]. In the study area, surface SOC density varied widely among different land-use systems from as low as 23 Mg/ha in wasteland to

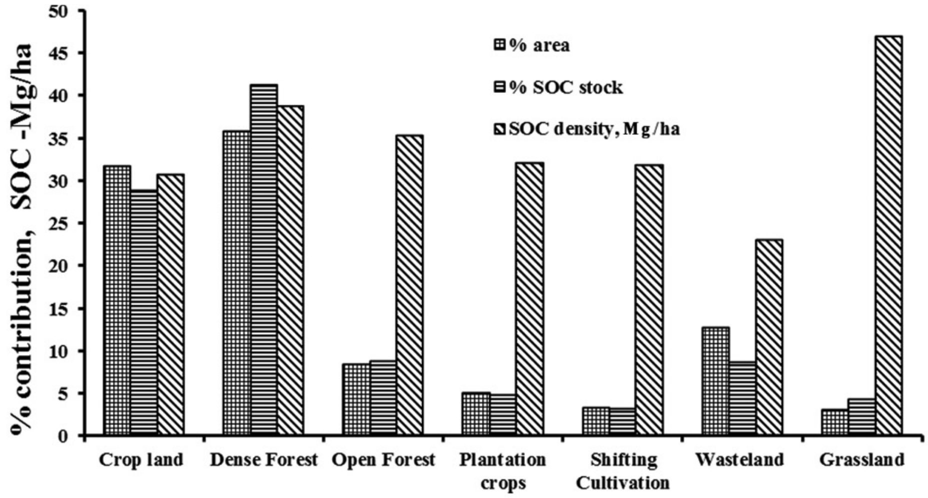

Figure 9. Relative contribution of area (%), SOC stock (%) and SOC density (Mg/ha)[33] under major land-use systems of the six NE states of India.

as high as 47 Mg/ha in grassland[34]. Plantation and horticulture, shifting cultivation and agriculture-based land-use systems had comparable SOC density (30.7–32.1 Mg/ha)[34] (Table 5 and Figure 9). Average SOC density for the estimated area (excluding built-up, waterbodies and snow-covered areas in Sikkim) was higher in Sikkim and Tripura (35.8 Mg/ha) compared to the other four states (32.8–33.5 Mg/ha; Figure 8).

Conclusion

Irrespective of land-use system practices across the six states of NER, SOC content and SOC density of the soils were high (>1%) in 98.54% GA of 15.61 m ha compared to other parts of the country[8,37,38]. A total of 339.82 Tg SOC stocks was registered for an area of 10.10 m ha surface soils representing major land-use practices, with a large share (>50%) coming from forest soils. Complex interaction among several factors ranging from variation in soil texture, climatic variables mainly rainfall and temperature, topography, and land-use practices might have influenced the significant variation in SOC inventories across NER. Sikkim located at higher altitude and latitude receives relatively higher rainfall and experiences lower temperature. It has significant proportion of area (>43%) under forests and grassland which might have favoured considerably higher SOC density compared to the other NE states of India. In the case of Assam and Tripura, the SOC content was low primarily due to their geographic location at lower latitude and altitude, and larger part of their GA is being intensively cultivated for crop production. Therefore, the current information on the spatial distribution of carbon stock would be useful to devise appropriate land use and conservation planning to ensure proper source–sink balance of carbon inventories in the long run.

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