SOIL ORGANIC CARBON DYNAMICS IN TWO MAJOR ALLUVIUMS OF BANGLADESH

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Abstract

This study was designed to evaluate the status, distribution, spatial variability, controlling factors, storage, and change in the levels of soil organic carbon (SOC) in two major alluviums of Bangladesh. The two alluviums—the Brahmaputra and the Ganges—were selected because they occupy a large area of Bangladesh with a wide diversity of agro-ecosystems. SOC levels were studied across the four sub-sites in the aforementioned alluviums at 0-30 cm depths to evaluate their spatial and temporal variability. The sub-sites, Delduar and Melandah, are in the Brahmaputra alluvium. The other two sub-sites, Mirpur and Fultala, are in the Ganges alluvium. Additionally, SOC and total nitrogen (TN) distribution were studied across eight soil profiles (0-120 cm depths) under the two alluviums.

The results revealed that the SOC contents were very low in all the sites. The classical statistics showed that the variability of the SOC was moderate across the four sub-sites. The SOC distribution was positively skewed across all the sub-sites except Fultala. A semivariogram model showed there was generally a weak spatial correlation ($R^2<0.5$) of SOC in the study sites. A relatively large sampling grid (1600m) and intensive soil management were perhaps responsible for the observed weak spatial dependency.

SOC variability is lower across the highland (HL) and medium highland (MHL) sites than the medium lowland (MLL) and lowland (LL) sites. Changes in land use and land cover were also more intensive in the HL and MHL sites than the MLL and LL sites. The reason for low SOC in the HL and MHL sites may be due to their lower inundation level, e.g., land levels in relation to flooding depths, together with greater intensity of use. Temporal variability of SOC datasets revealed that SOC has declined across all the sites during the last 20-25 years due to the intensive land use with little or no crop residue inputs. It is plausible that SOC has declined to an equilibrium level, and further decline may not occur unless land use intensity changes further.

The findings show that SOC is positively related to the TN and clay contents in the soils. This is not surprising as SOC is a major pool of TN, and soil clay fraction is known to protect SOC degradation. SOC and TN storage is higher in the surface soil horizon (0-20 cm) than the sub surface soils. Topsoil horizon is tilled and receives greater crop residue inputs which are subsequently mineralized resulting in higher accumulation of SOC and TN.

It appears that inundation land types and land management practices may be the major driving factors of SOC storage and distribution across the study sites.

Key words: SOC distribution, spatial variability, temporal variability, SOC storage, Inundation land types, Land use and land cover, C sequestration

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CHAPTER 1

1. Introduction

1.3 Rationale and Statement of the Problem

Bangladesh is a land-scarce agricultural country with a high density of population. Its net cultivated area (NCA) is 8.50 million hectares and the per capita NCA is about 0.060 ha (FAO, 2013; BBS, 2014), less than one-fourth of the estimated contemporary world per capita NCA of around 0.26 ha. The expanding population is putting stress on the land resources and facilitating unscrupulous exploitation. For this reason, double and triple cropping areas are an increasing trend. Cropping intensity has gradually increased during the last two decades at an alarming rate in Bangladesh (BRRI, 2013; BBS, 2014). Since there is an acute shortage of land in Bangladesh, conversion i.e., or competition is very common (Hasan et al., 2013). Agriculture, being the dominant land use, is in constant conflict with other land uses. So, the net result is a decrease in total agricultural land (Hasan et al., 2013). Thus, good quality agricultural lands are being used for non-agricultural purposes where such land cannot be returned into its original form. In this situation, Islam (2013) noted that land use change can be grouped into two broad categories—irreversible and reversible uses. Incremental increase in irreversible land-use is pushing the country into a famine.

Land use changes can be defined as conversion of existing land cover to another due to the changes in edaphic nature. Land use change is a dynamic process that plays a crucial role in relation to global carbon dynamics and at the same time, land use change has become a global concern due to its adverse affect on climate through emission of greenhouse gases (Post and Kwon, 2000). Many studies have demonstrated that changes in land use are inevitably followed by changes in carbon stores (Houghton, 1999; Canadell, 2002; Guo and Gifford, 2002; Grunzweig et al., 2004). Land use thus is an important factor in controlling and affecting global climate change. Eswaran et al. (1995) stated that the quantification of soil C losses and gains resulting from land use changes is a prerequisite to the understanding of greenhouse gases fluxes in different ecosystems. Soil is the largest terrestrial pool of organic carbon, with global estimates ranging from 1115 to 2200 Pg of C (Batjes, 1996), 1576 Pg of C (Eswaran et al., 1995), and 1220 Pg of C (Sombroek et al., 1993). Because of the significant capacity for C storage, soil has been the focus of increasing efforts in assessing the C sequestration associated with land use change and ecosystem succession (Post et al., 1982; Degryze et al., 2004; Sun et al., 2004). Lal (2009) reported that the source and sink of atmospheric carbon depends upon land use and land management. As a result, land use changes and land management can modify soil organic carbon (SOC). Soil organic carbon is thus an important component of the overall global carbon cycle.

Soil organic carbon is an index of sustainable land management (Woomer et al., 1994; Nandwa, 2001) and is simultaneously a source and sink for plant nutrients and plays a vital role in soil fertility maintenance (Bationo et al., 2005). Soil organic carbon (SOC) management can help lower the levels of greenhouse gases (GHGs) by increasing sequestration, while providing many other positive benefits such as improving crop yields, reducing erosion, lowering needs for external inputs, and increasing environmental and social aspects (FAO, 2001). In this aspect, Bationo et al. (2005) also noted that C sequestration has gained momentum in the recent decade and the amount of C in a system is a good measure of sustainability. Estimates of C stocks within different land management and cropping systems are an important element in the design of land use systems that promote sequestering C. Thus, the sequestration of carbon in soils is a win-win strategy. In this connection, Sanchez (1999) stated that the nature and quantity of soil organic carbon may affect many of the physical, chemical, and biological properties of soils. Soil pH, buffering capacity, nutrient supplies, and the activity of soil biota are all intimately related to soil organic carbon. Due to the importance of these relationships, soil organic carbon is considered a critical component when assessing soil quantity (Karlen et al., 2008).

In Bangladesh, low organic matter content is a general problem in most agricultural soils. Almost 50% of the soils in Bangladesh have <1% organic matter (FRG, 2012). This low organic matter content is related to many biophysical attributes of soils, particularly their aeration, structure, resilience and productivity. The depletion of organic matter is mainly caused by low input of organic material/residue and high cropping intensity. The characteristic hot humid climatic condition prevailing in this country encourages rapid mineralization and thus loss of organic matter. In Bangladesh, the cost of land degradation in terms of loss of soil productivity is estimated to be about US $685 million per year (Karim and Iqbal, 2001).

Information on soil carbon management, loss, or sequestration—although highly important—is very scarce in Bangladesh. It is therefore highly important to develop a carbon dynamics database for the soils of Bangladesh so that SOC changes can be monitored/managed. The most important agricultural lands in Bangladesh exist on the two major alluviums formed by the deposition of alluvium from the two mighty Rivers—the Ganges and the Brahmaputra. The Ganges River system emerges from the southern slope of the Himalayas while the Brahmaputra emerges from the northern slope of the same mountain range. The total area of Brahmaputra alluvium is estimated to be around 1.6 million hectares whereas that of the Ganges alluvium is about 1.4 million hectares (FAO-UNDP, 1988). These two alluviums are very diverse regarding cropping patterns and inundation land types. Cropping intensity in the Brahmaputra and the Ganges alluviums are more than 200%, indicating that most of the soils are used for agricultural purposes throughout the year (BBS, 2014). The soils of the Ganges alluvium are mildly calcareous and the clay fraction is dominated by smectite type of clay. The soils of the Brahmaputra alluvium, on the other hand, are mildly acidic and the mineralogy is different, e.g., kaolinite and mixed-layer minerals from those of the Ganges (Brammer, 1996; FRG, 2012).

Therefore, it is quite important to understand the dynamics of the soil carbon as well as its role in the carbon balance and the global carbon cycle. In developing countries like Bangladesh, where land use change is quite frequent, one would expect it could have a severe impact on the carbon sequestered /sink in soils. The amount of carbon stored in soils can be affected by changes in climate and atmospheric CO_2 concentration and land use practice. Thus, it is quite essential to identify the land use changes and quantifying their impact on soil carbon storage or loss. This project will also identify at-risk areas in Bangladesh that need to be managed carefully and ultimately the influence of soil carbon sequestration.

1.2 Research Aims and Objectives

The aim of this research is to examine the distribution of soil organic carbon and their stocks in the two major alluviums of Bangladesh. A major thrust of the work is to assess the impact of land use change on soil organic carbon (SOC) loss or storage. This will be achieved using current land use and SOC levels and comparing them with their historical records. The research has the following specific objectives:

- To estimate the SOC contents and their spatial distribution in the study sites.
- To assess storage and distribution of SOC across the inundation land types as well as the alluviums at 0-30 cm depths.
- To find out how inundation land types and cropping intensity affects SOC.
- To identify the land use as well as cropping intensity changes over the period 1989-1992 and 2012.
- To evaluate the SOC loss or sequestration by comparing the historical SOC datasets (1989-1992) with their current (2012) contents.
- To determine the SOC and total nitrogen (TN) distribution and storage across the study sites at 0-120 cm depths.
- To reveal the impact of inundation land types and soil depths on SOC and TN distribution and storage.

CHAPTER 2

Land Cover, Land Use, and Soil Carbon Management – A Literature Review

2.1 Introduction

Greenhouse gas emissions and climate change are important issues to agriculture, both because of their potential impacts on agricultural production and because agriculture is a major contributor to the build-up of greenhouse gases (GHGs) in the atmosphere. In 1995, according to the Intergovernmental Panel on Climate Change (IPCC) assessment, agriculture was estimated to be responsible for 20% of the annual increase in total anthropogenic GHGs emissions. Above all, soils being the largest terrestrial carbon pool, it is important to understand the dynamics of soil carbon as well as its role in the carbon balance and the global carbon cycle. In developing countries like Bangladesh, where land use change is quite frequent, one would expect that it could have considerable impact on soil carbon, and thus it (soil organic carbon, SOC) should be considered carefully while assessing or developing agricultural and environmental management policies and their implications on climate change. The amount of carbon stored in soils can be affected by change in climate and land use practices. In the Kyoto protocol, an agreement made under the United Nations Framework Convention on Climate Change (UNFCCC), signatory nations are required to produce accurate estimates of their C store and monitor changes with time. Several approaches have been used to estimate terrestrial C stores and many studies have used a combination of soil and vegetation, land cover and model predictions (Batjes, 1996; Milne and Brown, 1997; Scott et al., 2002; Bradley et al., 2005). It is thus important that accurate, reliable, and authentic data are needed for their estimation.

The content of soil organic carbon (SOC) is affected by a range of factors such as climate (Homann et al., 2007), topography (Tan et al., 2004), biota (Finzi et al., 1998; Wu et al., 2009), parent material (Sleutel et al., 2007; Wagai et al., 2008), time (Schlesinger, 1990), and land management (Blumfield et al., 2006; Gao et al., 2008; Xu et al., 2008; Yang et al., 2008). Many of these factors are mutually interactive (Sollins et al., 1996). Among the various factors, climate—especially temperature and precipitation—is the most important factor regulating SOC as it strongly influences vegetation type, biomass production, and decomposition of plant litter (Alvarez and Lavado, 1998). SOC in cropland is also strongly dependent upon crop and soil management practices, such as crop species and rotation, tillage methods, fertilizer and manure application, pesticide use, irrigation and drainage, and soil and water conservation (Heenan et al., 2004). All these practices control the input of organic carbon from crop residues and organic amendments, and the SOC output through decomposition into gaseous forms and transportation into aquatic ecosystems via leaching, runoff, and erosion (Turner and Lambert, 2000).

Soil management has a considerable impact on soil carbon. Much of the soil's original organic C loss from agricultural land can be attributed to reduced inputs of crop plant residues and their increased mineralization and tillage effects that decrease the amount of physical protection for soil organic carbon (Davidson and Ackerman, 1993). Land management practices can affect soil temperature and surface water regimes (Al-Kaisi and Yin, 2005), which can directly influence soil organic carbon content. Especially in dry areas, soil cover has an important role in water management, where it decreases the temperature, thus slowing the rate of organic matter mineralization (FAO, 2001). The selection of annual crops and the inclusion of annual and perennial pastures or fallow in rotation with annual crops can significantly impact SOC levels. In a long-term crop rotation trial at the Waite Institute in Australia, SOC contents have increased under permanent pasture and declined to varying degree under cropping systems (Tisdall and Oades, 1982). Crop rotation also affects soil C and complex/mixed rotations can maintain higher C contents than monocultures (Morari et al., 2004). Agboola (1981) reported a rapid decline in soil organic matter content and plant nutrient reserves with intensive cropping.

2.2 An Overview of Global Carbon

Organic carbon is a key component of terrestrial ecosystems and any variation in its abundance and composition has important effects on many of the processes that occur within the system (IPCC, 1990; Legros et al., 1994). Carbon is a highly versatile element that occurs abundantly in a number of geo-spheres such as biosphere, hydrosphere, atmosphere and lithosphere. The reserves of carbon in the geo-spheres of the earth are huge and are in dynamic equilibrium with each other (Eswaran et al., 1993). Geochemically carbon is a lithophile element (where carbon is found in the earth crust) and, in the form of carbon dioxide and methane, is one of the atmophile elements. The most conspicuous geochemical feature of carbon, however, is its strong bio-phile character; it is a primary constituent of all living matter. With the advance of time, more and more reliable estimates of the C contents in various geochemical reservoirs are now available. Disturbance in any of these pools has a direct effect on others because of the inter linkages among the various reservoirs. Eswaran et al. (1993) and Lal et al. (1995) presented an estimate of the global carbon pools (Table 2.1). From these estimates (Table 2.1), it is worth noting that oceans contain by far the largest part of the total global carbon pools. At the global scale, Eswaran et al. (1993) and Lal et al. (1995) estimated that the upper 1 m of mineral soils contain 1550 Pg C whereas according to Post et al. (1982) and Schlesinger (1986) the estimate was1300-1500 Pg C. The values, however, are more than twice the C stored in terrestrial plant biomass. Estimates of 1456 Pg SOC by Schlesinger (1984) and 1395 Pg by Post et al. (1982) were based on land area classified by major vegetation types or life zones, while estimates of 1576 Pg by Eswaran et al. (1993) and 1220 Pg by Sombroek et al. (1993) were based on global soil maps.

Table 2.1: Estimated global carbon pools

Sources	Quantity (Pg*)	%
Oceans	38,000	92.7
Atmosphere	750	1.8
Soils (as organic carbon)	1550	3.8
Biota (Terrestrial vegetation)	550	1.3
Others (Geological formation; mineral carbon, fossil carbon)	150	0.4
Total	41,000	100.0

*Pg (Petagram) = 10^{15} grams (one billon tonnes) Adopted from Eswaran et al. (1993) and Lal et al. (1995)

There has been no detailed estimation of global C stocks in cultivated soils. Data compiled by Bouwman (1990) regarding the distribution of FAO soil groups on cultivated lands, SOC contents by soil group from Sombroek et al. (1993), and additional data of Histosols (Cole et al.,1996), all of them estimated pre-cultivation C stocks of 222 Pg in the total area of land under cultivation. Accounting for C losses due to cultivation, the estimate of current agricultural soil C stocks at 168 Pg (Paustian et al., 1997) was very close to the 167 Pg estimated by Post et al. (1982). Houghton (1999) showed an estimation of carbon in the various vegetation and soils eco-zones of the world (Table 2.2). Whittakar and Likens (1973) and Schlesinger (1984) estimated C contents in some major ecosystems of the earth (Table 2.2). Tropical forests differ from forests of temperate and boreal zones in that more of the carbon of tropical forests is contained in vegetation than in soils. When inventories of soil carbon are not limited to the top 1m, this difference between regions may no longer apply because the temperate ecosystems are low temperature environments with consequential very slow organic matter decomposition, thus favouring an accumulation of organic carbon (Houghton, 1999). The author further added that tropical evergreen forest has the highest quantity of carbon per hectare (including soils, trees and other vegetation). The swamp soils of the world have the maximum accumulation of organic carbon per unit area among the ecosystems considered (Table 2.2). Because of poor drainage, the decomposition of organic matter is very much slow in the swamps and marshes.

In soils, carbon occurs mainly in two forms, inorganic soil carbon (SIC) and soil organic carbon (SOC). SIC is relatively ‘inert’ form of carbon, which is hardly involved in carbon transformations, while the other form is decomposable and biochemically active (Korschens, 1980). The global total soil C pool for the top 1-metre depth has been estimated to be about 2500 Pg, of which SOC is 1550 Pg, and SIC is 1000 Pg. The soil carbon pool is considerably larger when compared to about 550 Pg C in the biotic pool and 750 Pg C in the atmospheric pool (Korschens, 1980). Several authors (e.g., Bohn, 1976; Buringh, 1984; Kimble et al., 1990) have made attempts to estimate the total carbon content in various tropical and subtropical soils. Because of their varying premise and basis of calculation these estimates differ widely in some cases. According to estimates by Bohn (1982), 22×10^{14} kg C occurs in the mineral soils and 4×10^{14} kg C occurs in the global peat.

Table 2.2: Area, total carbon, and mean carbon content of vegetation and soils in major ecosystems of the earth

Major ecosystems	Area ($\times10^6$ ha)	Carbon in vegetation (Pg)	Carbon in soil (Pg)	Mean vegetation C (Mg C/ha)	Mean soil carbon (Mg C/ha)
Tropical evergreen forest	602	107	62	177	104
Tropical seasonal forest	1,459	169	125	116	86
Temperate evergreen forest	508	81	68	161	134
Temperate deciduous forest	368	48	49	131	134
Boreal forest	1,168	105	241	90	206
Tropical fallows(shifting cultivation)	227	8	19	36	83
Tropical open forest/woodland	307	15	20	50	64
Tropical grassland and pasture	1,021	17	49	16	48
Temperate woodland	264	7	18	27	69
Temperate grassland and pasture	1,235	9	233	7	189
Tundra and alpine meadow[1]	800	2	163	3	204
Desert scrub[1]	1,800	5	104	3	58
Rock, ice, and sand[1]	2,400	0.2	4	0.1	2
Cultivated, temperate zone	751	3	96	4	128
Cultivated, tropical zone	655	4	35	7	53
Swamp and marsh[1]	200	14	145	68	725
Total	13,765	594	1,431	-	-

[1] From Whittaker and Likens (1973) and Schlesinger (1984). Soil depth is 1 m (Source: Houghton, 1999)

Eswaran et al. (1995) estimated organic and inorganic C mass in soils of the world (Table 2.3), according to the US Soil Taxonomy (Soil Survey Staff, 1993). According to these estimates the Histosols and the Inceptisols together contain slightly less than half of the global soil C. From these estimates, it is clear that Histosols, Oxisols, and Spodosols contain most of the carbon in SOC form whereas Aridisols and Mollisols contain most of the carbon as soil inorganic carbon (SIC) form. On the other hand, Inceptisols, Entisols, and Alfisols have both SOC and SIC almost in equal quantities (Table 2.3). Eswaran et al. (1993) estimated organic carbon mass in the mineral and organic soils of the tropics (Table 2.4), which show that the wet soils of the world contain a huge quantity of organic carbon pool. Aquepts that occur extensively in the world contain high quantity of organic carbon. The wet mineral soils occupy about 6% of the land mass, of which about 5.8% is present in the tropics. About a third of the organic soils, which occupy about 1.9% of the global land mass, are present in the tropics and dominantly in South East Asia (Lal, 1995). Armentano et al. (1986) estimated that non-tropical soils occupy about 88% of the global organic soils. The stock of carbon in the wetlands is estimated to be about 498 Pg of which about 12% is in the wet mineral soils. The remaining 88% in the Histosols is slowly being reduced due to drainage of the land for agriculture. Armentano et al. (1986)

also estimated that about 5 to 6 Pg would be lost in the next 30 years, i.e., by the year 2016 due to burning of peat and utilization of peat lands for agriculture. Tropical soils contain 32% of the total global soil carbon, and deforestation causes a considerable loss of organic carbon in the tropics (Brown and Lugo, 1984).

Table 2.3: Organic and inorganic carbon mass (Pg) in the world soils based on soil orders*

Soil Orders	Organic carbon (SOC)	Inorganic carbon (SIC)	Total carbon (SOC+SIC)
Histosols	390	0	390
Andisols	69	1	70
Spodosols	98	0	98
Oxisols	150	0	150
Vertisols	38	25	63
Aridisols	110	1,044	1,154
Ultisols	101	0	101
Mollisols	72	139	211
Alfisols	136	127	263
Inceptisols	267	285	552
Entisols	106	117	223
Rocky land	13	0	13
Shifting sand	5	0	5
Miscellaneous land	18	0	18
Total	1,573	1,738	3,311

(Source: Eswaran et al., 1993)

* A brief description of the soil orders is given in Appendix 1

Table 2.4: Estimates of organic carbon mass in the wet mineral and organic soils of the Tropics (Values in parentheses are percentages of the total land mass)

Soil Sub-Orders	Area (km^2)		Organic C Global (Pg)
	Global x 10^3	Tropical x 10^3	
Aquods	210 (0.16)	-	4
Aquerts	84 (0.06)	84 (0.17)	1
Salids	1,130 (0.84)	134 (0.27)	5
Aquults	563 (0.42)	501 (1.01)	5
Aquolls	-	-	-
Aqualfs	701 (0.52)	69 (0.14)	6
Aquepts	4,644 (3.44)	2,050 (4.13)	67
Aquents	1,362 (1.01)	30 (0.06)	20
Total	8,808 (6.53)	2,868 (5.78)	108
Histosols (Organic soil)	1,745 (1.9)	286 (0.57)	390
Total	10,553 (7.82)	3,154 (6.35)	498

(Source: Eswaran et al., 1993)

Tarnocai (1997) prepared a database of soil organic carbon and soil carbon mass of nine soil orders in Canada along with their US classification (Table 2.5). The highest average surface carbon content was found in the Histosols (18.7 kg/m^2), followed by Gleysols and Cryosols (11.7 kg/m^2 and

11.3 kg/m^2 respectively). Spodosols have more average surface C than the Inceptisols or Entisols, whereas Entisols or Mollisols and Alfisols have more or less similar C content (Table 2.5).

Table 2.5: Amount of soil organic carbon and its mass in various soil orders in Canada and correlation of Canadian and U.S. soil classification terminology

Soil classification		Soil carbon content (kg/m^2)		Soil carbon mass (Pg)		Area (km^2)
Canada	US	Surface	Total	Surface	Total	x1000
Brunisol	Inceptisol	5.2	9.3	6.1	10.9	1170
Chernozem	Boroll	7.4	12.4	3.2	5.4	434
Cryosol	Pergelic subgropus	11.3	40.6	28.7	102.7	2530
Gleysol	Aqu-suborders	11.7	20.0	2.7	4.6	230
Luvisol	Boralf and Udalf	4.9	9.3	3.0	5.7	611
Organic	Histosol	18.7	133.7	14.9	106.3	795
Podzol	Spodosol	9.9	19.3	12.5	24.4	1267
Regosol	Entisol	5.6	11.8	0.8	1.7	144
Solonetz	Mollisol and Alfisol	5.8	11.5	0.3	0.6	52
Total	-			72.2	262.3	7233

(Source: Tarnocai, 1997)

Organic carbon in soils is present in different forms, depending on their pools of stabilities. Based on soil carbon dynamics, Duxbury (1991) suggested four kinds of C pools (Table 2.6) in different soil orders of the world. The first one is an active or labile pool which is readily oxidizable. The controlling factors of this pool are residue inputs and climate. Agronomic factors affect the size of this pool. The second is a slowly oxidizable pool associated with macro-aggregates. The controlling factors of this pool are soil aggregates and mineralogy. Agronomic factors, particularly tillage, affects the size of this pool. The third one is a very slowly oxidizable pool (within micro-aggregates). The controlling factors of this pool are water stable micro-aggregates. Agronomic factors have little impact on this pool. The fourth one is a passive or recalcitrant pool. The controlling factors are complexes of clay minerals; microbial decomposition may have reduced this carbon to elemental form. Agronomic factors do not influence this pool. There are insufficient detailed studies to proportion carbon into each of these pools and thereby to estimate the rates of change in these pools. From the view of losses from the system, the active pool is the most important and consequently is the most transient (Eswaran et al., 1995). This pool dominates the surface horizons of soils where they are not only most easily oxidized but also most easily lost through erosion (Lal et al., 1995). The very slowly and passive pools would be present in significant amounts in Andisols, and the highly weathered Oxisols and Ultisols. In the latter two soils, stable micro-aggregate formation with entrapped organic carbon is frequent.

Table 2.6: Estimates of relative amounts of carbon pools in different soil orders of the globes

	Carbon pools in subsurface horizons			
Soil	Active	Slowly oxidizable	Very slowly oxidizable	Passive
Histosols	*****	***	**	*
Andisols	***	***	**	*
Spodosols	**	**	***	****
Oxisols	*	**	***	****
Vertisols	****	***	**	*
Aridisols	**	**	*	*
Mollisols	*****	***	**	*
Ultisols	***	**	***	****
Inceptisols	*****	*	*	*
Entisols	*****	*	*	*

(Source: Duxbury, 1991) *detectable; **low; ***moderate; ****high; *****dominance

From Table 2.6, it is obvious that soils type influences the global carbon cycles depending on their origin, nature, and properties. Land use change, deforestation, drainage, and cultivation lead to a rapid loss of C from organic soils by oxidation, volatilization, and mineralization. Dried peat and muck soils are also prone to burning and wind erosion. Cultivation of organic soils leads to a rapid loss in the thickness of the organic horizon. Regarding upland soil orders in relation to the global carbon cycle, Andisols, soils of volcanic origin, are young and inherently fertile soils. Because of their high biomass productivity, these soils have a large potential to sequester C (Lal et al., 1998). Aridisols especially derived from calcareous parent materials, have low SOC. Mollisols, the grassland soils are naturally fertile and possess granular structure. Their cultivation has greatly reduced the carbon storage, in many cases by 50% (Lal et al., 1998). Through conservation tillage and increased biomass return to the soils, they have the ability to be a major sink for carbon storage. Another group of soils that is important regarding the global C cycle is hydromorphic soils. These soils are inundated or they remain saturated or nearly saturated most of the time and their surface horizons undergo anaerobiosis; this inhibits carbon breakdown and thus they are rich in SOC. Hydromorphic soils are widely used for rice cultivation in the tropics and subtropics. Tropical ecosystems and soils of the tropics (Oxisols, Ultisols, and Alfisols) play a dominant role in the greenhouse effect. Deforestation of the tropical rainforest affects SOC dynamics directly or indirectly. The impact of biomass burning, intensive cultivation for seasonal or annuals, and conversion to pastures have a major impact on the SOC budget (Lal et al., 1998).

2.3 Land Cover Change and SOC Stock

The land cover of the planet can be considered as a connecting link between the geological and the biological cycles of carbon. After decomposition in soil, plant, and animal residues and their decomposition products undergo chemical and physical transformations and become closely associated with mineral particles especially the clay minerals to form stable aggregates. This close association with mineral particles in the form of stable micro-aggregates and the chemical stabilization provide organic carbon with self-protection from further decomposition (Lal et al., 1998). Lal et al. (1998) proposed that there are two sets of processes by which organic carbon in soils may either increase or decrease – the pedospheric processes (Fig. 2.1). Sedimentation and deposition as well as humification will increase organic carbon in soils. On the other hand, quick decomposition and erosion will result in impoverishment of organic carbon in soils. Leaching and aggregation are thus two fundamentally opposite processes that determine the fate of organic carbon in soils. The relative contribution of the above two mechanisms differs from soil to soil. It is the net balance between these SOC aggrading and degrading processes, as influenced by land use and anthropogenic factors that determines the net SOC pool in the pedosphere (Lal et al., 1998).

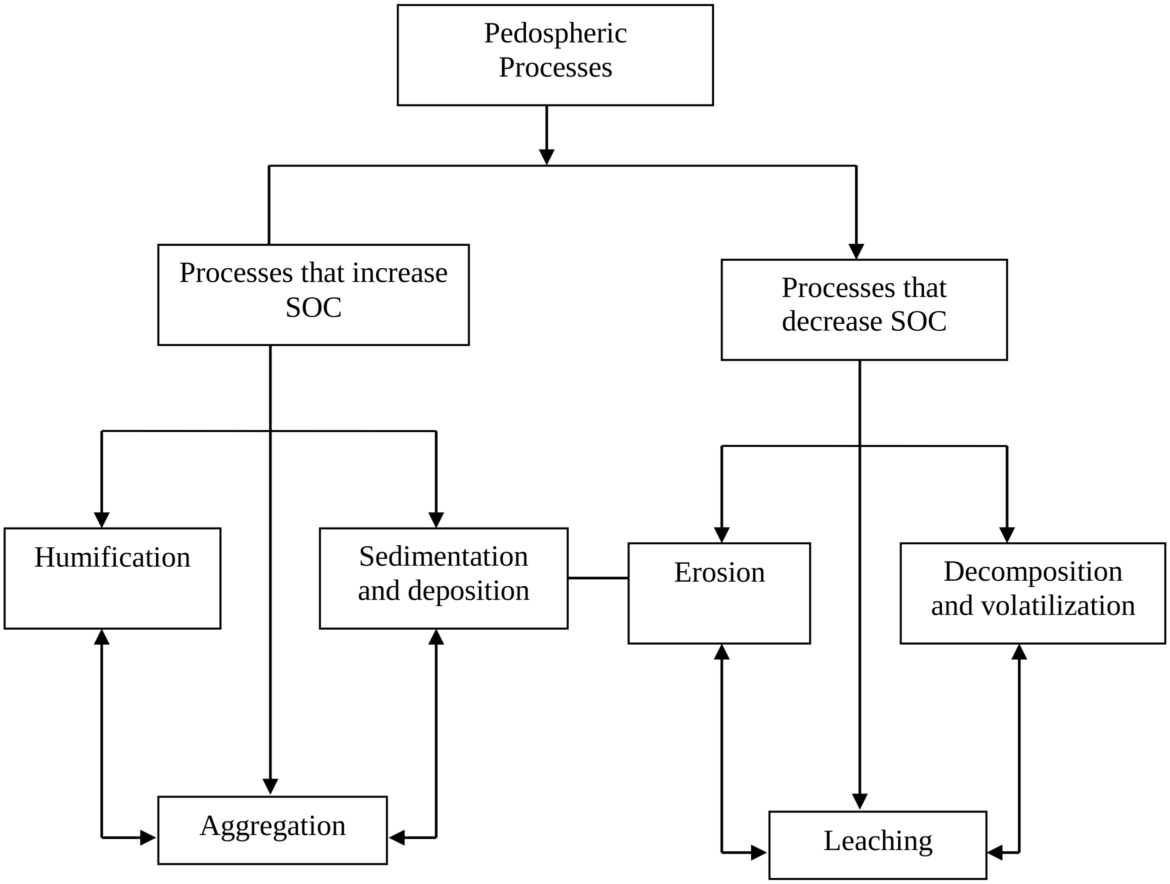

Figure 2.1: Principal pedospheric processes by which organic carbon in soils may either increase or decrease affecting SOC contents (Source: Lal et al., 1998)

Physical and chemical degradation, which are the primary processes, very often result in biological degradation (Robert and Stengel, 1999). Erosion by water and wind is quantitatively by far the most important SOC degradation process. In tropical regions, human induced soil degradation affects 45 to 65% of agricultural lands, depending on the continent (Oldeman et al., 1991). This soil degradation enhances deposition of soil materials in the lower level of landscapes. Thus, this situation presents a considerable scope for carbon sequestration in degraded tropical soils. Related benefits of carbon sequestration in such lands are improvements in chemical properties, bioavailability of nutrients and resilience against physical degradation in the pedospheric processes (FAO, 2001). On the other hand, Lal et al. (1998) noted that small changes (losses) in the SOC pool could have dramatic impacts on the concentration of CO_2 in the atmosphere. For better quantifying the response of terrestrial C, a large proportion of which derives from the soil, it is essential to understand the nature and extent of the earth's response to global warming. Understanding interactions between climate and land-use change is very much important.

Equilibrium carbon stock in soil is the result of a balance between inputs to and outflows from the pool. Changes in land cover are likely to alter such balance resulting in different carbon stores under different land cover systems in addition to the impacts of global climate change (FAO, 2001). The equilibrium between C inflows and outflows in soil is disturbed by land-use change until a new equilibrium is eventually reached in the new ecosystem, thus the land use change significantly affects soil C stock (Guo and Gifford, 2002). The equilibrium dynamics of C in different land-use options are a function of the plant residues returned to the soil, the litter C content, the amount of soluble vs. non-soluble C components, the mineralization rates of the C components, the placement of above-ground vs. below-ground inputs and the degree of soil aggregate disturbance (Post and Kwon, 2000).

Various changes in land-use result in very rapid declines in soil organic matter (Mann, 1986; Schlesinger, 1995) and such losses can be attributed to reduced inputs of organic matter, increased decomposition of crop residues, and tillage effects that decrease the amount of physical protection to decomposition. Because of the significant capacity for C storage, soil has been the focus of increasing efforts in assessing its carbon sequestration associated with land use change and ecosystem succession (Post et al., 1982; Sun et al., 2004). Land use change affects soil carbon stores by altering the input rates of organic matter in some cases, changing the decomposability of organic matter inputs that increase the light fraction organic carbon (Cambardella and Elliott, 1992) and enhancing physical protection through either intra-aggregate or organo-mineral complexes (Post and Kwon, 2000). Ultimately, the soil carbon and nitrogen stocks depend on whether the changed land-use is favourable or prohibitive to the C storage processes.

Land use change often can cause a significant change in land cover and an associated change in carbon stocks (Bolin and Sukumar, 2000). Guo and Gifford (2002) estimated the percentage of SOC stock under different land cover change or conversion (Table 2.7) and reported that converting forest or grassland to crop lands caused significant loss of SOC. Conversion of forestry to grassland did not result in SOC losses in all cases because of granular type of soil structure, whereby the colloidal properties of the soils give rise to chemical bonding between organic molecules and inorganic materials, which leads to immobilization of C in the soils (Shoji et al., 1993; Wada 1995). Total ecosystem C does, however, decrease due to loss of the tree biomass C. Similar results have been reported in Brazil, where total ecosystem C (vegetation biomass included) losses were large, but soil C did not decrease following conversion of forests to grasslands (Veldkamp, 1994; Moraes et al., 1995; Neill et al., 1997; Smith et al., 1999).

Table 2.7: SOC stock (%) under different land cover change

Land use from	Land use to	Mean % C stock change
Pasture	Plantation	-10
Native forest	Plantation	-13
Native forest	Crop	-42
Pasture	Crop	-59
Native forest	Pasture	+8
Crop	Pasture	+19
Crop	Plantation	+18
Crop	Secondary forest	+53

(Source: Guo and Gifford, 2002)

Grassland management systems possess a greater potential to store SOC than forestland (Franzluebbers et al., 2000). Stevenson (1982) indicated that SOC content of grassland soils was substantially higher than for forest soils if other factors were constant. Hence, soil C stocks could be higher under natural grasslands than under natural forests. Tate et al. (2000) also reported that total soil profile C stock was 13% higher in the grassland than in the forest. Organic soils hold enormous quantities of SOC, accounting for 329-525 Pg C, or 15-35% of the total terrestrial (soil and plant biomass included) carbon (Maltby and Immirizi, 1993). The potential for SOC loss from land use change on highly organic soils is therefore very large. The change from one ecosystem to another could occur naturally or be the result of human activity. Each soil has a carbon carrying capacity, i.e., equilibrium carbon content depending on the nature of vegetation, precipitation, and temperature (Gupta and Rao, 1994).

Post and Kwon (2000) advocated that land use and vegetation type exert considerable control over SOC quantities and forms, as well as the aggregate with which they are associated. Sombroek et al. (1993) conducted a study in parts of the tropics and sub-tropics, which showed 20 to 50% loss of the carbon in topsoil after clearing of forest and their conversion to farmland. These losses account for soil structure deterioration and increased erosion rates and decomposition of SOC in topsoil. In another study, Wilson (1978) reported that the conversion of land use from native vegetation to agriculture resulted in sharp declines in soil organic matter. Land use change and disturbance history are often related to the numerous processes of the carbon cycle; the recent evolution of terrestrial carbon sinks (Schimel et al., 2001; Nabuurs et al., 2003) and the famous ‘residual sink’ (Caspersen et al., 2000). Carbon sink is carbon storage in a natural or artificial reservoir that accumulates and stores it for an indefinite period, whereas ‘residual sink’ is terrestrially missing carbon released as carbon dioxide (CO_2) by anthrpogenic activities which does not match changes observed in the atmosphere and the ocean. Post and Kwon (2000) observed that land use change and disturbance history govern the large variability of C sequestrations in soils. In an another estimation, Buringh (1984) noted the average loss of soil carbon after conversion of forest to cropland as 48%, of forest to grassland 28%, and of forest to mixed cropland and grassland 35 % over one meter depth. Similarly, Kimble et al. (2001) and Agboola (1990) reported that the effect of continuous maize cultivation with complete fertilizer, SOC decreased over time enhancing the decrease in yield (Table 2.8).

Table 2.8: SOC changes over time and the effect on maize yield with complete fertilizer*

Crops**	Egveda Series		Iowa Series		Cambari Series	
	OC %	Yield (kg/ha)	OC %	Yield (kg/ha)	OC %	Yield (kg/ha)
1st crop	1.61	3100	1.73	3800	1.21	2500
3rd crop	1.03	2000	1.38	2600	0.51	1000
7th crop	0.46	1000	1.03	1800	0.34	800
10th crop	0.34	700	0.57	1000	0.17	200

*Complete fertilizer means fertilizer containing N, P, K, the three major elements required for plant nutrition.
**Here the land use or crop is only maize. (Source: Kimble et al., 2001; Agboola, 1990)

According to Lal (1995), the factors that are responsible for augmenting soil resilience can be grouped into two categories: endogenous and exogenous. The important endogenous factors that are responsible for enhancement of soil resilience are: unconsolidated soil mass having sufficient rooting depth, high organic carbon content, loam to clay loam texture, structurally active soils, and gentle to rolling terrain, good internal drainage and favourable microclimate. On the other hand, the exogenous factors include land use and crop management. Appropriate land use and adoption of suitable management technology can enhance and sustain high productivity, on one hand, and accentuate resilience of the soils on the other. Although tropical conditions favour organic carbon decline, its levels seldom reach a stage of complete exhaustion. Rather, over-cultivated soils tend to attain a steady state, described as a lower equilibrium limit by Buyanovsky and Wagner (1997). According to them, there is an upper limit of organic carbon, which they define as the equilibrium content typical for a virgin eco-system. If organic matter displacement by erosion is not a factor, then its level in properly managed cultivated soils fluctuates between these two extremes. Cultivation alone tends to shift this towards the lower equilibrium point; organic matter additions and fertilization tilt it in the direction of the upper equilibrium ceiling. Hence, in the tropics, low organic matter additions as well as accelerated degradation and loss due to year-round prevalence of biologically active temperature and moisture regimes lead to rapid reductions in the soil organic carbon pool (Katyal, 2000).

Effects of long-term fertilization on SOC built up in Indian soils (Table 2.9) were reported by Nambiar (1995) and Swarup and Gaunt (1998). Katyal (2000), who assessed the results obtained from long-term experiments in India, confirmed the validity of the observation on organic carbon dynamics in two situations like virgin sites and sites already in cultivation. In the virgin sites, with control (Table 2.9), during the initial 5 to 7 years, soil organic carbon remained constant and corresponded to the initial value. During the next 7 to 8 years (up to 15 years from the start of the experiment), soil organic carbon fell sharply to 50% of the original value. Further decline was some-what reversed since it touched 34% of the base level in the next 5 to 7 years (Table 2.9). Beyond this point, soil organic carbon did not fall and seemed to have stabilized at a lower equilibrium level as was described by Buyanovsky and Wagner (1997). With fertilizers, soil organic carbon remained stable over the first decade, but subsequently fell to about 40% of the initial value (Katyal, 2000). This level was reached over a period of about 3 years. With manure (15 t ha/yr), the soil organic carbon content remained stable over the 25 years of the study. On the other hand, in cultivated soils, long term fertilization had already shifted SOC to a new equilibrium. In these soils (control treatment), SOC levels declined without any fertilizer application. In variance, soil organic carbon levels were either maintained or increased with an adequate NPK treatment, whereas i.e., SOC levels invariably increased with the manure treatment (Katyal, 2000).

Table 2.9: Effect of long-term fertilization on organic carbon built up in Indian soils

Cropping system, Location and Soil	Initial SOC %	SOC %**		
		Control*	NPK	NPK-FYM
Rice-rice, Bhubaneshwar, Inceptisols	0.27	0.41	0.59	0.76
Rice-wheat, Pantnagar, Mollisols	1.48	0.50	0.95	1.51
Rice-wheat, Faizabad, Inceptisols	0.37	0.19	0.40	0.50
Rice-wheat-jute, Barrackpore, Inceptisols	0.71	0.42	0.45	0.52
Rice-wheat-cowpea, Pantnagar, Mollisols	1.48	0.60	0.90	1.44
Maize-wheat, Palampur, Alfisols	0.79	0.62	0.83	1.20
Fallow-rice-wheat, Karnal, Alkali soil	0.23	0.30	0.32	0.35

Note: FYM = farm yard manure; * treatment without any manures or fertilizers; **after 20 years of cropping
(Source: Nambiar, 1995; Swarup and Gaunt, 1998)

Proper soil conservation measures should be addressed to minimize erosion as well as loss of organic matter. In the tropics, climatic conditions favour its disappearance as carbon dioxide. Measures are really lacking on replenishing the loss and maintaining it at acceptable levels. Farmers are really not entirely aware about the knowledge of SOC management as well as soil conservation measures. Katyal (2000) also reported that due to the lack of knowledge about the value of its use and inadequate communication among the farmers, largely due to competing uses and lack of well-organized system of returning by-product wastes to farm fields, is the key constraint to the loss of organic matter.

Cheng (1984) reported the effect of different cropping systems on SOC content in South China (Table 2.10). From Table 2.9 and 2.10, it may be noted that in double-cropped rice areas, SOC levels are relatively stable, even if manure or straw residues are not practiced. Apparently, the nature of two/three flooded rice crops, without an upland crop phase grown in aerated soil, is enough to slow down C decomposition. The chemical nature of SOC at their relatively higher soil C levels, however, appears to be altered (Olk et al., 1996). Rice in the upland crop rotations such as rice-wheat or rice-dry land crops generally have lower SOC than rice-rice systems.

Table 2.10: Effect of cropping systems on organic carbon content of paddy soils in South China

Location	Cropping systems	Organic matter (%)
Hubei	Continuous rice	2.03-2.15
	Rice-dry land crops	1.85-1.94
Zhejiang	Continuous rice	3.11-5.21
	Rice-cotton	2.01-2.87
Taihu Lake region	Rice-wheat-rice	2.74± 0.94
	Rice-wheat	2.45± 1.04
Shanghai Suburbs	Rice-rice-wheat	2.14± 0.19
	Rice-wheat	1.58± 0.14

(Source: Cheng, 1984)

Rasmussen and Albrecht (1997) reported the effect of different cropping systems on SOC over time (Table 2.11). The addition of manure improved the retention of C in soil in annual cropping as well as in rotations that included fallow. It appeared difficult to prevent the loss of SOC from soil with high C content when fallow was included in crop rotation, even with manure addition. Manure application to soil with lower C content maintained SOC at equilibrium when cropped to wheat-fallow rotation (Rasmussen and Parton, 1994). Carbon input from manure is substantial, and can represent from 30 to 80% of total C input which is highly variable, depending on soil type, moisture content, and method of application (Rasmussen and Collins, 1991). The primary factors affecting SOC in semi-arid soils are level of C input into soil through crop residue and manure and frequency of fallow in crop rotations. In general, little C is lost from soil when cropped every year and residues are incorporated rather than removed. Increasing crop yield through improved technology appears beneficial as long as residues are returned to the soil. But, at present, maintaining SOC at equilibrium in rotations that include fallow appears nearly impossible when cropped with inversion tillage. Adoption of no-till may be the way to produce conditions suitable for soil C aggrading (Rasmussen and Albrecht, 1997).

Table 2.11: Soil organic carbon (SOC) change as affected by different cropping systems over time, 1931-1990, Pendleton, Oregon

Cropping Systems	Initial /1931	Final/1990	SOC change	SOC change/year
			t/ha	
Grass pasture	35.40	45.09	+9.69	+0.162
Wheat-fallow (plough*)	35.40	28.49	-6.91	-0.115
Wheat-fallow (mulch**)	33.73	30.55	-3.18	-0.080
Wheat-pea (plough)	31.62	30.68	-0.94	-0.034
Wheat-pea (mulch)	31.62	33.66	+2.04	+0.073
Winter crops-wheat (plough)	36.16	35.48	-0.68	-0.011
Winter crops-wheat (no-till)	31.45	32.29	+0.84	+0.093

*Plough, mouldboard ploughed at 20 cm deep, **mulch, non-inversion tillage <10 cm deep; all the cropping systems were manured/fertilized and all crop residues for pea vines in the wheat-pea rotation were returned to the soil (Source: Rasmussen and Albrecht, 1997)

After land cover or use change, a prolonged period of constant management is required to reach a new equilibrium. The equilibrium level of SOC depends on the balance between factors and processes that increase or decrease SOC content. The rate of change of SOC in soil depends on the amount present and the land management practices (Stevenson, 1982). Thus, the SOC accretion and humification are influenced by i) rate of biomass return through litter fall and crop residues, ii) root biomass and its distribution with depth, and iii) soil fertility management including use of inorganic fertilizers and organic amendments. Whereas, processes leading to decline in the SOC content are: i) mineralization and oxidation of organic substances, ii) soil erosion and iii) leaching.

FAO (2001) noticed that SOC stock depends on the factors of soil formation but can be heavily modified by land use changes and land management. Major loss of SOC is caused by conversion of virgin forest and grassland to cropland and the subsequent ploughing and related activities (Jenkinson, 1991). Patterns of changing land use will have a substantial effect on terrestrial carbon storage (IPCC, 1995). Post and Kwon (2000) indicated that land use patterns, which strongly influence SOC pools and flux, also vary at relatively fine spatial resolutions. According to Houghton and Hackler (2001), the net flux of carbon between the terrestrial biosphere and the atmosphere during the period between 1850 and 1990 was 124 Pg C from deliberate changes in land cover and land-use. DeFries et al. (1999) estimated that total C loss from human induced land cover changes were almost 1200 Pg C including removal of vegetation and trees. Lal et al. (1998) estimated that agricultural soils globally have lost 40 to 50 Pg C during the last century and about 80 to 117 Pg C have been released from biomass due to change in land use for agriculture. On the other hand, substantial amount of organic carbon can be sequestered in agricultural soils. For example, Cole et al. (1996) estimated that globally, between 0.4

and 0.8 Pg C /year could be sequestered in agricultural soils for 50-100 years through good soil management. Above all, Paustian et al. (1997) calculated that the capacity for C sequestration in agricultural soil on a global scale is about 20-30 Pg C over the next 50-100 years. Lal and Bruce (1999) estimated that the total soil C sequestration potential of the world cropland is about 0.75-1.0 Pg/year or about 50% of the annual emissions by deforestation and other agricultural activities. IPCC (2000) reported that by 2040, the potential net C storage is expected to be 0.85 Pg C/year for developed countries and 1.32 Pg C/year for the developing countries.

Thus, it can be said that the SOC pool depends on rates of renewal (source) and removal (loss) of carbon from the soil. The primary source of the soil carbon is through biomass produced and its incorporation into the soil. The principal loss of carbon is through respiration, decomposition, erosion and leaching. Land use and management affect both the magnitude of biomass production and rate of removal of SOC. Maximizing C input to the terrestrial biosphere from the atmosphere is possible in agricultural system (Lal et al., 1998) through a variety of management options, including i) plantation, ii) conservation tillage operations, iii) fertilizer management, iv) integrated nutrient management, v) mulching and manuring that promote the stabilization of soil aggregates which ultimately resist SOC to decomposition.

2.4 Land Management Options and C Sequestration

On crop lands, tillage is the most important practice, which can have a major effect on the soil carbon pool. Conventional tillage or ploughing enhances SOC loss whereas conservation tillage helps maintain its levels in crop lands. The favourable effects of conservation tillage are considerable in carbon management. Conservation tillage includes crop residue management onsite, which ensures the input of organic matter. The production of biomass by plant cover or mulch requires water, so the practice depends on rainfall. Biomass obtained after crop rotation enhances the C sequestration budget, which could reach 1 tonn C /ha/year (FAO, 2001). Fertilization, with the resulting increase in biomass, increases the C available for sequestration in soil. Thus fertilization with the use of irrigation water combined with good drainage permits an increase in biomass production (FAO, 2001). All the above practices, e.g., conservation tillage, mulching, crop rotation and fertilization, are aimed at accumulating carbon in croplands and restoring the degraded soils or prevent erosion. IPCC (2000) noted that croplands under improved management practices can help in carbon gains at the rate of 0.32 t/ha/year. Cole et al. (1996) introduced some best management practices (BMPs) which are important regarding C sequestration, (Table 2.12) biomass production, and agronomic yield.

Table 2.12: Some examples of best management practices (BMPs) on SOC sequestration in different regions of the world

Location	Land use/degradation process	C sequestration rate	References
North America	Best management practices	0.05-1.5 Mg/ha/yr	Lal et al. (1998)
India	Fertilization and manuring	0.02-0.08 % (>25 yr)	Nambiar (1995)
Karnal, India	Saline soil reclamation	0.07%/yr	Singh et al. (1994)
Northern India	Alkali soil reclamation by afforestation	4 Mg/ha/yr	Garg (1998)
West Africa	Manuring	0.03-0.7% (long term)	Smith and Naazie(1998)
Northern Nigeria	Fallowing	0.015%/yr	Onyeanuforo (1994)
Pampas, Argentina	Cover crops , pasture	0.0225%/yr	Demmi et al. (1986)
Para, Brazil	Fallowing	0.9 Mg/ha/yr	Sommer (1996)
South China	Intensive rice cropping	1.0-2.4% (long term)	Cheng (1984)
Sumatra, Indonesia	Manured rubber plantation	3.1 Mg/ha/yr	Van Noordwijk et al. (1995)
Europe	Manure at 10 Mg/ha/yr	23.4×10^6 Mg/yr for 100 yr	Smith et al. (1998)
Australia	N-fertilization	0.15% over long time	Grace et al. (1998)

(Source: Cole et al., 1996)

Agroforestry, the association of trees with crops or pastures, can represent a sustainable alternative to deforestation and shifting cultivation (Winterbottom and Hazlwood, 1987; Sanchez et al., 1999; Schroeder, 1994; Sanchez, 1995). It has a huge potential for carbon sequestration in crop lands (Sanchez et al., 1999). Schroeder (1994) carried out a global evaluation of the land potentially available for conversion to agroforestry. Even if the potential extent is as much as 600 to 1000 million ha, Schroeder (1994) estimated that 160 million ha are suitable only in the tropics. The global C storage would be somewhere between 1.5 and 8.0 Pg (only in trees) from 600-1000 M ha. Other estimates of the extent of suitable land available for agroforestry are higher: 400 million ha for the next 25 years, including 100 million ha of forest (devoted to deforestation) and 300 million ha of degraded agricultural lands (IPCC, 2000). The estimates consider two types of evaluation to arrive at realistic rates for annual land conversion.

The first concerns the transformation of forests after slash-and-burn or other kinds of deforestation and estimates this at 10.5 million ha/year. Secondly, agroforestry systems can be established on unproductive croplands with low levels of organic matter and nutrients. Such areas are widespread in sub-humid areas of tropical Africa. In this case, below-ground carbon is the main concern. The conversion to agro-forestry would permit tripling the soil C stocks, from 23 to 70 t/ha over a 25-year period in Africa. In sub-humid, tropical Africa, the benefit would be around 0.04 - 0.19 Pg C/year. As a first step, a leguminous cover crop can be used, such as *Sesbania sesban*, *Tephrosia vogelii*, *Gliricidia sepium*, *Crotalaria grahamiana*, or *Cajanus cajan*, which can supply 0.1 to 0.2 t N/ha/year. In principal, therefore, agroforestry would be one of the means of changes in land-use related to C sequestration, for various reasons. First, the surface area involved is considerable and the rate of C gain in soil is relatively high, 0.2 - 3.1 t/ha/year (IPCC, 2000). Secondly, it can off-set the important CO_2 emission coming from deforestation (Dixon, 1995). Thirdly, it could provide a sustainable system from technical, ecological, and economic points of view. Therefore, agroforestry is a major contributor to carbon sequestration.

Crop biomass production increases organic matter input into the soil, for example through introduction of new varieties as well as through agronomic management such as nutrient management (especially nitrogen) and crop rotation. About 70-100 kg of N is necessary for sequestering 1 ton of C (Swift et al., 1994). An increase in CO_2 content in the atmosphere due to climatic change can have a similar positive influence, the so-called 'CO_2 fertilization effect' (Bazzaz and Sombroek, 1996). The soil has to be protected during the initial period of crop growth by incorporating crop biomass into the soil. In European countries specifically in Belgium, the above all factors, showed that without the application of manure and even with conventional tillage practices, the organic matter content increased in the cultivated soils using crop biomass and water management (FAO, 2001). Crop residue management is an integral part of the conservation tillage system. FAO (2001) also reported that water management or irrigation, with an associated increase in productivity, can produce similar effects, e.g., increased biomass production, especially in semi-arid regions.

Crop residue management is an important method of sequestering C in soil and increasing the soil organic matter. Residue burning has negative consequences, even if they are sometimes mitigated by the great stability of the mineral carbon which is formed. The positive effects of using crop residues to induce C sequestration have been estimated by Lal (1997) at the rate of 0.2 Pg C/year. Crop residues applied on the surface, decompose more slowly than those that are incorporated by tillage, because they have less contact with soil microorganisms and soil water. Angers et al. (1995) reported that conversion of maize residue C into soil organic matter in the 0 to 24 cm layer was about 30% of the total input which is higher than the above estimation (0.2 Pg C/year) by Lal (1997). Evidently, there are qualitative differences between the crop residues, depending on the crop types. The lignin content of the residue has a highly positive effect on the accumulation of carbon (FAO, 2001).

Mulch farming and plant cover are land management practices allowing both coverage of the soil by specific plants, giving protection against erosion, and providing biomass residues to increase soil organic matter. The quantity of mulch should be in the range of several dozens of t/ha/year in order to provide an important carbon soil input of up to 0.1 C t/ha/year, depending on the climatic zone (Lal, 1997). The quality of the plant residues is also an important factor, providing mulch or covering crops (Heal et al., 1997; Drinkwater et al., 1998). The soil cover or mulch increases the water infiltration rate and prevents water evaporation (FAO, 2001), and hence soil moisture storage and conservation is increased. Green manures and cover crops provide an important contribution to soil carbon where 45,000 farmers in Central America have adopted Mucuna (Velvet bean) based systems, in which 150 kg N can be fixed per ha per year and 35-50 tonnes of biomass added to the soil per/ha/year, representing a very large sequestering of carbon (FAO, 2001).

Apart from climatic factors, the main processes causing losses in soil carbon are soil erosion and mineralization of organic matter. Leaching of dissolved organic and inorganic carbon is another important mechanism of loss of carbon from the soil. Soil erosion by water and wind, represents the most important soil degradation process and affects more than 1 billion hectares globally (FAO, 2001). The soil loss through erosion generally ranges from 1-10 t/ha/year (FAO, 2001). Hence, a decrease in erosion through soil conservation and management practices can help soil organic C sequestration.
FAO (2001) reported that tillage has a long history, dating back millennia that stimulate N release from soil organic matter (SOM). The increase in aeration of the soil and the intense disturbance are the main factors stimulating the mineralization of organic matter by the soil micro-organisms. Balesdent et al. (2000) demonstrated that tillage plays a main role in the 'deprotection' of organic matter present in macro and, to some extent, in micro aggregates. Tillage practices have been causing the general decrease in SOM of intensively cultivated soils (FAO, 2001). Conservation agriculture favours biological functioning of the soil, the most evident change being the increase in soil fauna and micro-flora. The function of conservation agriculture (including zero tillage systems), is to protect soil physically from the action of sun, rain and wind, and feed soil biota. The result is to reduce soil erosion and improve the soil organic matter and as well as carbon content. Robert (1996) noted that organic matter and the biological activity have a major influence on the physical and chemical properties of soils. Thus the stock of organic carbon present in natural soils represents a dynamic balance between the input of dead plant material and loss from decomposition. Lal (1999) summarized different land management options and their impacts on SOC sequestration in dry lands and tropical areas (Table 2.13).

Table 2.13: Impacts of land management practices on carbon sequestration (t/C/ha/yr) in the dry lands and tropical areas

Land management practices	Dry lands	Tropical areas
Conservation tillage	0.1-0.2	0.2-0.5
Mulch farming or plant cover	0.05-0.1	0.1-0.3
Conservation agriculture	0.15-0.3	0.3-0.8
Composting	0.1-0.3	0.2-0.5
Nutrient management	0.1-0.3	0.2-0.5
Water management	0.05-0.1	-
Grassland and pastures	0.05-0.10	0.1-0.2
Agroforestry	-	0.2-3.1

(Source: Lal, 1999)

Thus, it can be concluded that appropriate land use management options like conservation tillage, mulch farming, cover crops, agroforestry farming, biomass production farming as well as crop residue management etc. all enhance SOC. The above management practices decrease decomposition, improve soil structure and aggregation, decrease soil degradation processes, and increase nutrient cycling and other ecosystem restorative mechanisms.

2.5 Main Consequences and Impact of C Sequestration

Carbon sequestration and a consequential increase in soil organic matter have a direct positive impact on soil quality and fertility and ultimately the agro-environment (FAO, 2001). Organic matter is of particular interest for tropical soils having a very low cation exchange capacity. Increase in organic matter increases soil cation exchange capacity, as organic colloids being rich source of charges on them. With regard to physical properties, organic matter and living organisms associated with SOC play a major role in soil aggregation (Tisdall and Oades, 1982; Robert and Chenu, 1991). Aggregation and carbon sequestration processes are strongly associated (Golchin et al., 1994). Carbon sequestration improves soil's aggregate stability and thus has a considerable influence on a range of soil physical properties. Many properties depend on the soil aggregate and on its stability, water retention and its release to plants, infiltration rate and resilience to erosion, and other physical degradation processes.

Soil structure has a major influence on the ability of soil to support root development, to receive, store and transmit water, to cycle carbon and nutrients, and to resist soil erosion and the dispersal of chemicals of anthropogenic origin (Kay, 1990). Particular attention must be paid to soil structure in managed ecosystems because of its sensitivity to land use practices. Management practices can alter soil structure directly by processes like tillage. Sustainable land use practices must maintain the structure of soil, over the long term, in a state that is optimum for a range of processes related to crop production and environmental quality. A key consideration in designing such practices must, therefore, be management of the organic carbon in soils. Kay (1990) also noticed that the dominant factors influencing soil structure are characteristics such as texture, clay mineralogy, composition of exchangeable ions, and organic carbon content. Other factors influencing soil structure include climate, biological processes, and management practices. An assessment of the influence of organic carbon on soil structure must, therefore, be considered in the context of other factors—specifically, texture controls structure because aggregate size and stability depend on the balance between plasma (mostly clay and silt) and skeleton (mostly sand and gravel) soil constituents (Buol et al., 1997). The finer-textured soils accumulate more organic C for several reasons: i) they produce more plant biomass, ii) they lose less OC because they are less well aerated, and iii) more of the organic material is protected from decomposition by being bound in clay humus complexes.

The mechanisms responsible for stabilizing SOC can be categorized as i) biochemical recalcitrance, ii) chemical stabilization, and iii) physical protection (Christensen, 1996). Biochemical recalcitrance may be due to the chemical characteristics of the substrate itself which means lignin derivatives (Stott et al., 1983) or melanin's produced by fungi and other soil organisms (Martin and Haider, 1986) or may result from transformations during decomposition, including incorporation into the excrement of soil meso- and micro-fauna (Kooistra and van Noordwijk, 1995). Chemical stabilization occurs because of chemical and physico-chemical associations between the decomposable compounds and soil mineral components. For example, organic compounds sorbed to clay surfaces often by polyvalent cation bridges, or those intercalated between expanding layers of clays are quite resistant to degradation (Martin and Haider, 1986; Christensen, 1996; Tisdall, 1996).

In addition, the drying of organics may cause them to be denatured or polymerized, thereby protecting them chemically from decomposition (Dormaar and Foster, 1991). Soil structure, however, plays a dominant role in the physical protection of soil organic matter by controlling microbial access to substrates, microbial turnover processes, and food web interactions (Elliott and Coleman, 1988). Relatively labile material may become physically protected from decomposition by incorporation into soil aggregates (Oades, 1984; Gregorich et al., 1988) or by being deposited into micro-pores inaccessible even to bacteria (Foster, 1985). Because of the physical protection afforded by soil structure, significant interactions exist between SOC dynamics and the formation, stabilization, and degradation of soil aggregates. In soils, where organic matter is the major aggregate binding agent, plant growth and the decomposition of organic inputs lead to the development of a hierarchical aggregate structure (Tisdall and Oades, 1982; Oades and Waters, 1991). The exact nature and stability of this structure in a given soil depends on the relative amounts and strengths of various types of organo-mineral associations that function as aggregate binding and stabilizing agents at each hierarchical level of organization. At the same time, the nature of these organo-mineral associations and their spatial locations within the aggregate hierarchy determine the degree to which SOC is physically protected from decomposition and, consequently, result in organic pools with various input and turnover rates.

Carbon sequestration in agricultural soils counteracts the desertification process through the role of increased soil organic matter in structural stability and water retention, and the essential role of soil surface cover by plant debris or mulch in preventing erosion and increasing water conservation. Wetland rice culture represents the most complex system in relation to carbon sequestration. If OC is accumulated in wetland soil, CH_4 is also formed. The greenhouse effect of methane is far greater than that of CO_2. According to IPCC (1995), methane (CH_4), in terms of its global warming potential, is 21 times more potent than carbon dioxide (CO_2). The usual strategy for preventing CH_4 formation is to decrease the duration of water logging so that OC will be less protected and CO_2 and N_2O or NH_3 can be emitted (Paustian et al., 1997). In view of these various effects, it seems very difficult to concurrently manage wetland rice production and C sequestration. Recent developments in conservation agriculture for rice-wheat systems are very positive, where rice yields can be maintained or improved without the need of keeping the fields submerged or saturated, by puddling with major water savings in the rice growing periods (FAO, 2001). Natural wetlands have similar anaerobic conditions with a smaller CH_4 emission than wetland rice fields and a greater potential for C sequestration. When fresh organic matter in the form of mulch or plant residues is present at the soil surface, there is an increase in the different categories of fauna, mainly of decomposers. An increase in carbon sequestration causes an increase in the operational biodiversity and more effective soil biological functioning. An increase in CO_2 concentration in the atmosphere induces an increase in biomass or in the net primary production (NPP) by carbon fertilization, playing a major role in plant photosynthesis and growth (FAO, 2001).

With regard to soil C sequestration, another factor that plays an important role is temperature, which has seen increases over part of the globe in the last few decades (FAO, 2001). Such an increase provokes a higher rate of organic matter mineralization by microbes and a higher respiration rate by roots. This effect of temperature on mineralization is very significant in cold countries, where temperature is often a limiting factor in organic matter mineralisation, and thus, an increase in CO_2 emissions may be expected, i.e., increase in global temperature will increase mineralisation (in cold areas) and consequential increase in CO_2 emissions from the soil system (Van Ginkel et al., 1999). Soil carbon is in steady state equilibrium in natural forest, but as soon as deforestation or afforestation occurs, the equilibrium will be affected. It is estimated that currently 15 to 17 million ha/year are being deforested, mainly in the tropics (FAO, 1993) and very often part of the soil organic carbon is lost, giving rise to considerable CO_2 emission. Therefore, where deforestation cannot be stopped, proper management is necessary to minimize C losses. Afforestation, particularly on degraded soils with low organic matter contents, will be an important method of long-term C sequestration both in biomass and in the soil. Agroforestry practices also have considerable potential to increase the soil content of sequestered carbon, in both temperate and tropical regions. The magnitude of the changes that can be attained depends on several soil factors.

2.6 SOC Management Challenges in Bangladesh

For attaining sustainable agricultural development, it is essential to maintain an optimum fertility level in the soils (Abrol and Katyal, 1990). In a low-input agriculture, the gradual net loss of nutrients from soils is a common phenomenon (Karim and Iqbal, 2001) and may have an adverse impact on food grain production (Karim et al., 1999). Agriculture in Bangladesh is practiced on moderately fertile soils, often without application of adequate quantities of farmyard or organic manures. As a consequence, the crop yields have started to become stagnant or even declining in many areas (Pagiola, 1995). The decrease in yields has been estimated to be around 1% per year, and in the more adversely affected areas it is higher than that (Asaduzzaman, 1995; Duxbury et al., 2000). During the last few decades, the total grain crop production has gradually increased in Bangladesh. According to the estimate of the World Bank, over the last 10 years, growth in total agricultural output in Bangladesh has been only 2.1%, and average rice yields have increased by 2.5% (World Bank, 1995).

There has been a steady increase in the yields of high-yielding rice cultivars and the rice yield increases have come mainly from the transition from local to high yielding varieties (Pagiola, 1995). Nutrient mining in soils has been thus noted as a serious and widespread problem (Ahmed and Hassanuzzaman, 1998). In this regard, Karim and Iqbal (2001) estimated a total loss of 1.25 million tons of nitrogen, phosphorus and potassium from the agricultural lands of Bangladesh every year. Loss of potassium alone from the soils is the highest and has been reported to be more than one million tons per year. The growing demand of ever increasing population of Bangladesh for the need of more food, fiber and fuel has resulted in rapid loss of SOC as well as nutrients in soils. The net result is the decline in soil structure development at an alarming rate which ultimately accelerates top soil degradation. Rijpma and Jahiruddin (2004) also noted that in Bangladesh the level of organic carbon is low and in about 60% of arable land organic carbon has decreased to 0.87%. Khan (2008) reported that several factors are responsible for such situations which are intensive cropping, rapid decomposition of organic matter, deforestation, soil erosion, removal of crop residues, etc. Gradual decrease of organic carbon in the agricultural soils of Bangladesh is a serious concern for agricultural scientists (Hossain, 2001). Karim and Iqbal (2001) showed a simplified SOC status of Bangladesh soils (Table 2.14). Almost 50% of the agricultural land in Bangladesh have <0.6% soil organic carbon (Table 2.14). Such a low level of organic carbon in most of the mineral soils of Bangladesh is alarmingly low. The reason for low SOC is perhaps due to the low residual input with higher cropping intensities without any fallow periods.

Table 2.14: A simplified picture of organic carbon status of Bangladesh soils

SOC Level	Organic carbon (%)	Total area (million ha)	% of net cultivated area
Very low	<0.6	4.05	45
Low	0.6-0.98	1.56	17
Medium	0.98-2.03	1.94	21
High including peat soils	>2.03	1.56	17

(Source: Karim and Iqbal, 2001) Note: % SOM = % SOC*1.72

In Bangladesh, the use of imbalanced fertilizer in agricultural soils with the target of higher cropping intensity causes the porosity and permeability of the soils to decrease (Hussain, 2002). As a consequence, the physical fertility of the soils regarding loss of SOC either remains stagnant or worsens. Organic carbon is lost from the surface soils mostly by erosion when flood water passes over them and the eroded materials are deposited in the lower part of the landscape. While some parts of the landscape may lose carbon, others may gain carbon. This causes a gradual and hidden degradation of the soils, resulting in soil carbon loss. This causes a general decrease in the yield of crops per unit area all over the country. Lal and Bruce (1999) reported that when a soil is continuously cultivated, the SOC content declines until an equilibrium level is reached and the magnitude of the equilibrium state depends on the climate, land use and cropping systems. Mia et al. (1993) reported a gradual depletion of SOC due to the increase of cropping intensity over time in different agro-ecological zones (AEZs) of Bangladesh (Table 2.15). The surface organic carbon content in the highland and medium highland areas has been declining over time (Table 2.15).

Table 2.15: Depletion of soil organic carbon (SOC) under different land types and cropping intensity in some agro-ecological zones (AEZs) of Bangladesh

Name of AEZs	Land type	Average cropping intensity (%)		SOC % (average)		Total SOC depletion (%)
		1969-70	1989-90	1969-70	1989-90	
Madhupur Tract (AEZ 28)	High land	150-200	150-300	1.06 (0.75-1.38)	0.67 (0.35-0.98)	36.79
Level Barind Tract (AEZ 25)	High land and medium high land	100-200	100-200	0.88 (0.61-1.15)	0.66 (0.51-0.80)	25.00
Old Himalayan Piedmont Plain(AEZ 1)	High land	100-200	200-300	0.76 (0.57-0.96)	0.67 (0.46-0.87)	11.84
Tista Meander Floodplain (AEZ 3)	High land and medium high land	150-200	200-300	0.89 (0.84-0.93)	0.67 (0.46-0.87)	24.71
Northern and Eastern Hills (AEZ 29)	High land and medium high land	100-200	200-250	1.14 (0.86-1.42)	0.72 (0.58-0.87)	36.84
Old Meghna Estuarine Floodplain (AEZ 19)	High land	200	200-300	1.3 (1.10-1.50)	0.72 (0.58-0.87)	44.61
High Ganges River Floodplain (AEZ 11)	High land	100-150	200-300	0.65 (0.37-0.93)	0.49 (0.18-0.80)	24.61
Old Brahmaputra Floodplain (AEZ 9)	Medium high land	150-250	200-300	0.93 (0.62-1.24)	0.70 (0.52-0.89)	24.73

(Source: Mia et al., 1993)

According to Ali et al. (1997), a similar situation in organic carbon depletion was observed in the intensive cropping areas of Bangladesh. It is believed that soil productivity is declining due to the depletion of organic carbon by increasing cropping intensity, higher rates of decomposition of organic matter under the prevailing hot and humid climate, little or no use of organic/green manure practices (Hossain, 2001). Crop residues and animal manures are widely used as fodder and fuel, thus these are not returned to the soil. Eighty-one per cent of the total biomass fuel is consumed in Bangladesh for domestic cooking (Mia and Karim, 1995). The past 20 years of intensive rice cultivation has resulted in SOC decline in the top soils (Ali et al., 1997). Karim and Iqbal (2001) developed scenarios of SOC content in different agro-ecological zones of Bangladesh using the National Agricultural Research Systems (NARS) database (Fig. 2.2).

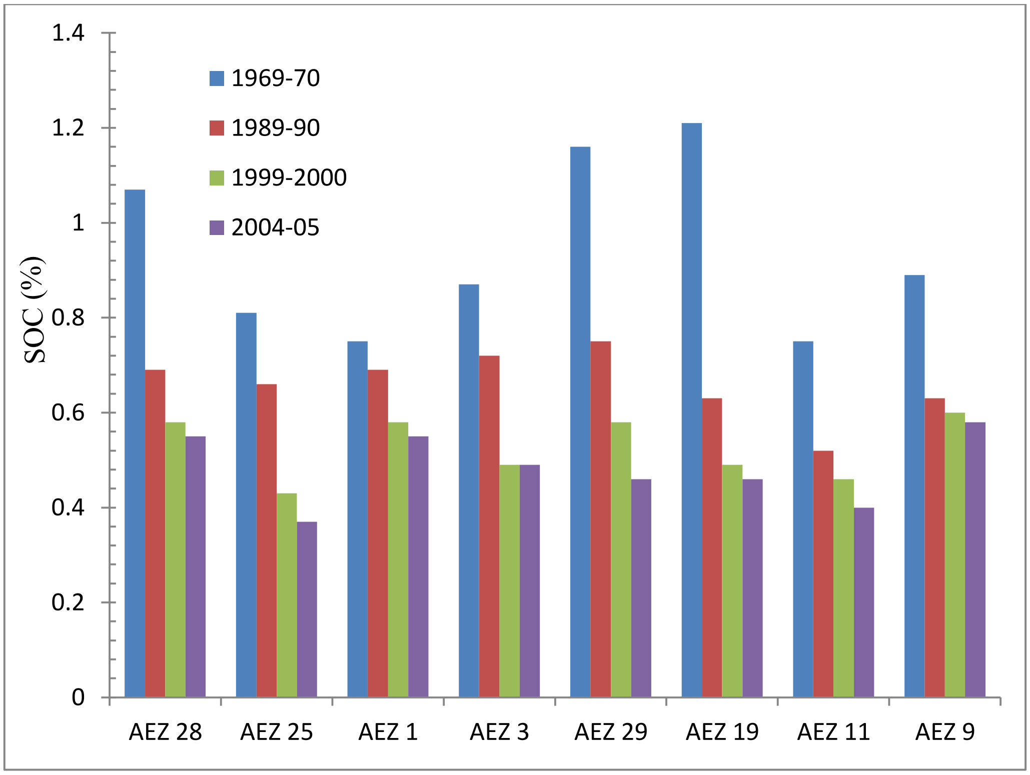

Figure 2.2: Scenarios of SOC (%) in different agro-ecological zones (AEZs) of Bangladesh during 1969-2005 (AEZ 28, Madhupur tract; AEZ 25, Level Barind tract; AEZ 1, Old Himalayan piedmont plain; AEZ 3, Tista meander floodplain; AEZ 29, Northern and Eastern Hills; AEZ 19, Old Meghna estuarine floodplain; AEZ 11, High Ganges River floodplain; AEZ 9, Old Brahmaputra floodplain)
(Source: Karim and Iqbal, 2001)

Saheed (1994) noted that the notable land degradation processes such as soil erosion, soil salinization, continuous water logging, river bank erosion, acidification, plough pan formation, organic carbon reduction, deforestation, etc. are caused by inappropriate land management practices. Karim and Iqbal (2001) reported a comprehensive estimation regarding land degradation hazards in Bangladesh (Table 2.16). Among the estimated land degradation processes, organic carbon depletion is a major cause of land degradation, as is soil fertility depletion (Table 2.16). Decreased organic carbon causes degradation of soil physical properties including water-holding capacity and reduced nutrient retention capacity, leading to reduced release of nutrients from mineralization (FAO-UNDP, 1994). In the recent past, the introduction of high-yielding rice cultivars with frequent irrigation over the year, the SOC increased in some lowlying areas of Bangladesh, and in this situation SRDI (2001) reported that organic carbon tends to show a slight increase in lowland rice areas under water logged conditions. Kirk and Olk (2000) also reported that crop intensification from one to two or two to three crops grown per year affects the amount of organic matter recycled as crop residues.

Table 2.16: Estimated land degradation (as area in M ha) hazards in Bangladesh

Land degradation	Trends of degradation			Total area (M ha)
	Low	Moderate	Strong	
Water erosion	0.1	0.3	1.3	1.7
Soil fertility decline	3.8	4.2	-	8.0
Organic carbon depletion	1.9	1.6	4.0	7.5
Water logging	0.7	-	-	0.7
Salinization	0.30	0.43	0.12	0.85
Plough pan formation	-	2.82	-	2.82
Acidification	-	0.06	-	0.06
Deforestation	-	0.3	-	0.3
Total	6.8	9.7	5.4	21.9

Source: (Karim and Iqbal, 2001)

Thus, the low organic carbon content is related to many biophysical attributes of soils, particularly their aeration, structure, resilience, and productivity. The depletion of organic carbon is mainly caused by low organic residues inputs and high cropping intensity. Proper technical options are necessary to restore the SOC levels in soils. As soil quality is related to organic matter, without increasing the level of organic matter, the soil quality cannot be enhanced.

2.7 Soil Degradation, Sedimentation, and Carbon Dynamics

Soil erosion is a major form of soil degradation (Coote, 1984; Sparrow, 1984). Eroded soils reduce plant yield due to high bulk density, poor tilth, reduced organic matter content, low nutrient availability, and reduced water-holding capacity (Dormaar et al., 1986; Tanaka and Aase, 1989). Studies in Alberta (Larney et al., 1995) using an artificial erosion approach, demonstrated drastic reductions in crop yield for every increment in erosion level. The study suggested that soil productivity could be restored by replenishing nutrients with commercial fertilizers or manure (Izaurralde et al., 1994). Restoring the productivity of eroded soils brings the potential of not only increasing economic benefits to producers but also storing atmospheric carbon in soil organic matter (Lal, 1995; Cole et al., 1996). Soil organic carbon concentration is a direct reflection of factors that affect plant growth such as erosion level, topography and texture (Izaurralde et al., 1998).

In the context of C dynamics, it is the magnitude of soil displaced and its carbon contents that are more relevant than the land area affected. Brown (1984) estimated that the world's cropland area is losing about $23x10^9$ Mg of soil in excess of new soil formation each year. Walling (1987) revised these data and estimated that total material transport to the oceans by the world's river is about $19x10^9$ Mg/year, comprising $14x10^9$ Mg/year as suspended load, $4x10^9$ Mg/year as dissolved load, and $1x10^9$ Mg/year as bed-load or surface load. The sediment load carried by the world's rivers originates over the land due to several processes of soil erosion. Out of the total sediments detached, only a fraction is transported into the major river system and finally into the ocean. The sediment delivery ratio is a complex problem due to several sinks or storage systems within the watershed (Walling, 1983; Meade, 1982). It is generally believed that the sediment delivery ratio may be as low as 10% e.g., only 10% of the sediment originating over the watershed is eventually transported to the ocean (Lal, 1995). There is a wide range of total load carried in Rivers of the world. Lal (1995) stated that the major rivers—the Ganges-Brahmaputra, the Hwang Ho, and the Amazon—are carrying the highest total sediment load. Among them, the Amazon carried the highest load. The total sediment load in major rivers is in the following order: Hwang Ho>Ganges-Brahmaputra>Magdalena>Irrawdy. Some of the lowest suspended and dissolved loads are carried by the rivers in Central and Western Africa (Walling and Webb, 1987).

Lal (1995) presented an estimation of the impact of global soil erosion by water on C dynamics (Table 2.17). It is also noted that world soil contain about 1500x10^{15} g C in the top 1 m depth over the total land area of 14.8x10^{9} hectares or 29% of the earth's surface (Schlesinger, 1984; Buringh, 1984). The global sediment transport to the ocean of 19x10^{15} g /year is equivalent to 190x10^{15} g /year of soil displaced from terrestrial ecosystems assuming the mean delivery ratio of 10% (Walling, 1987). Lal (1995) reported that with a mean C content of 3%, total C displaced in soil from the terrestrial ecosystems is 57x10^{15} g/ year. It is assumed that C in soil displaced is easily decomposed, and as much as 20% is mineralized each year and released into the atmosphere as CO_2. Therefore, C flux into the atmosphere from soil physically displaced by erosion processes from terrestrial ecosystems is estimated at 1.14x10^{15} g/ year. Assuming mean organic C content of 3%, organic carbon transported with sediments to the ocean is about 0.57x10^{15} g/year. With a total global runoff of 42.4x10^{3} km^{3} containing mean dissolved C content of 6 mg/L, this amounts to a rate of 0.254x 10^{15} g/ year of sediment-borne organic C transport to the ocean. Annual rate of soil displacement by erosion in terrestrial ecosystems accounts for only 0.38% of the C stored in world soils. Organic carbon transported to the world oceans accounts for one-tenth of the displaced carbon or 0.038% of the C in world's soils (Lal, 1995).

Table 2.17: Soil erosion and C dynamics

References	Statistics	Total C (10^{15} g/ yr)
Soil erosion	• Delivery ratio of 10% • Total sediment displaced = 190x 10^{15} g /year • Organic carbon content of 3%	5.7
Decomposition	• 20% of the C displaced is biodegraded, mineralized, and released as CO_2 over the watershed.	1.14
Sediment	• Global sediment transport to the oceans is 19x10^{15} g/ year. • Organic carbon content of sediment is 3%	0.57
Runoff	• Total runoff is 42.4x 10^3 km^3 • Total C is 6 mg/L	0.255

(Source: Lal, 1995)

Mean rates of soil erosion over the tropics are difficult to estimate. On the basis of literature surveys (Lal, 1990; 1995), the data presented in Table 2.18 show the SOC loss due to soil erosion in the tropical watersheds. Using these data, the total transport or movement of C displaced with soil erosion is estimated at 1.59x10^{15} g /year. These estimates range from a low of 0.80x 10^{15} g /year to a high of 2.40x 10^{15} g /year. However, only a fraction of soil moved from its original place is transported out of the watershed. The delivery ratio for tropical watersheds may also be as low as 10%. This implies that as much as 0.16x 10^{15}g C /year may be transported out of tropical watersheds with a range of 0.08x 10^{15} g C /year to 0.24x 10^{15} g /year. Schlesinger and Melack (1981) estimated that world's river transport about 0.37x 10^{15} g C /year. The estimates for tropical rivers are at 0.16x 10^{15} g C/year, implying thereby that about 40% of C transported in world's rivers is contributed by those draining tropical watersheds.

Table 2.18: Organic carbon loss in soil erosion from tropical lands

Land use	Area (10^6 ha)	Soil erosion rate (t /ha/year)	Carbon content or eroded sediment (%)	Transport of carbon (10^{12} g/ year)
Arable	418.4	15	2.5	156.9
Permanent crops	51.4	12	3.0	18.5
Permanent pastures	1226.0	15	2.0	367.8
Forest and woodland	1867.5	10	3.5	653.6
Other lands	1320.5	15	2.0	396.2
Total	-	-	-	1593.0

(Source: Lal, 1995)

In the USA, the total suspended sediment transport was about 400 MMT/yr in the 1980s (Meade and Parker, 1984). The load in 12 major US Rivers in 1991 was estimated at 336 MMT/yr for suspended load and 113.5 MMT/yr for dissolved load (Leeden et al., 1991). Assuming that 75% of the suspended load (mostly due to erosion) is contributed by cropland, sediment transport attributed to cropland is about 250 MMT/yr. Assuming a delivery ratio of 10% and SOC content sediment of 3% (Lal et al., 1998), total SOC displaced by soil erosion from cropland in the USA is 75 MMT/yr. If 20% of the SOC displaced and redistributed over the landscape is mineralized, C exposed by disruption of aggregates is easily accessible to microorganisms, and the erosion caused emission amounts 15 MMTC/yr. However, erosion based emission can be mitigated through adoption of effective erosion control measures.

In Bangladesh, there is no estimate of soil erosion regarding soil C dynamics. However, water erosion is the most widespread form of soil degradation, affecting some 25% of agricultural land (Karim and Iqbal, 2001). Accelerated soil erosion has been remarkably encountered in the hilly regions of the country which occupy about 1.7 million hectares. Though the loss of topsoil due to water erosion is evident in the vast floodplain areas, only a very limited research results are available for the quantification of soil loss and associated C dynamics. The huge supply of sediment to the Bengal basin is provided mainly by the Ganges-Brahmaputra Rivers originating from the Himalayas. Many estimates of sedimentation rate in the Bay of Bengal have been made; whilst all support the enormousness of sedimentation, they are considerably variable (Table 2.19). The Ganges, the Brahmaputra and the Meghna (GMB), World’s largest River systems (Wells and Coleman, 1984) discharge about 35,000m^3 of water per year (Siddiqui, 1989). The estimated total sediment volumes supplied to the central zone of Bangladesh range from 1099 to 2180 million tons /year to the Bay of Bengal (Barua, 1991; Milliman and Meade, 1983). These sediments due to dynamical processes accrete in one place and erode in another place. Due to flat terrain, the rivers in the floodplain of Bangladesh have low gradients causing deposition of substantial quantities of river-borne sediments on the river beds forming sandbars, while the rest of the 2.5 billion tons of the sediments annually move to the offshore areas through the Meghna estuary (Coleman, 1969).

Table 2.19: Estimates of sedimentation (t/yr) in the Bay of Bengal, Bangladesh

Names of River systems	Sedimentation rate t/yr	Sources
Ganges-Brahmaputra-Meghna	2.46 billion t/yr	Coleman, 1969
Ganges-Brahmaputra-Meghna	1.5-2.4 billion t/yr	Siddiqui, 1989; Nishat, 1989
Ganges-Brahmaputra-Meghna	1.3 billion t/yr	Anwar, 1989
Ganges-Brahmaputra-Meghna	1.0-2.1 billion t/yr	Barua, 1991
Ganges-Brahmaputra-Meghna	2.5 billion t/yr	Hossain, 1992

In addition to its on-site and off-site economic impacts, global soil erosion also has a major impact on C dynamics. Ecological and environmental effects of erosion induced changes in soil carbon warrant serious and planned effort to reduce soil erosion risks, and minimize transport of sediments into Bangladeshi waterways.

2.8 Land Use and Distribution of SOC

Land use and its impact on the SOC pool and its dynamics are important and should be addressed in making appropriate policy decisions. Most studies done so far were limited to the surface layers of soil profiles. However, pedogenesis of lower horizons can be affected by disturbances to the surface horizon. Lantz et al. (2001) reported that any disturbance in the surface horizons affects soil porosity, internal ped faces as well as water movement and even SOC in the sub-soil. Therefore, studies on quantifying the SOC contents in subsoil may provide information on how land use affects the SOC pool, and such data may help better estimate the potential of different land uses as source or sink for C. Lantz et al. (2001) also studied the differences in SOC pools in cropped, pastured and forested sites in Ohio, up to the depth of 170 cm, where pastured sites showed higher SOC pools than the forested ecosystems. Cultivation reduced the SOC pool in the top 0-10cm layer and increased it in the 10-25 cm layer, not decreasing the total SOC pool. Smith et al. (2000) reported that SOC levels are known to be influenced by a large number of factors, many of which are mutually interactive e.g., soil colour, soil texture, land use, management, climate, topography and drainage etc. Manipulation of some of these factors, especially management related ones, may be used to increase C sequestration in soils and thus mitigate climate change commitments (Smith et al., 2000). Landscape units influence water movement and the nature and extent of erosion or deposition processes occurring at any given location in a field (Mermut et al., 1983; Pennock and Jong, 1987). The degree of erosion affects the distribution of organic matter in the soil profile and its aggregates (Bajracharya et al., 1998).

The morphologic significance of soil colour has been widely recognized by soil scientists (Simonson, 1993). This is supported by Franzmeier (1983) who noted relationships between organic matter concentration, soil colour and soil texture for Indiana soils. He also outlines an equation correlating organic matter and Munsell colour value and chroma. On the other hand, Nichols (1984) examined Southern Great Plains soils to determine if SOC concentrations could be predicted from several environmental factors. The percentage of clay content was found to be the best predictor of organic carbon in this study (r= 0.86). Franzmeier (1983) also noted that organic matter concentration generally increased for Indiana Ap horizon soils with increasing clay content. Konen et al. (2003) also reported that clay contents was highly correlated (r^2= 0.71) with SOC in Iowa soils and that the SOC increased linearly with the clay content.

Land use change alters the inputs of organic matter, thus affecting SOC and soil organic nitrogen (SON) stores accordingly (Zhou et al., 2007). Net losses of SOC and SON due to land use change may occur as a result of decreased organic residue inputs and changes in plant litter composition and increased rates of SOM decomposition and soil erosion (Lugo and Brown, 1993).There is a good relationship between SOC and SON. In this aspect, Jenkinson (1981) noted that immobilization of nitrogen takes place when the C/N ratio of the residues is greater than 30/1. This ratio can be decreased by adding fertilizers or by using the residues and even the nitrogen containing waste. Jenkinson (1981) and Himes (1998) reported increased quantities of C and N sequestered in the fertilized Broad Balk field at Rothamsted over the non-fertilized field (Table 2.20).The findings are based on a long-term (1843 to 1963) continuous wheat trial. The concentration of organic carbon in the un-manured plot did not vary in the 120 years. The annual application of N, P, K and Mg increased the total C by about 15%. The ratio of the C and N sequestered was 12.8/1. To sequester the 4000 kg of C, 314 kg of N was required. The quantity of C sequestered will be limited if there is insufficient nitrogen. Thus, C/N ratio is a good indicator of the degree of decomposition and quality of the organic matter in the soil.

Table 2.20: Carbon and nitrogen sequestered in the fertilized Broad Balk Plot at Rothamsted under continuous wheat since 1843-1963

Treatment	Organic C %	Nitrogen %	kg C/ha	kg N/ha
Unmanured	0.90	0.098	20.160	2.195
Manured NPKMg annually	1.08	0.112	24,192	2,590
Element sequestered	-	-	4,032	314

(Source: Jenkinson, 1981; Himes, 1998)

Batjes (1996) estimated world's soil carbon and nitrogen pool (Table 2.21). The average SOC stored in the upper 100 cm was estimated to be between 1462 and 1548 Pg C. Based on this study, SOC in the tropics was estimated to be 201-213 Pg C, 384-403 Pg C and 616-640 Pg C in the 0-30, 0-100 and 0-200 cm layers, respectively. Batjes (1996) also used the same methodology to estimate soil nitrogen as that for C pools, with global estimates of 63-67 Pg N at 0-30 cm depths and 133-140 Pg N to a depth of 100 cm. The latter values are greater than the 92-117 Pg N calculated using an ecosystems approach (Zinke et al., 1984), possibly because most profile descriptions in World Inventory of Soil Emissions Potentials (WISE) used by Batjes (1996) for agricultural soils may have been amended with N fertilizers.

Table 2.21: World soil carbon and nitrogen pools (Pg)

Regions	Soil C and N	Depth range (cm)		
		0-30	0-100	0-200
Tropical regions	Soil Organic C	201-213	384-403	616-640
	Soil Carbonate C	72-79	203-218	-
	Total	273-292	587-621	-
	Soil N	20-22	42-44	-
Other Regions	Soil Organic C	483-511	1078-1145	1760-1816
	Soil Carbonate C	150-166	492-530	-
	Total	633-677	1570-1675	-
	Soil N	43-45	91-96	-
World	Soil Organic C	684-724	1462-1548	2376-2456
	Soil Carbonate C	222-245	695-748	-
	Total	906-969	2157-2296	-
	Soil N	63-67	133-140	-

(Source: Batjes, 1996)

Soil texture specifically clay affects SOC because of its stabilizing properties. Lal (1998) reported that clay offers chemical protection to organic matter through adsorption onto clay surfaces, which prevents organic matter from decomposition. Organic matter trapped in the very small spaces between clay particles making them inaccessible to micro-organisms and therefore slows down its decomposition. Soils with high clay content therefore tend to have higher SOC than soils with low clay content under similar land use and climatic conditions. This can be explained by the fact that soils with high clay content have higher potential to sequester C than soils with low clay content. Stevenson (1982) noted that clays tend to retain organic substances using mechanism such as clay-organic complexes, adsorption to mineral surfaces (through cation exchange, bridging by polyvalent cations, hydrogen bonding or Van der Waals forces) or within the interlayers of expanding type clays (Stevenson, 1982). This means the type of clay will have a strong effect on the sequestration of C.

Granular structure refers to soil aggregates that have a spherical arrangement. Developing stable granular aggregates usually requires intimate mixing between the mineral matrix and organic matter. For soils of the temperate and cold regions, SOM (Duchaufour, 1982) and soil fauna (Pawluk, 1985) have a dominant influence in soil aggregation processes. Among mineral soils, Mollisols are particularly effective in sequestration and stabilization of C through humification and aggregation processes.

Bulk density is critical for converting SOC percentage by weight to content by volume, but it varies with structural condition of the soil. The bulk density is strongly influenced by soil characteristics such as texture, organic carbon content and management practices. When other factors are constant, site-specific studies show that the total porosity or bulk density generally increases with increasing organic carbon content (Lal et al., 1994; Schjonning et al., 1994). Neill et al. (1997) noted that forest conversion to pasture in Rondonia, Brazil had a large and predictable effect on pH and cation exchange capacity (CEC) due to plant-derived C inputs to surface soils, where soil pH in the top 10 cm increased by 1 to 2 units within 3-5 years and CEC showed a similar increase in young pastures. The finding revealed that land-use conversion from forest to pastures impacts on soil pH and CEC. FAO (2001) also noted that cation exchange capacity (CEC) increases as a function of increase in organic matter.

2.9 Potentials of Carbon Sequestration

The sequestration of organic carbon in soil indicates the addition of carbon, which involves the formation of complex organic structures with mineral materials. Reddy and Hodges (2000) outlined the major agricultural activities that may lead to enhancement of SOC content and thus C sequestration in cropland soils. They use conservation tillage, residue management, restoration of salt affected soils, and restoration of degraded lands, irrigation management and adoption of improved cropping systems, liberal use of organic amendments. Wetland rice cultivation represents the most complex system in relation to carbon sequestration (Golchin et al., 1994) where residue management is an important method of sequestering C in soil and increasing the soil organic matter content. Crop residues vary in their inherent decomposability due to differences in their physicochemical characteristics (Andren and Paustian, 1987).Thus, the use of different crop types represents a potential management control method of decomposition.

Tillage affects decomposition processes through the physical disturbance and mixing of soil, by exposing soil aggregates to disruptive forces, and through the distribution of crop residues in the soil (Oades, 1984; Elliot, 1986; Beare et al., 1994). Tillage also affects soil temperature, aeration and water relations by its impact on surface residue cover and soil structure (Paustian et al., 1997). By increasing the effective soil surface area and continually exposing new soil to wetting/drying and freezing/thawing cycles at the surface, tillage makes aggregates more susceptible to disruption and physically-protected inter-aggregate organic material becomes more available for decomposition (Elliott and Coleman, 1988; Beare et al., 1994). In this connection, Lal (2004a) additionally suggested that potentials for C sequestration include erosion prevention and control through conservation tillage and residue management, improved cropping systems, land restoration, land conversion and irrigation and water management. Lal (2004a) showed strategies of SOC sequestration through land use change and soil and vegetation management (Fig. 2.3).

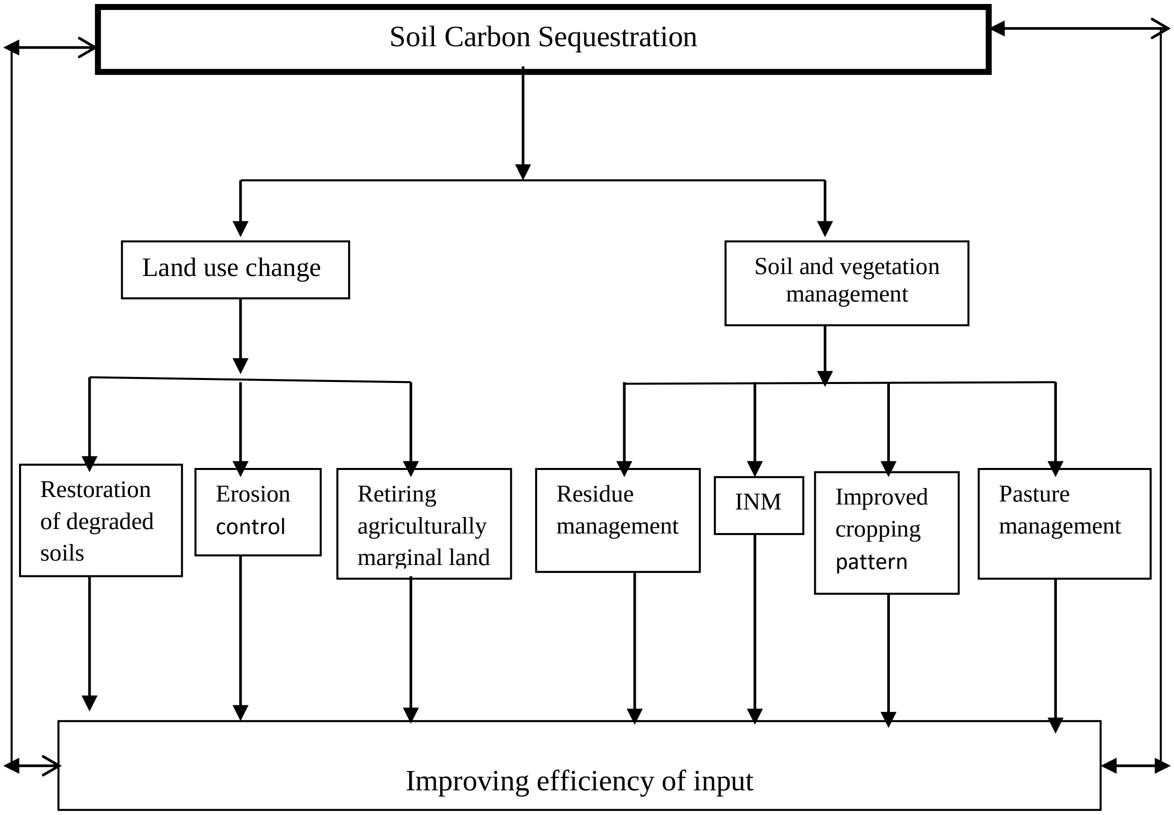

Figure 2.3: Strategies of soil carbon sequestration through land use change, soil and vegetation management (INM: Integrated Nutrient Management (Source: Lal, 2004a)

Changes in the soil organic carbon content result from carbon input (via plant litter and manure) and carbon loss (via decomposition and leaching).To bring out a net gain in C storage there must be an increase in the amount of carbon entering the soil or there must be suppression in the rate of soil carbon loss due to erosion, which redistributes carbon across the landscape.This way, upland landscapes may lose carbon while the lowlands may gain carbon but the overall situation is not likely to change from this redistribution. Breaking down of soil aggregates leads to rapid mineralization of carbon previously encapsulated within the aggregates. Hussain (2002) reported that four main strategies can be followed for increasing SOC in the agricultural lands of Bangladesh which were: (a) reduction in tillage intensity to control surface erosion, (b) reduction in use of cropping systems, (c) adoption of yield promoting practices including high doses of nutrients and amendment, and (d) re-establishment of permanent perennial vegetation like forestry and pasture.

The decomposition of SOC is also very fast, partly due to the local climate and also unsustainable land management practices. However, if properly managed, croplands in Bangladesh or elsewhere can be a major source for C sequestration. Aggregate formation and organic matter storage in soils are intimately associated with each other. The organo-mineral associations function as aggregate binding and stabilizing agents. The nature of various organo-mineral associations and their spatial locations within soil aggregates determine the extent to which SOC is physically protected and chemically stabilized which results in its storage. A close understanding of the nature and dynamics of organo-mineral associations are necessary for a better understanding of soil structural dynamics and of C cycling and sequestration in soils (Bruce et al., 1999). Likewise, Lehmann et al. (2007) noted that stabilization of C in soil is mainly achieved through two processes—clay-organic interactions and occlusion of these aggregates by clay particles. Thus, stabilizing C has great importance for biogeochemical cycles of an ecosystem as well as sequestration potential. Through adoption of holistic approaches and identifying and implementing appropriate policies, the vast potential of Bangladesh cropland to sequester carbon and mitigate greenhouse effect can be realized (Ali, 1997; Hussain, 2002). Soil organic carbon, like other components of an ecosystem should be considered as a valued commodity (Lal, 2006). The economic importance of SOC will depend on several on-site and off-site factors. In other words, SOC is a dynamic entity and is affected by many interacting factors. In the temperate region soils, according to Rasmussen and Collins (1991), the SOC accretion and humification are influenced by the following measures: (i) rate of biomass return through litter fall and crop residues, (ii) root biomass and its distribution with depth, (iii) activity of soil micro fauna, and (iv) soil management including the use of inorganic fertilizers and organic amendments.

Since agricultural soils in Bangladesh presently have very low organic carbon, there exists a very high potential for sequestering organic carbon because the average annual temperature and even hyperthermic nature (soil temperature $<25^0$ C) is suitable for crop growth throughout the year and the average annual rainfall is 2100 mm (Hussain, 2002) which is favourable for C sequestration – but loss too because that will inevitably cause erosion.Thus appropriate land management practices can enhance agricultural production as well as sequestration of organic carbon in soils to a significant extent. It is important to note that carbon sequestration in soils is a slow process and may take centuries to build up a stable stock of organic matter. From the above discussions, it is apparent that soils’ potential to sequester carbon appears to be linked with the formation of durable organo-mineral complexes leading to the stabilization of aggregates and imparting increased resistance to their breakdown by physical and chemical forces. The strength and stability of organo-mineral bonds tend to increase with complexity of organic compounds, possibly through more intimate physical interaction and chemical protection. Thus, a combination of physical occlusion and chemical recalcitrance (Cambardella and Elliott, 1992) likely results in the stabilization of SOC within the aggregate hierarchy.

2.10 Soil Carbon Sequestration and Global Food Security

Global hotspots of soil degradation with a high priority for soil restoration and C sequestration are Sub-Saharan Africa, central and south Asia, China, the Caribbean, and the savannas of South America (Lal, 2004b). Complete crop residue removal for fodder and fuel is common in south Asia and Africa. Thus, depletion of SOC stock from the root zone has adversely affected the soil productivity and environmental quality of these regions. Lal (2004b) highlighted that “the poor farmers passed on their suffering to the land through extractive practices where they cultivate marginal soils with marginal inputs, produce marginal yields and perpetuate marginal living and poverty.” As a source of nutrients for growing crops, the SOC pool is a means of production in subsistence farming systems of Sub-Saharan Africa, which accounts for only 2.5% of the fertilizer consumption and 2% of the world’s irrigated land area, both essential to SOC sequestration. Benefits of recommended management practices (RMPs) cannot be realized in severely degraded soils due to depletion of their SOC stock. Lal (2004b) also noted that an optimum level of SOC stock is needed to hold water and nutrients, decrease risk of erosion and degradation, improve soil structure and tilth, and provide energy to soil microorganisms. Fertilizer application is an important strategy of increasing crop yield in Sub-Saharan Africa (Pieri, 1986), but its effectiveness is enhanced when used in conjunction with crop residue mulch (Yamoah et al., 2002).

An increase in SOC stock increases crop yield even in high-input commercial agriculture (Bauer and Black, 1994) but especially in soils where it has been depleted (Johnston, 1986). High SOC stock is also needed to maintain consistent yields through improvements in water and nutrient holding capacity, soil structure and biotic activity. The critical limit of SOC concentration for most soils of the tropics is 1.1 % (Aune and Lal, 1997). Increasing SOC concentration from a low of 0.1-0.2 % to a critical level of 1.1 % is a major challenge for tropical ecosystems. Yet, a drastic reduction in the SOC pool in Sub-Saharan Africa and elsewhere must be reversed in order to advance food security (Lal, 2004b). The beneficial impact of increasing the SOC pool on soil quality and agronomic production is often more on degraded soils with severely depleted SOC pool than those with slightly or moderately depleted SOC reserves. Lal (2006) showed an estimate of the magnitude of increase in the crop yield in developing countries like Bangladesh (Table 2.22) with increase in SOC in the root zone at the rate of 1ton C/ha/yr. Lal (2004b) reported that an increase in SOC could enhance food production, which may help meet the current and projected food demands. He also introduced a vicious cycle of depleting SOC stock (Fig. 2.4) and crop yields, as well as degradation of soil and environmental quality, which ultimately scaled on poverty, malnutrition, hunger, and substandard living.

Table 2.22: Improvement in crop yields in developing countries by increase in soil organic carbon through adoption of recommended management practices (RMPs)

Crops	Potential yield increase (kg/ha per ton of SOC)
Maize (*Zea mays*)	200-400
Wheat (*Triticum aestivum*)	20-70
Soybean (*Glycine max*)	20-30
Cowpeas (*Vigna unguiculata*)	5-10
Rice (*Oryza sativa*)	10-50
Millet (*Pennisetum purpureum*)	50-60
Beans (*Phaseolus spp.)*	20-30

(Source: Lal, 2006)

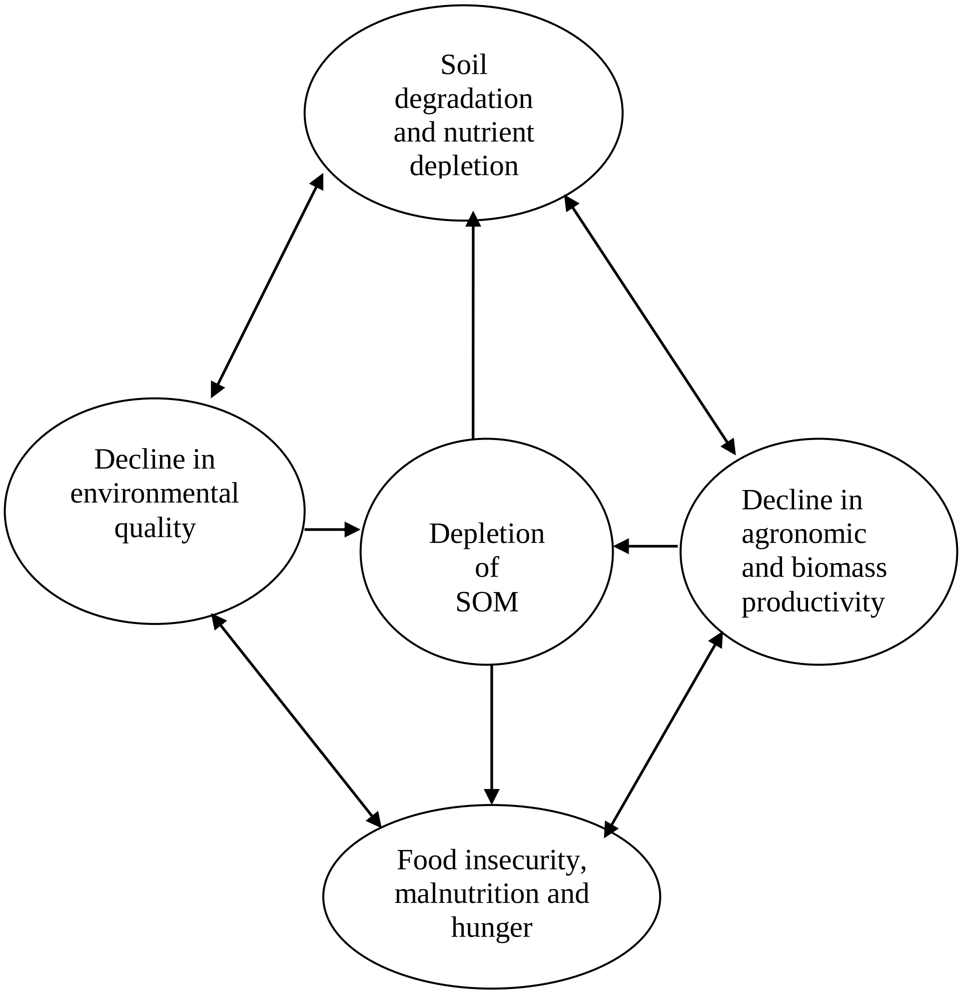

Figure 2.4: Vicious cycle of soil organic matter (SOM) depletion, declines in environmental quality, Agronomic and biomass productivity, enhancing food insecurity, malnutrition and hunger (Source: Lal, 2004b)

An important strategy of soil C sequestration is to reverse the degradative trends, restore degraded soils and ecosystems, and adopt RMPs on cropland and grazing land. Adopting sustainable land use is an important strategy of SOC sequestration (Singer et al., 2000). Research conducted in Central Asia has documented the impact of several technological options on improvement in soil quality and SOC pool (Table 2.23). Conservation agriculture in the broadest sense (e.g., elimination of intensive tillage and summer fallow, integrated nutrient management, efficient use of irrigation water, improved cropping systems) and phytoremediation of degraded soils and ecosystems are important options in enhancing SOC sequestration. Afforestation and improving degraded rangelands are equally important (Kuliev, 1996). The SOC concentration is often higher underneath the shrubs than around them (Zayed, 2000). Thus, tree species affect the SOC pool (Faituri, 2002) where pasture is another option in increasing SOC concentration. Teryukov (1996) observed in Western Kazakhstan that improved pastures should comprise a mixture of shrub species and perennial grasses. Grasses are especially important to enhancing soil fertility. In Uzbekistan, Mirzaev (1984) observed that green manures (winter pea, winter rape) together with N and P fertilizers and perennial grasses increased soil organic matter content. The conservation farming with residue mulch includes increasing the available water storage in the root zone by enhancing infiltration rate and reducing soil temperature (Bakajev et al., 1981), reducing evaporation losses (Al-Darby et al., 1990) and improving water-use efficiency (Lopez and Arrue, 1997). However, conservation farming or no till does not always produce the best yield, and the appropriate tillage methods may be soil and crop specific (Suleimenov et al., 1997; Hemmat and Oki, 2001). The effectiveness of enhancing the SOC pool and improving crop yield is accentuated by including legume-based rotations elimination of summer fallow, and controlled grazing (Jenkinson et al., 1999; Murrillo et al., 1998).

Soil C sequestration is a strategy to achieve food security through improvement in soil quality. It is a by-product of the inevitable necessity of adopting ‘recommended management practices (RMPs)’ for enhancing crop yields on a global scale.While reducing the rate of enrichment of atmospheric concentration of CO_2, soil C sequestration improves and sustains biomass or agronomic productivity. From a global policy perspective, it must be recognized that a programme that restores degraded croplands and increases soil carbon as well as contributing to reduction of atmospheric CO_2, represents an enormous opportunity. Such a programme could simultaneously increase agricultural productivity especially in developing countries and reduce the rate of climate change. Soil C sequestration is thus very cost effective and could take effect very quickly (FAO, 2008). It also constitutes a valuable win-win approach combining mitigation (CO_2 is removed from the atmosphere) and adaptation, through both increased agro-ecosystem resilience to climate variability and more reliable and better yields.

Table 2.23: Technological options for soil restoration and carbon sequestration in Central Asia

Technology	Ecosystems/Soil/ Terrain	Region/Country	References
Afforestation	Foothill plains	Balkan range	Lalymenka and Shadzhikov (1996)
Integrated Nutrient Management (INM)	Chernozem	Central Asia	Kogut et al. (1998)
Phyto amelioration	Degraded pasture	Kazakhstan	Teryukov (1996)
Rangeland restoration	Volga-Ural sands	Kazakhstan	Makulbekova and West (1996)
Soil reclamation	Solonetz soils	Kazakhstan	Okorokov and Abileva (1995)
Conservation or minimum tillage	Light and heavy soils	Kazakhstan, Monocco	Suleimenov et al. (2003) and Marabet (2002)
INM/Compost	Irrigated crops	Kyrgyzstan, Spain	Zoloev et al. (1993) and Coelho et al. (2002)
Organic farming	Ecological agriculture	Tajikistan, Egypt	Odinayev (1995), El-Shalweer et al. (1998)
No-till farming	Irrigated agriculture in sandy desert areas	Turkmenistan	Babaev and Ovezliev (1994)
Afforestation	Desertification control	Turkmenistan	Kuliev (1996)
Agroforestry	Plain and mountain	Uzbekistan	Alibekov (2000)
Phyto amelioration	Degraded rangeland	Uzbekistan	Reizvikh and West (1995)

2.11 Conclusion

Inappropriate land use and land management can render world soils as a major source of greenhouse gases. Soil degradation, caused by land misuse, ecologically incompatible farming systems, and inappropriate soil management practices, can be a major cause of fertility depletion and gaseous emissions from soil (Lal, 1999). Soil degradation and desertification are serious problems in several tropical ecosystems, especially in dry and hot climates. Soil degradation in the tropics is responsible for total emission of about 130 Tg C/yr. Tropical deforestation may cause an additional loss of 100 to 200 Tg C/yr (Lal, 1993). Total emission from soils of the tropics may be 0.5 Pg C/yr. In addition to increasing emissions of greenhouse gases from soils, soil degradation reduces the net primary productivity (NPP) of land, that is, the rate of carbon uptake by plants or biota from the atmospheric pool of carbon.

Consequently, the current rate of loss of carbon from plant and soils in the tropics is about 10 times that of temperate regions e.g., 2 Pg C/yr vs. 0.2 Pg C/yr (Houghton and Skole, 1990). Agricultural practices that exacerbate emission include: mechanized methods of deforestation, plough-till farming, continuous cropping on marginal lands and ecologically-sensitive eco-regions, low-input and resource-based shifting agriculture and subsistence farming leading to fertility depletion and soil degradation, and overgrazing. In contrast, agricultural practices that replenish SOC and restore soils capacity as a carbon sink include afforestation, conservation tillage and mulch farming, use of cover crops, judicious use of chemicals, agro-forestry etc.

World soils can be a major source or sink of atmospheric CO_2 depending upon the land use and management. Soils are an important sink of CO_2 and CH_4 through conversion to a restorative land use and adoption of RMPs which create positive C and elemental budgets. FAO (2001) reported that proper land management can profoundly affect soil C stocks and careful management can be used to sequester soil C. As with all human activities, the social dimension needs to be considered when implementing soil C sequestration practices. Since there will be increasing competition for limited land resources as world population increases, soil C sequestration cannot be viewed in isolation from other environmental and social needs. IPCC (2007) have noted that global, regional, and local environmental issues such as climate change, loss of biodiversity, desertification, stratospheric ozone depletion, regional acid deposition, and local air quality are inextricably related. The best option is to identify and undertake measures that increase C stocks whilst at the same time improving other aspects of the environment (improved soil fertility, decreased erosion, or higher profitability, improved yield of agricultural and forestry products). There are a good number of holistic approaches of management available that could be implemented to protect and enhance existing C sinks now and in the future.

The quantification of soil carbon losses and gains resulting from land use changes is a prerequisite to the understanding of greenhouse gases fluxes in different ecosystems (Eswaran, 1995). Modeling the fluxes of greenhouse gases, specifically due to land use changes, requires detailed knowledge of the factors regulating carbon and nitrogen cycles.Thus, C sequestration has gained momentum in the recent decade and the amount of C in a system is a good measure of sustainability. Estimates of C stocks with different land management and cropping systems are an important element in the design of land use systems that protect or sequester carbon (Bationo, 2004).

CHAPTER 3

Materials and Methods

This chapter outlines the materials and methods used in this PhD project as well as other relevant information. It includes soil sampling, laboratory methods, and data/spatial analysis.

3.1 Sampling synopsis

Three soil sampling strategies were employed in this PhD project. They were grid sampling, targeted composite sampling, and profile sampling. Grid sampling is a systematic method of soil sampling and is considered useful for mapping soil parameters' spatial variability within the sample site, and is thus helpful in spatial analysis. The purpose of using grid sampling was to map SOC spatial varibility by collecting 268 grid soil samples at the latitude and longitude intersection points by one-minute intervals.

Grid sampling can be very resource-intensive if the grid size is small, relative to the size of study area. A greater grid size may not capature the spatial structure and variability, leading to biasness and uncertainity in the data. Further limiations in grid sampling may arise where geographic features like settlements, industry, woodlands, water bodies, river channels and other infrastructue obstacles prevent sampling from the exact grid locations.

Composite soil sampling is a widely used technique that combines a number of discrete samples collected from a spatial location to make a single homogenized/composite sample. Here, targeted composite sampling was used because the previous sampling was done by the Soil Resource Development Institute (SRDI) of Bangladesh using the same methodology.This is essentially revisiting the previously sampled sites so that any change in SOC during the two sampling periods can be assessed. This part of the study, which is separate from the grid sampling described above, involved collecting 190 composite soil samples by revisiting the earlier sampled locations. While composite sampling is a widely used soil sampling method, one major drawback of such sampling technique is the variability around the sampling location is lost due to compositing. Ideally all samples collected from a location should be individually analysed to make better assessment i.e., mean and standard deviation. This however would have increased the number of samples by a factor of 5, as each compiste sample was comprised of 5 sample cores.

Soil profile sampling was used to assess the distribution and storage of SOC and TN in the whole soil profiles. Soil profile samplings can be done in three ways: horizon sampling, incremental sampling and fixed depth sampling. The profile sampling in this work followed fixed depth sampling.The main objective of this sampling was to account vertical SOC and total nitrogen (TN) storage and distribution. This resulted in 48 soil samples, collected based on 4 inundation land types across the two alluviums – 8 soil profiles in total, and the sampling depths were: 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, 80-100 cm, 100-120 cm.

The main limitation of the profile samping in this study is one soil profile from each land type from each alluvium is not likely to be representative of the land type. Ideally a soil profile should have been opened at each grid location (n=268) but that would have been very resource-intenstive and time-consuming. Nonetheless attempts were made to select these 8 soil profile locations in a way that under each inundation land type, land use, texture and cropping intensity were similar. It should be noted that the soil profile sampling was used mainly to supplement the information gathered from the grid sampling.

Overall, 506 soil samples (268 grid samples, 190 targeted composite samples and 48 soil profile samples) in the study.

3.1.1 Grid Sampling

Soil samples were collected in one-minute latitude and longitude interval (1 minute = 1600 m and 1 second = 26.5 m), equating to a grid size of 1600 m. Whilst a smaller size grid would have better captured the spatial variability, resource and time contraints prevented the use of a more intensive sampling strategy. GPS Magellan (Model: 320) was used to identify the geographic coordinates as well as sampling locations. Land and soil resource utilization guides (LSRUG) of the Soil Resource Development Institute (SRDI) were used as a base material during field visits and soil samplings. Four Upazilas or sub-sites (Delduar, Melandah, Fultala, and Mirpur) were selected across the two major alluviums of Bangladesh (Fig. 3.1) where they fall under the diverse agro-ecological regions. Delduar and Melandah Upazilas under the Brahmaputra alluvium covered 66 and 80 grid points respectively (Figs. 3.2-3.3). Mirpur and Fultala sub-sites under the Ganges alluvium covered 96 and 26 grid points respectively (Figs. 3.4-3.5). Thus, 268 soil samples were collected at the 0-30 cm depths (on a grid basis) across the four sub-sites. It may be noted that SOC is mainly concentrated in the upper 30 cm of the mineral soil horizon which may be readily depleted by soil erosion and anthropogenic activities. Inundation land types, soil texture, and drainage data were identified during field visit as described by FAO, (2006).

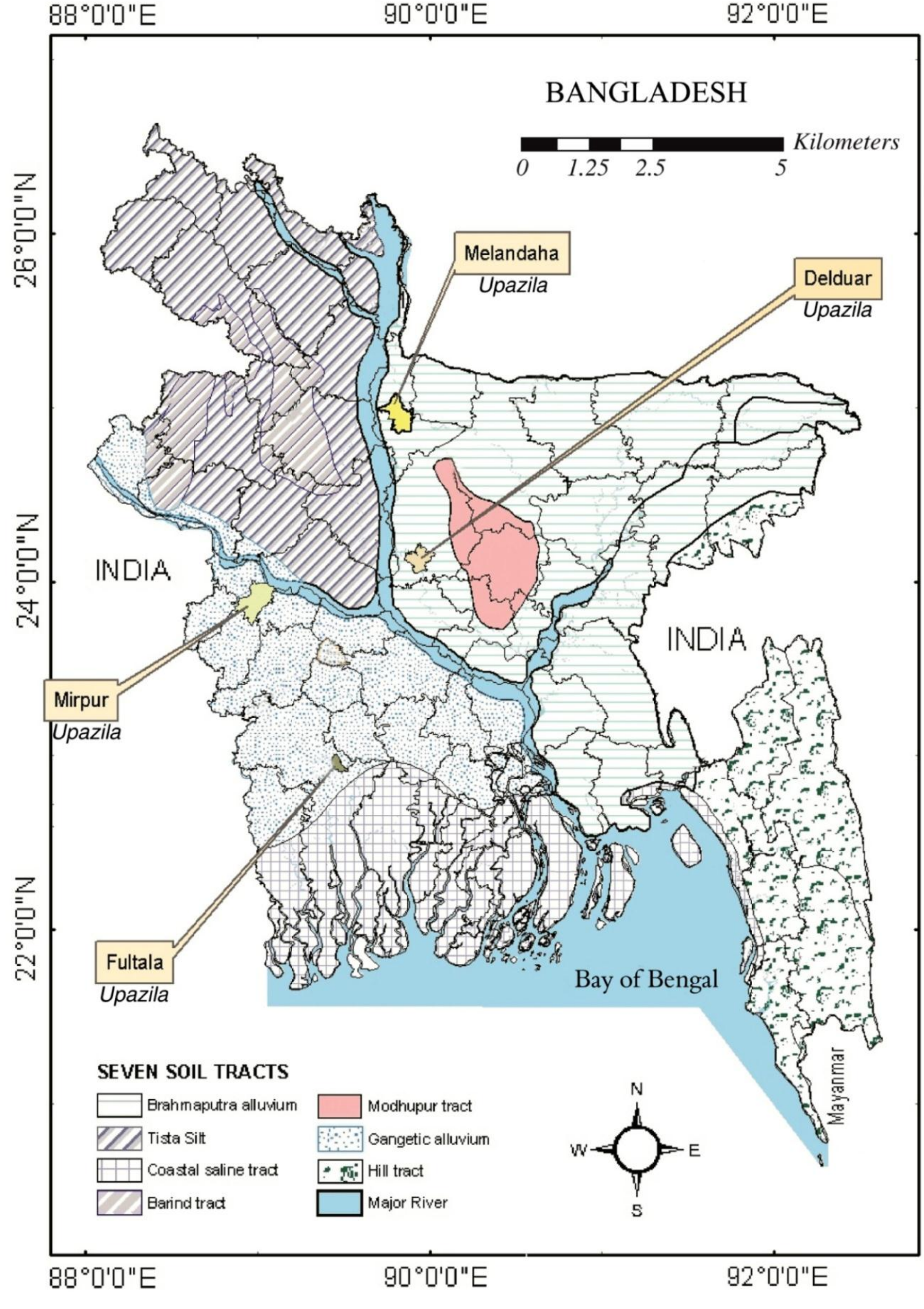

Figure 3.1: Location maps of the four sub-sites across the Brahmaputra and the Ganges alluviums of Bangladesh

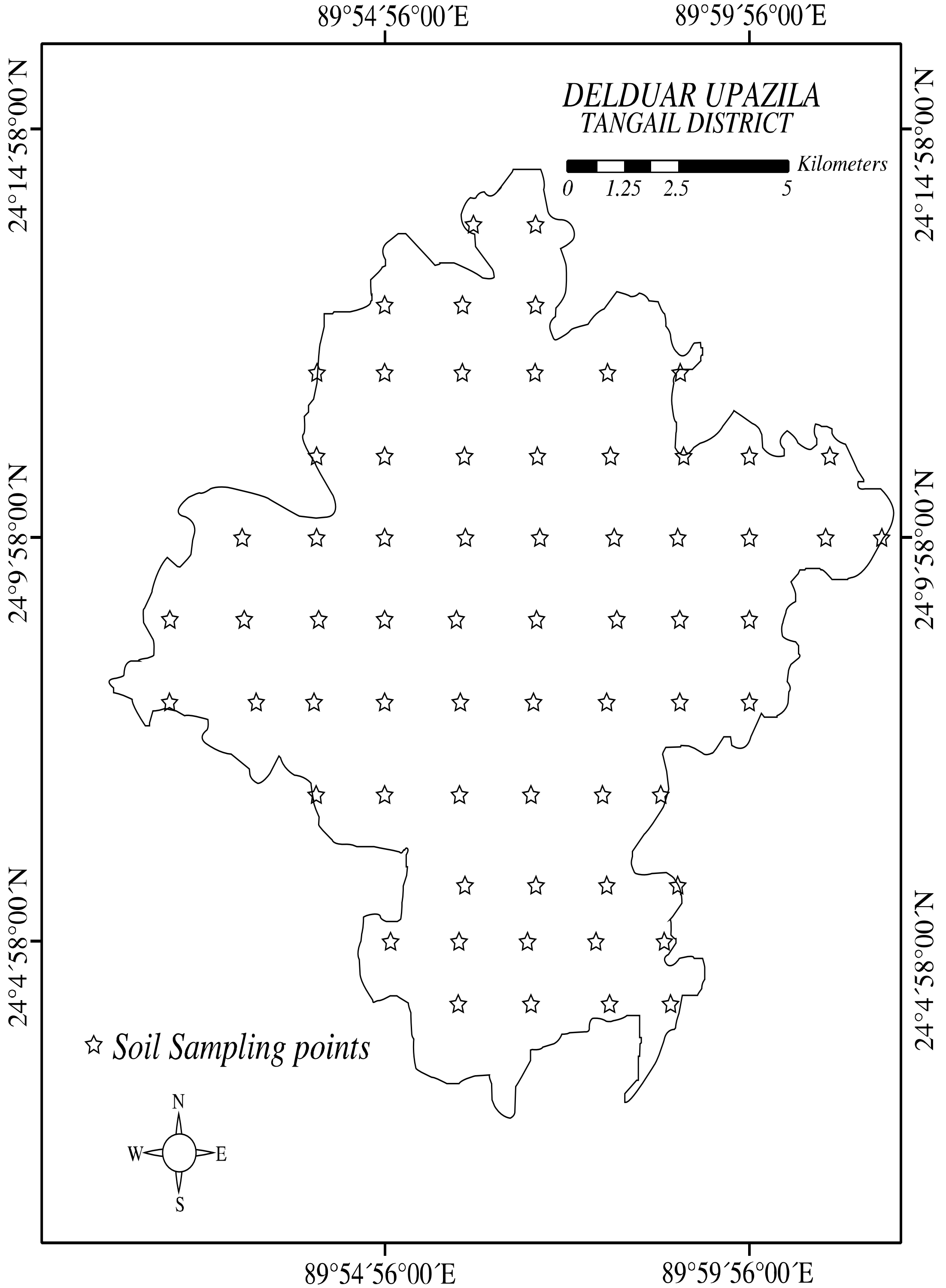

Figure 3.2: Soil sampling sites across the Delduar sub-site of the Brahmaputra Alluvium

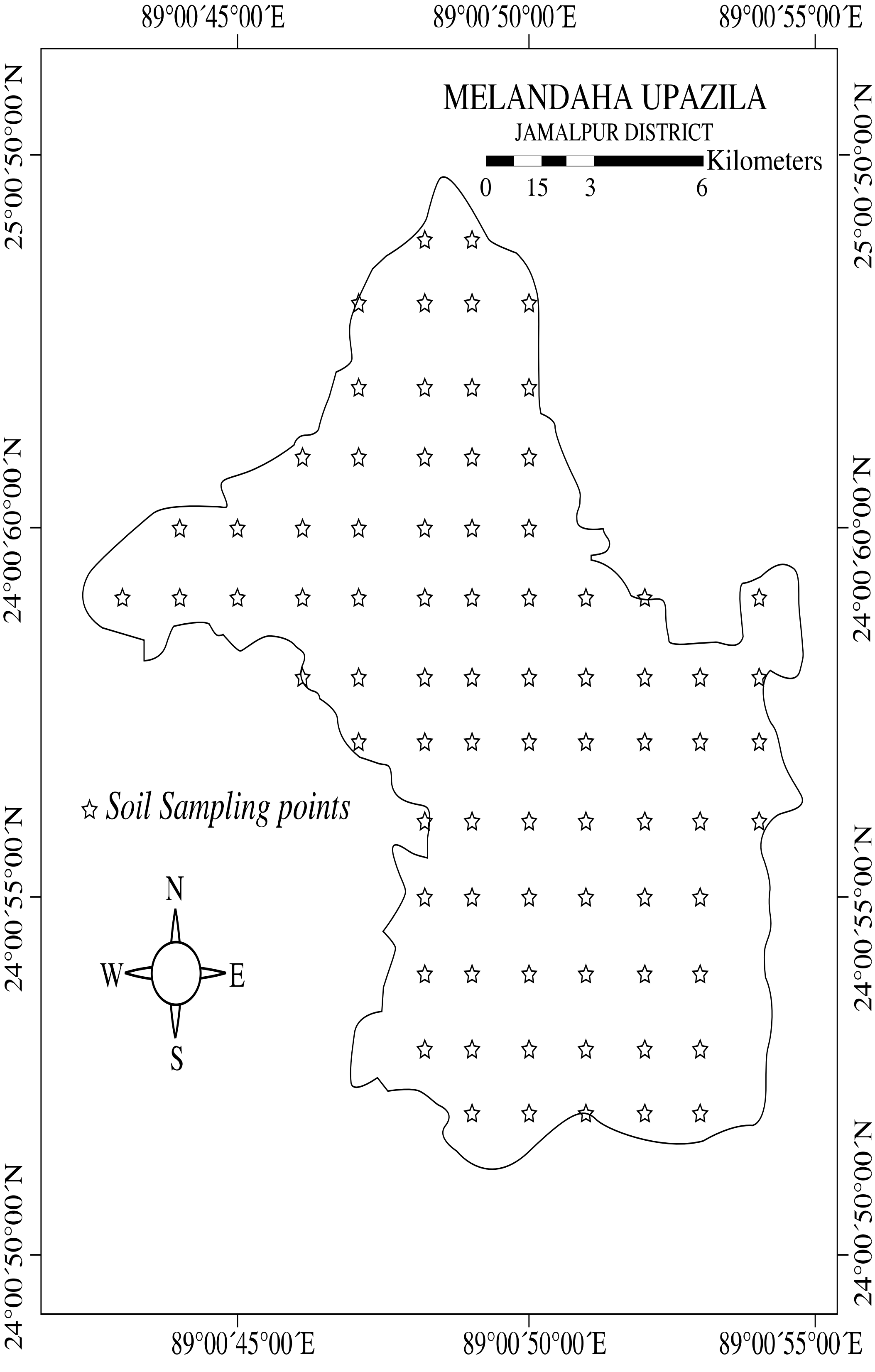

Figure 3.3: Soil sampling sites across the Melandah sub-site of the Brahmaputra Alluvium

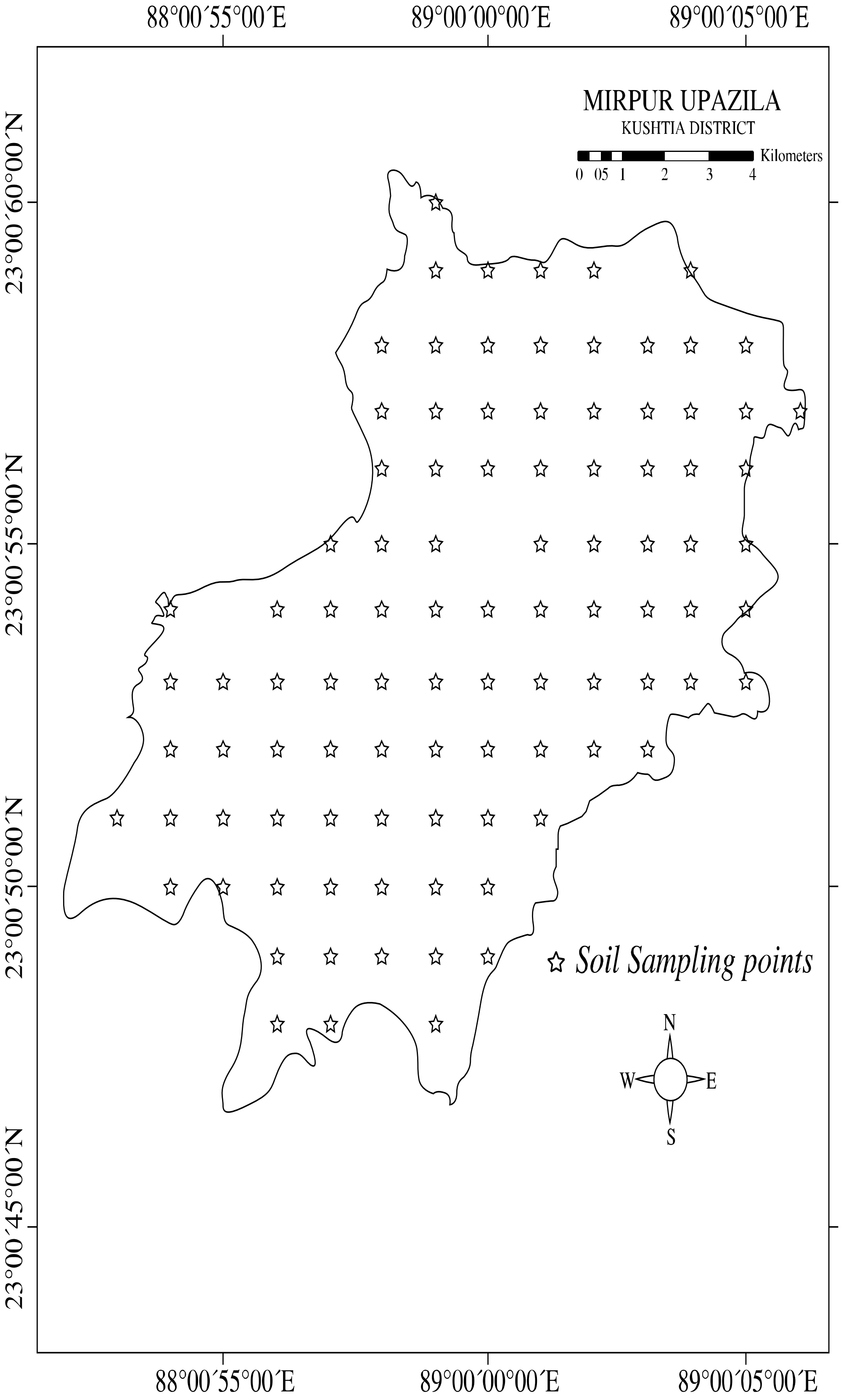

Figure 3.4: Soil sampling sites across the Mirpur sub-site of the Ganges Alluvium

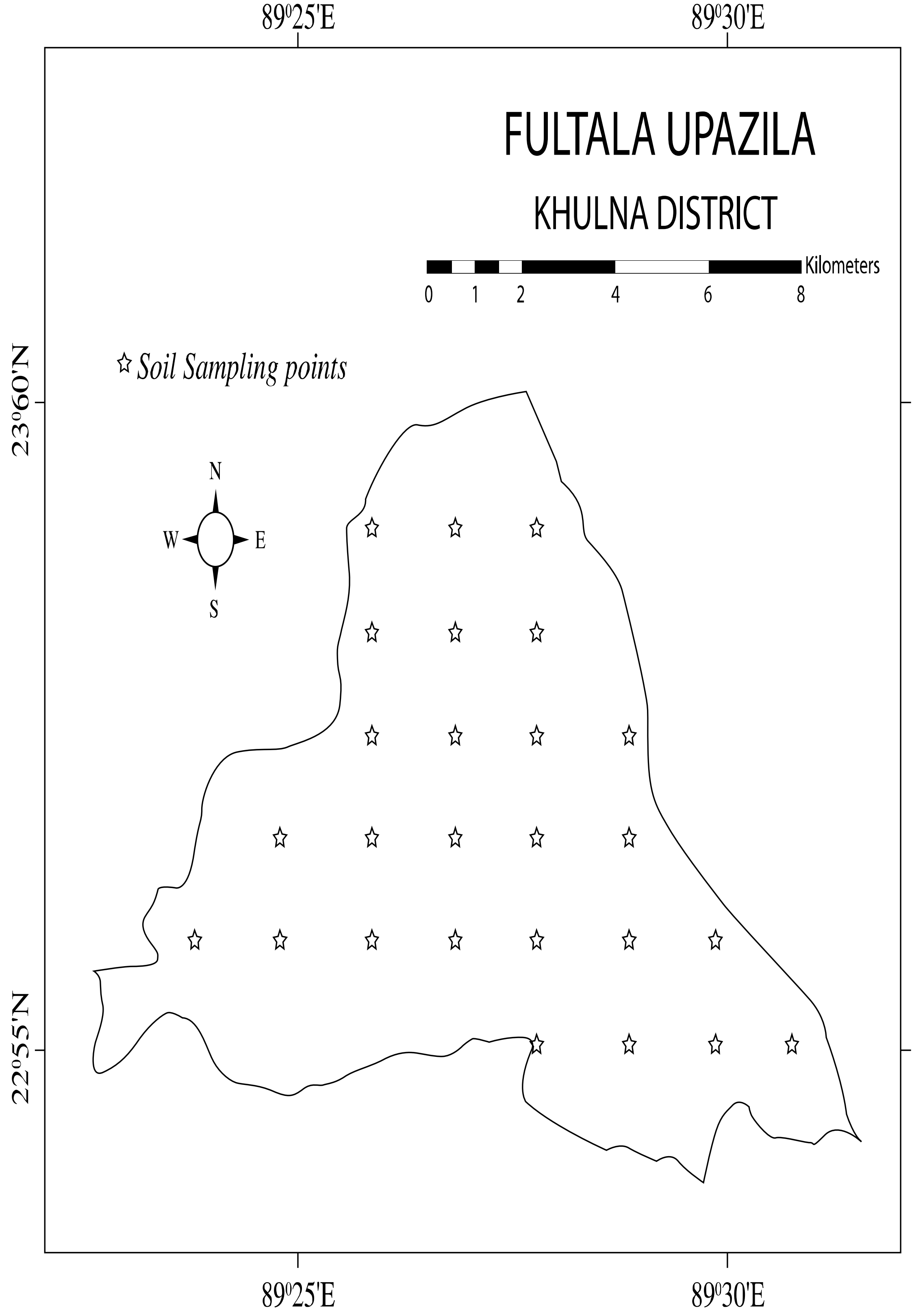

Figure 3.5: Soil sampling sites across the Fultala sub-site of the Ganges Alluvium

3.3.1.1 Spatial Analysis

In the spatial analysis, geostatistical methods such as semivariogram construction, kriging, and mapping have been widely used. A flow chart as shown below depicts the procedural steps in the spatial analysis (Fig. 3.6). The semivariogram analysis was estimated using the software Gamma Design (Robertson, 2008). Data interpolation through kriging and Inverse Distance Weighting (IDW) were performed in ARCGIS 9.3 (ESRI, 2000). When the spatial structure is strong, krig interpolation was done and on the other hand, when the spatial structure is weak, then IDW interpolation was used. Details on semivariogram model, its parameters, and data interpolation are discussed in Chapter 4.

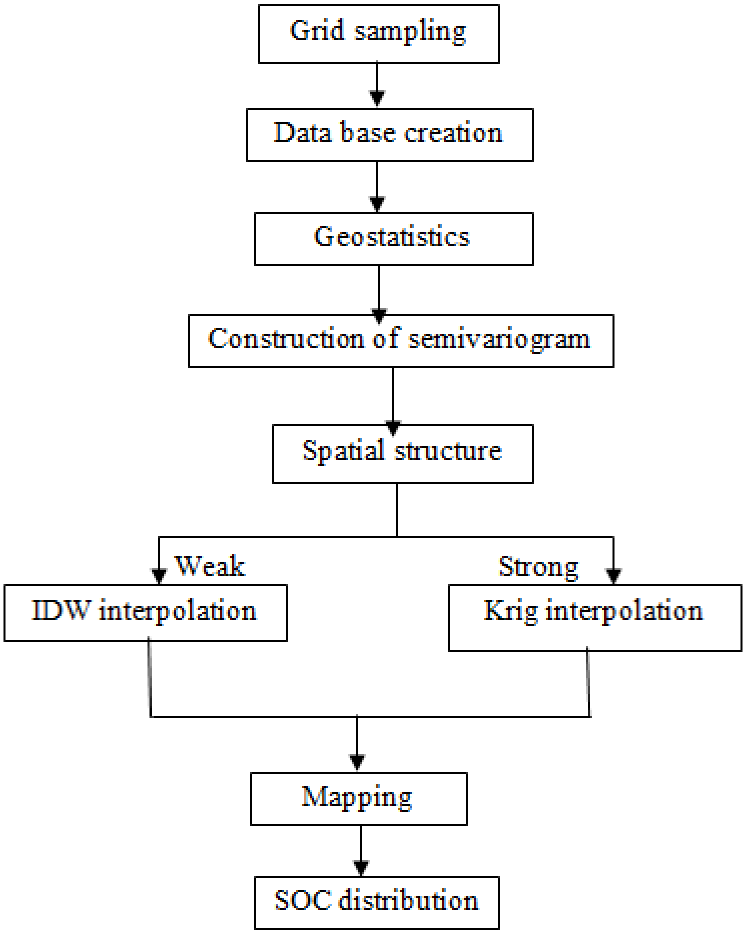

Figure 3.6: Flow chart showing the geostatistics and data interpolation of SOC in the study sites

3.1.2 Composite Sampling

A total of 190 composite (0-30cm) soil samples were collected from the four sub-sites under the two major alluviums. These sites were previously sampled by the Soil Resource Development Institute (SRDI) during the period between 1989 and 1992. The main purpose of revisiting these previously sampled locations was to assess the changes in SOC and cropping intensity (CI) between the two sampling periods i.e., 1989/92 and 2012. The land and soil resource utilization guide (LSRUG) maps of SRDI were used in the field for revisiting the sampling sites. These LSRUG maps were used to identify the sampling location by geo-coordinates (using latitudes and longitudes) in the respective sites. Global Positioning Systems (GPS) device was used in the field to locate the exact locations of the sampling sites. At each location, five randomly slected soil cores were collected with a 10m radius; they were mixed together to form a composite sample for the location.

3.1.3 Profile Sampling

Forty eight soil samples from four inundation land types under the two alluviums (eight soil profiles in total) at different soil depths (0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, 80-100 cm and 100-120 cm) were collected. These samplings at different soil depths were used for the purpose of SOC and TN storage and distribution as affected by soil depths and inundation land types. The inundation land type is a unique feature in Bangladesh and has to be taken into account in land management (FAO-UNDP, 1988). In Bangladesh, five categories of inundation land types were identified by FAO-UNDP (1988). These were highland (HL), medium highland (MHL), medium lowland (MLL), lowland (LL), and very lowland (VLL), as outlined in Table 3.1.

Table 3.1: Classification of land types in Bangladesh based on inundation flood level

Land Types	Flooding depth	Bangladesh % (Total)	Brahmaputra Alluvium (%)	Ganges Alluvium (%)
Highland (HL)	Land which is above normal flood level	29	1.6	4.2
Medium highland (MHL)	Land which normally is flooded up to about 90 cm deep during the flood season	35	12.2	13.7
Medium lowland (MLL)	Land which normally is flooded up to between 90 cm and 180 cm deep during the flood season.	12	2.4	2.4
Lowland (LL)	Land which normally is flooded up to between 180 cm and 300 cm deep during the flood season.	8	3.6	<1
Very lowland (VLL)	Land which is normally flooded deeper than 300 cm during the flood season.	1	1.0	<1

These inundation land types are regarded as the biophysical units of a landscape. Thus, four soil profiles along with their present land uses of the Brahmaputra alluvium were shown in plates 3.1-3.4. Another four soil profiles along with their present land uses of the Ganges alluvium were shown in plates 3.5-3.8.

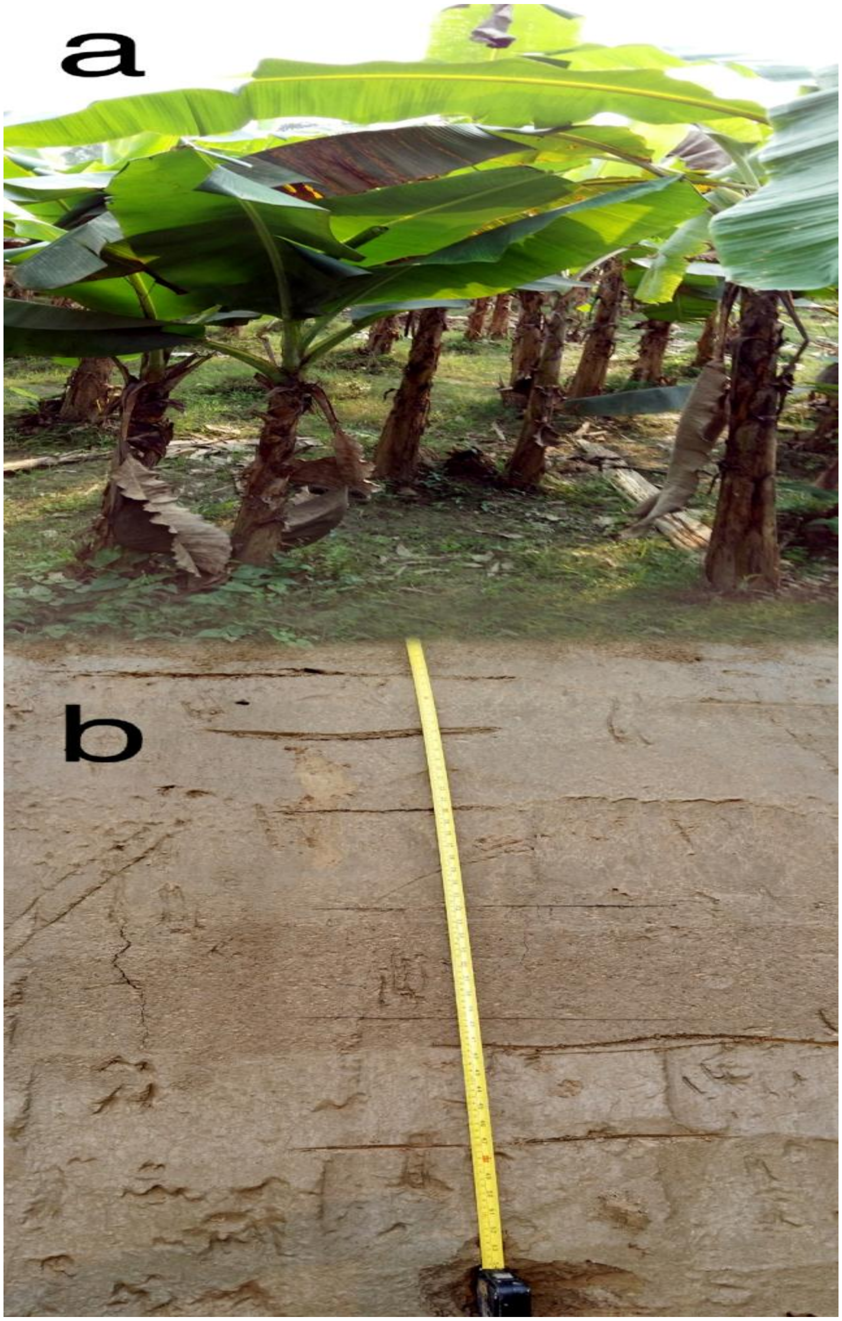

Plate 3.1: Highland (HL) site of the Delduar sub-site under the Brahmaputra Alluvium: (a). Banana plantation-Fallow as present land use/cover; (b) Sonatala soil profile

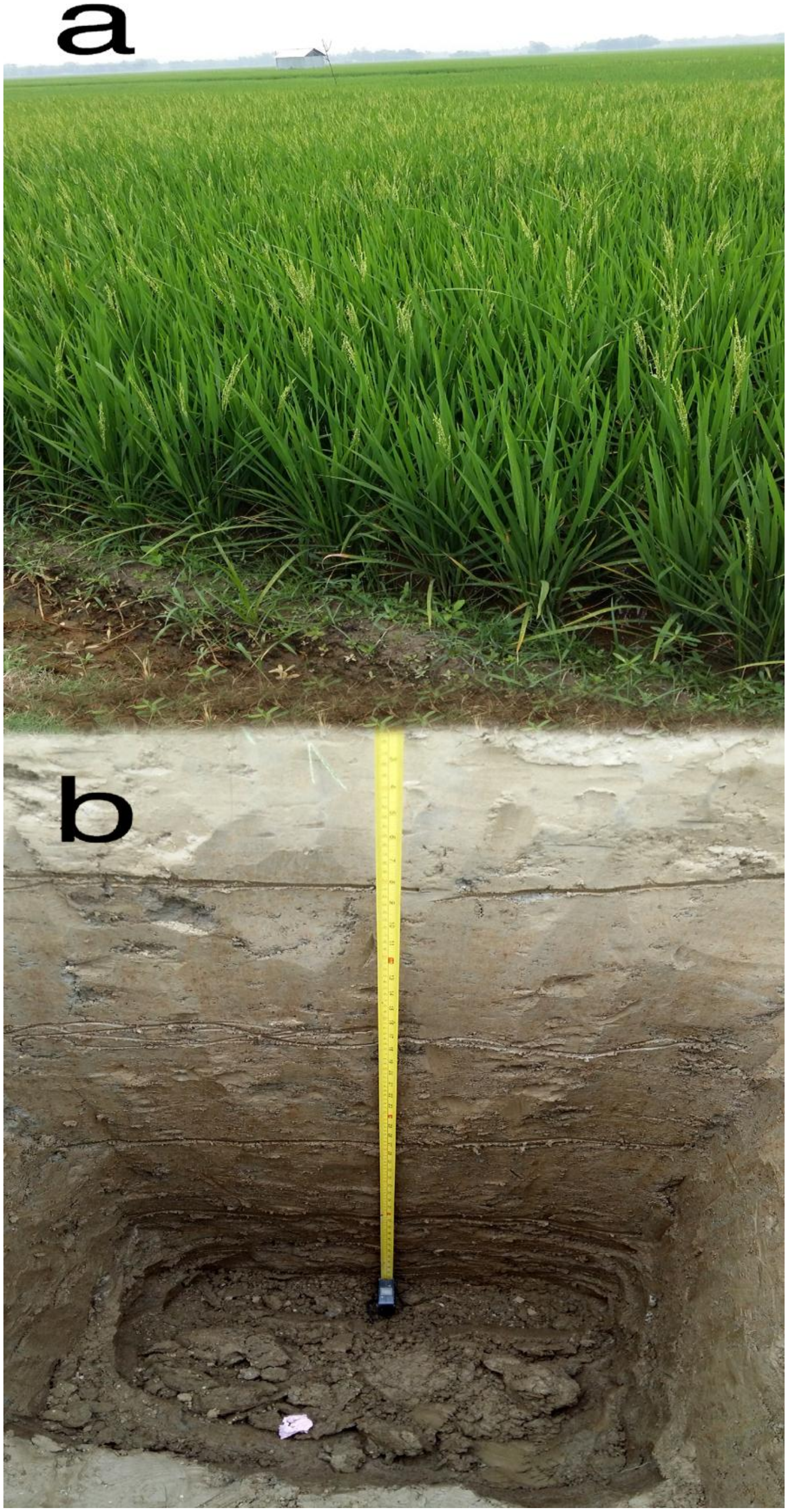

Plate 3.2: Medium highland (MHL) site of the Delduar sub-site under the Brahmaputra alluvium: (a). HYV Boro rice-T. Aman rice as present land use/cover; (b) Silmandi soil profile

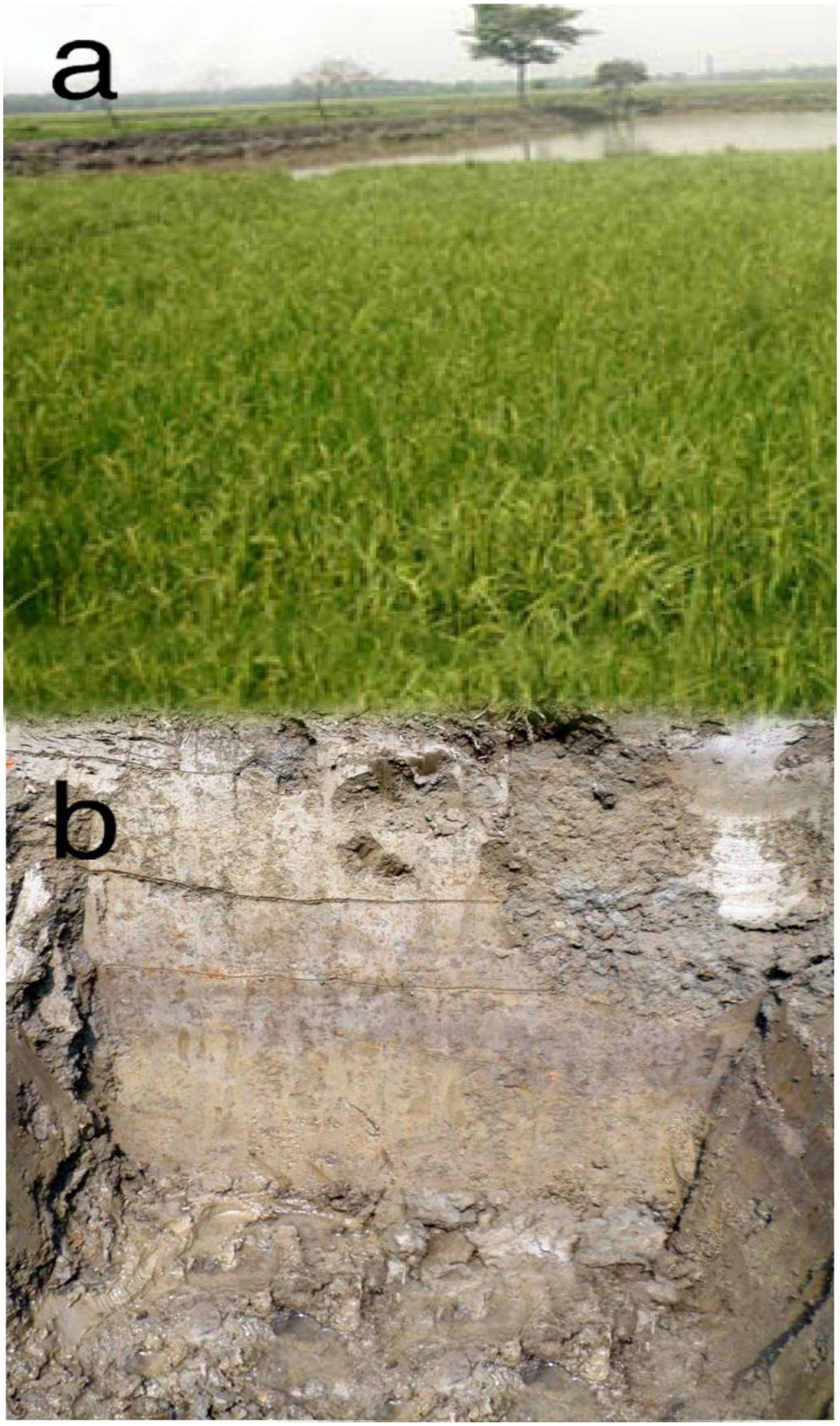

Plate 3.3: Medium Lowland (MLL) site of the Delduar sub-site under the Brahmaputra alluvium: (a) HYV Boro rice- Fallow as present land use/cover; (b) Ghatail soil profile

Plate 3.4: Lowland (LL) site of the Delduar sub-site under the Brahmaputra alluvium:
(a) HYV Boro rice-Fallow/grazing grass as present land use/cover; (b) Balina soil profile

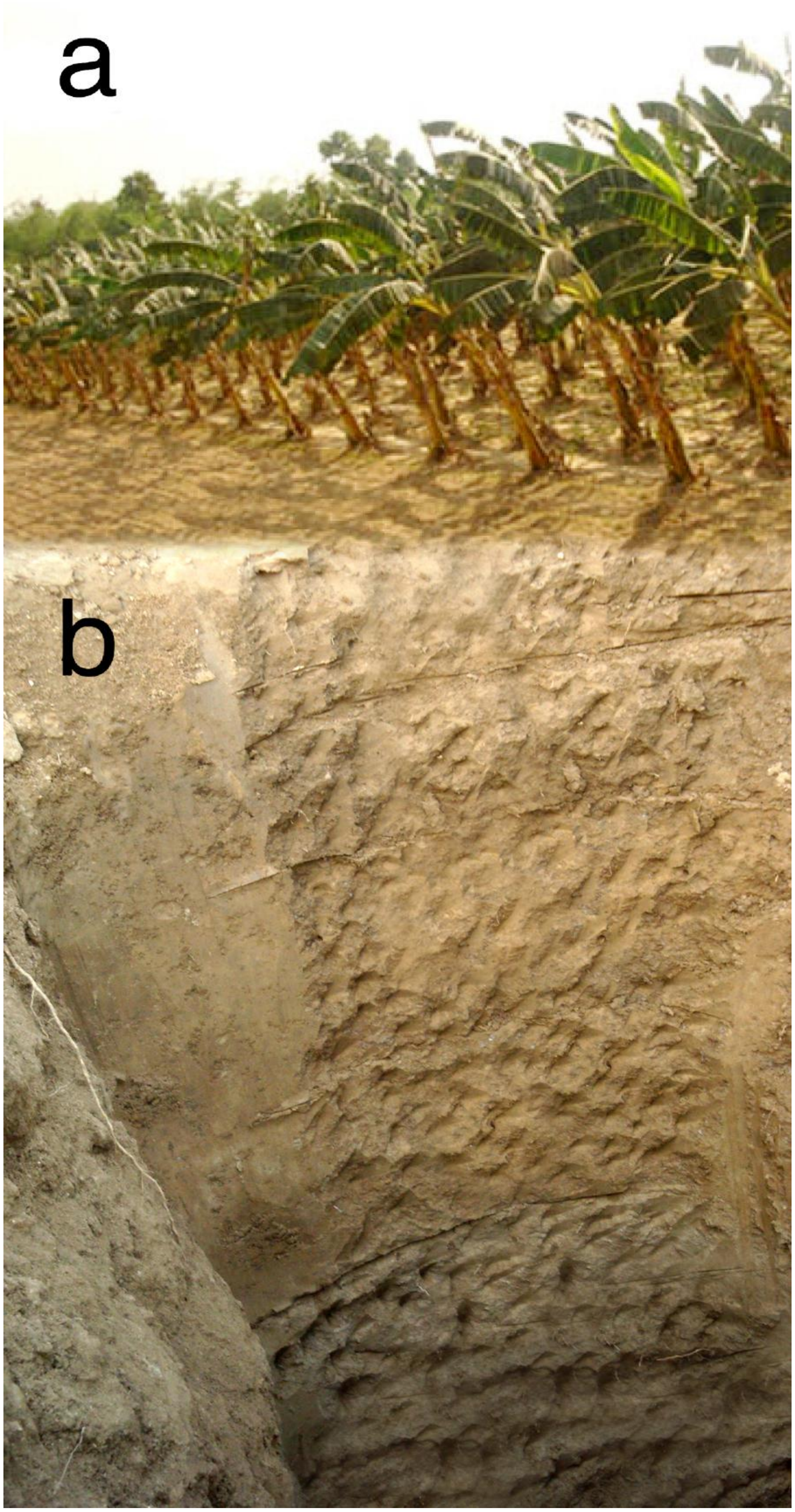

Plate 3.5: Highland (HL) site of the Mirpur sub-site under the Ganges alluvium:
(a) Banana/Orchards-Fallow as present land use/cover; (b) Sara soil profile

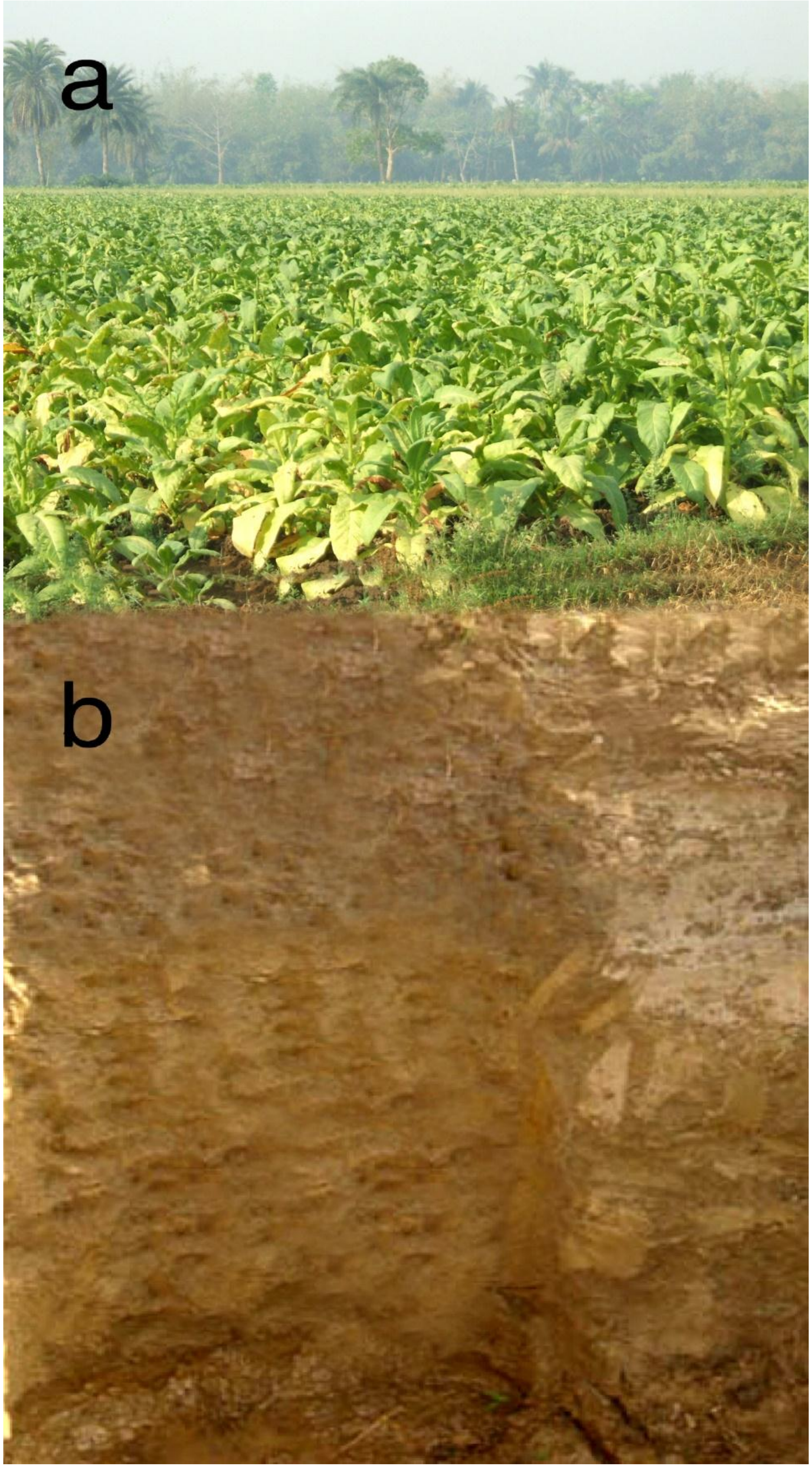

Plate 3.6: Medium Highland (MHL) site of the Mirpur sub-site under the Ganges alluvium: (a) HYV Boro rice- Tobacco/T. Aman rice/Pulses as present land use/cover; (b) Ishurdi soil Profile

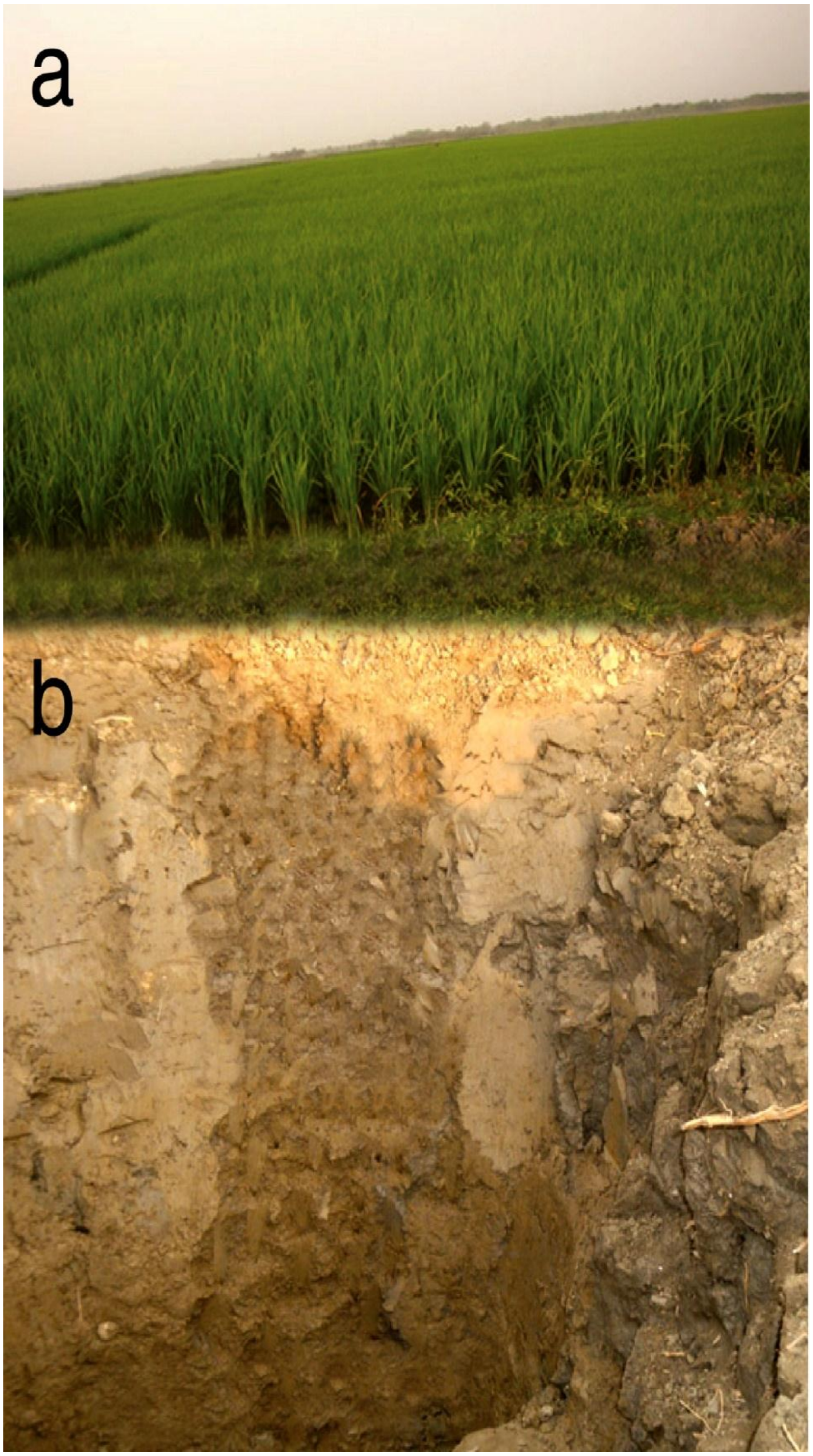

Plate 3.7: Medium Lowland (MLL) site of the Mirpur sub-site under the Ganges alluvium: (a) HYV Boro rice-T. Aman rice/Fallow as present land use/cover; (b) Gheor soil profile

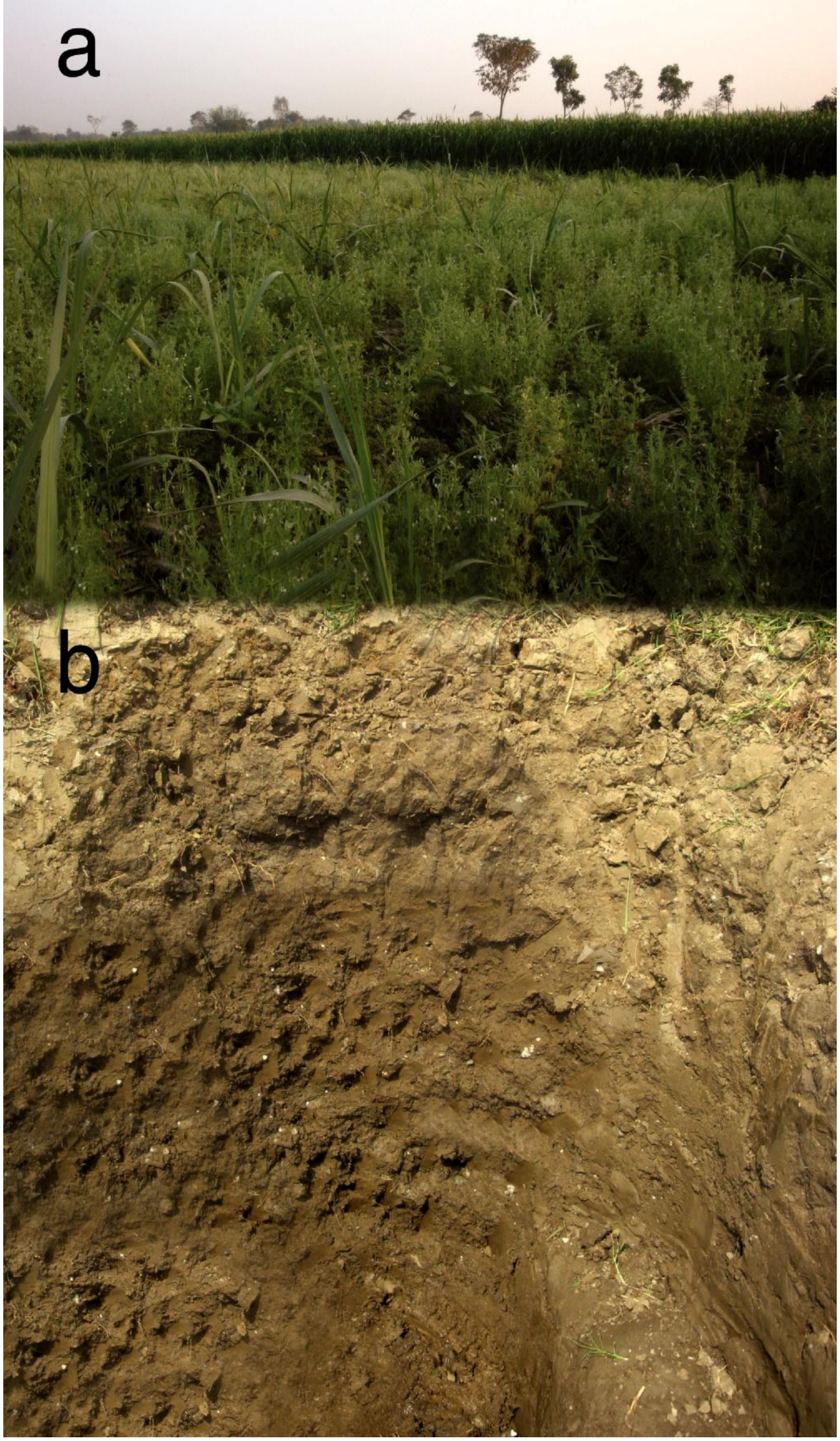

Plate 3.8: Lowland (LL) site of the Mirpur sub-site under the Ganges alluvium:
(a)T. Aman rice/Rabi vegetables-Fallow as present land use/cover; (b) Garuri soil profile

3.2 Sample Processing

Soil samples from each sampling strategy (grid, composite and soil profile sampling) site and each soil depths were collected in polythene sample bags. The bags were sealed properly precluding moisture loss from the samples and transferred as quickly as possible to the laboratory for relevant analyses. Prior to analysis, the representative soil samples were spread on a polythene sheet and big lumps were broken and air dried under shade. The soil samples were then gently ground by rolling a wooden rod and also with a wooden hammer, passed through a 2-mm (10 mesh) sieve, and mixed thoroughly. The samples were then preserved in plastic bags for laboratory analysis.

3.3 Analytical Methods

Soil Organic Carbon (SOC): Organic carbon in soil was determined by the wet oxidation method of Walkley and Black (1934) as described by Nelson and Sommers (1982). Organic C determinations are often used as the basis for organic matter estimates through multiplying the organic C value by a factor. It may be noted that the Van Bemmelen factor of 1.724 was used on the assumption that organic matter contains 58% organic carbon.

Soil pH: 20 gm of air-dry soil sample was taken in a beaker and 50 ml of distilled water was added. The contents were mixed thoroughly with a glass rod and allowed to stand for one hour. The soil pH was then measured in a calibrated Hanna-212 pH meter (Page et al., 1982).

Bulk Density: Soil bulk density is the ratio of the oven-dried mass of soil to its volume either at time of sampling or at specified moisture content. It is usually expressed in terms of grams per cubic centimeter (g/cm^3). Bulk density was measured by the core method as described by Blake and Hartge (1986).

Particle Size: Particle size distribution was determined by hydrometer method after pretreatments as described by Gee and Bauder (1986). Soil textural class was determined using USDA texture triangle.

Total Nitrogen (TN): TN was determined using Micro-Kjeldahl apparatus as illustrated by Bremner and Mulvaney (1982).

SOC and TN stock or storage: The SOC and TN storage were calculated using the equations of Batjes, (1996); Chen et al. (2007) and Zhang et al. (2013), the details of which are given in chapter 7.

CHAPTER 4

Spatial Variability of Soil Organic Carbon in the Agricultural Soils

4.1 Introduction

Soils are inherently variable over time and space; therefore, an understanding of the distribution of soil properties at the field scale is important for refining agricultural management practices and assessing the effects of agricultural land use on soil quality (Cambardella et al., 1994). Natural variability of soil results from complex interactions between geology, topography, climate as well as soil use (Jenny, 1980; Quine and Zhang, 2002). As a consequence, soils can exhibit marked spatial variability (Brejda et al., 2000; Vieira and Paz-Gonzalez, 2003). Soils are characterized by the high degree of spatial variability due to the combined effect of physical, chemical or biological processes that operate at different intensities and scales (Goovaerts, 1998). Soil chemical and physical properties are highly variable, often displaying spatial structure over many scales of observation (Grigal et al., 1991; Goovaerts, 1998; Ettema and Wardle, 2002). The causes of this spatial heterogeneity are diverse and include both abiotic and biotic processes (Stark, 1994).

Soil organic carbon (SOC) has an important influence on the physical, chemical and biological properties of soil and is critical for improving soil fertility and quality, increasing the water holding capacity of soil, reducing soil erosion, and enhancing crop productivity (Rossi et al., 2009; Wang et al., 2010). With climate change and environmental issues dominating global concerns, SOC has received increasing attention worldwide because of its important role in the global carbon cycle and its potential feedback on the global warming (Schlesinger et al., 1996; Amundson, 2001; Davidson and Janssen, 2006; Su et al., 2006). As one of the largest and most dynamic components in the global C cycle, the SOC stock is at least two times the amount of C stored in the vegetation and atmospheres (IPCC, 2000).Thus a small loss of SOC pool due to changes in fertilization, cropping system, farming practices, and soil erosion could significantly increase the atmospheric CO_2 (Li et al., 2004; Zhang and McGrath, 2004; Don et al., 2007; Liu et al., 2011).

Reliable assessment of the spatial patterns of SOC is essential for understanding the potential of soils to sequester C, for quantifying the SOC sink or source capacity of soils in changing environments, and for developing strategies to mitigate the effects of global warming (Venteris et al., 2004; Hoffmann et al., 2012). A better understanding of the spatial variability of SOC is also important for refining agricultural management practices and for improving sustainable land use. It provides a valuable base against which subsequent and future measurements can be evaluated (Liu et al., 2006).

Soil organic carbon and its relation to site characteristics is important in evaluating regional, continental, and global soil C stores and projecting future changes (Feng et al., 2002). However, due to high soil heterogeneity, it is difficult to obtain an accurate assessment of SOC stock (Don et al., 2007). As a result, there is a considerable interest in understanding the spatial variability of SOC in different terrestrial ecosystems (Arrouays et al., 2001; Liu et al., 2006). Geostatistics has been widely used to assess the spatial characteristics of SOC (Evrendilek et al., 2004). SOC is a determinant of SOC stock (Don et al., 2007), and its spatial distribution is intimately related to the changes in environmental factors (Wheeler et al., 2007; Throop and Archer, 2008). However, the relative importance of the edaphic factors as drivers or constraints of spatial heterogeneity of SOC content in the alluvium soils of Bangladesh is not well understood.

Describing the spatial variability has been difficult until new technologies such as Global Positioning Systems (GPS) and Geographic Information Systems (GIS) were introduced. The emphasis of spatial analysis is to measure properties and relationships, taking into account the spatial localization of the phenomenon under study. GIS is useful to produce interpolated maps for visualization, and for raster GIS maps; algebraic functions can calculate and visualize the spatial differences between the maps (Wang et al., 2008). For studies on the spatial distribution patters of SOC, geostatistics have been widely applied (Saldana et al., 1998; McGrath and Zhang, 2003; Sepaskhah et al., 2005; Liu et al., 2006) and based on the theory of regionalized variables (Webster and Oliver, 2007), geostatistics provides tools to quantify the spatial features of soil parameters and allows for spatial interpolation.

This study makes use of GIS in combination with classical statistics and geostatistics to assess the spatial variation characteristics of SOC in the Brahmaputra and the Ganges alluvium of Bangladesh. The specific objectives of this chapter were (i) to estimate the SOC contents in the study sites; (ii) to reveal the spatial variability or distribution of SOC through semivariogram models; (ii) to make the spatial distribution of SOC through spatial interpolation in the study sites.

4.2 Materials and Methods

4.2.1 Description of the Study Area

The study sites are situated in the Bengal basin; the Ganges-Brahmaputra (G-B) delta (Fig. 4.1) represents the world's largest delta system, comprising about 100,000 km^2 of riverine channels, floodplains, and delta plains. An important feature of this G-B delta system is the huge sediment load of about 1 billion tonnes/year delivered to the basin (Goodbred et al., 2003). The Bengal Basin in the northeastern part of Indian sub-continent, between the Indian Shield and Indo-Burman Ranges, comprises three geo-tectonic provinces: (1) The Stable Shelf, (2) The Central Deep Basin and (3) The Chittagong–Tripura Fold Belt (Fig. 4.1). Due to location of the basin at the juncture of three interacting plates, viz., the Indian, Burma and Tibetan (Eurasian) Plates, the basin-fill history of these geo-tectonic provinces varied considerably. Precambrian Meta sediments and Permian–Carboniferous rocks have been encountered in the stable shelf province. After Precambrian peneplanation of the Indian Shield, sedimentation in the Bengal Basin started in isolated graben-controlled basins on the basement. With the breakup of Gondwanaland in the Jurassic and Cretaceous, and northward movement of the Indian Plate, the basin started downwarping in the Early Cretaceous and sedimentation started on the stable shelf and deep basin and since then sedimentation has been continuous for most of the basin. Subsidence of the basin thus attributed to differential adjustments of the crust, collision with the various elements of south Asia, and uplift of the eastern Himalayas and the Indo-Burman Ranges. Movements along several well-established faults were initiated following the breakup of Gondwanaland and during downwarping in the Cretaceous.

By Eocene, because of a major marine transgression, the stable shelf came under a carbonate regime, whereas the deep basinal area was dominated by deep-water sedimentation. A hinge zone-demarcated the stable shelf and the deep basinal area (Fig 4.1). A major switch in sedimentation pattern over the Bengal Basin occurred during the Middle Eocene to Early Miocene as a result of collision of India with the Burma and Tibetan Blocks. The influx of clastic sediment into the basin from the Himalayas to the north and the Indo-Burman Ranges to the east rapidly increased at this time; and this was followed by an increase in the rate of subsidence of the basin. At this stage, deep marine sedimentation dominated in the deep basinal part, while deep to shallow marine conditions prevailed in the eastern part of the basin. By Middle Miocene, with continuing collision events between the plates and uplift in the Himalayas and Indo-Burman Ranges, a huge influx of clastic sediments came into the basin from the northeast and east. Throughout the Miocene, the depositional settings continued to vary from deep marine in the basin to shallow and coastal marine in the marginal parts of the basin. From Pliocene onwards, large amounts of sediment were filling the Bengal Basin from the west and northwest; and major delta building processes continued to develop the present-day delta morphology.

Thus, the Bengal basin is being thus deformed by the Indo-Burman fold belt that impinges from the east and the over thrust block of Shillong Massif to the north. This compressional deformation and associated faulting has forced the uplift of terraces in the various parts of the regions (Barind tract, Madhupur terrace, and Comilla terrace etc.; Fig. 4.1). These features partition the delta into sub basins that are often poorly connected and thus lead to alternating sediment inputs and starvation as the rivers avulse to different portions of the delta system. Another important feature in the Bengal basin is the 'Swatch of No Ground' (Fig. 4.1) which represents a shelf canyon that deeply incises the Bengal shelf near the Ganges-Brahmaputra river mouth, cuts the forestbeds of the subaquous river delta and acts as temporary depocenter between river mouth and Bengal fans.

The current research was conducted across the two major alluviums—the Brahmaputra and the Ganges—as much of the agricultural land in Bangladesh belongs to these two alluviums. Table 4.1, summarizes the geographic location, soils, the mean annual temperature and precipitation, soil types, and nature of parent materials of study sites.

Table 4.1: Geographic location, area, and climate and soil information across the alluviums

Study sites	Sub sites	Geographic locations	Area (ha)	Annual mean T ˚C* and ppt** (mm)	Soil types	Nature of parent materials
Brahmaputra Alluvium	Delduar	23˚ 14′ to 24˚ 03′ N; 89˚ 50′ to 90˚ 02′ E	18,097	25.2˚C; 2275 mm	Inceptisols and Entisols	Non-calcareous
	Melandah	24˚ 51′ to 25˚ 04′ N; 89˚ 43′ to 89˚ 54′ E	23,992	25.6˚C; 2275 mm	Inceptisols and Entisols	Non-calcareous
Ganges Alluvium	Fultala	22˚ 54′ to 23˚ 01′ N; 89˚ 23′ to 89˚ 31′ E	7,438	25.7˚C; 1458 mm	Inceptisols, Entisols and Histosols	Calcareous
	Mirpur	23˚ 47′ to 24˚ 01′ N; 88˚ 51′ to 89˚ 07′ E	30,454	25.7˚C; 1842 mm	Inceptisols and Entisols	Calcareous

*T, temperature; ** ppt, precipitation in mm

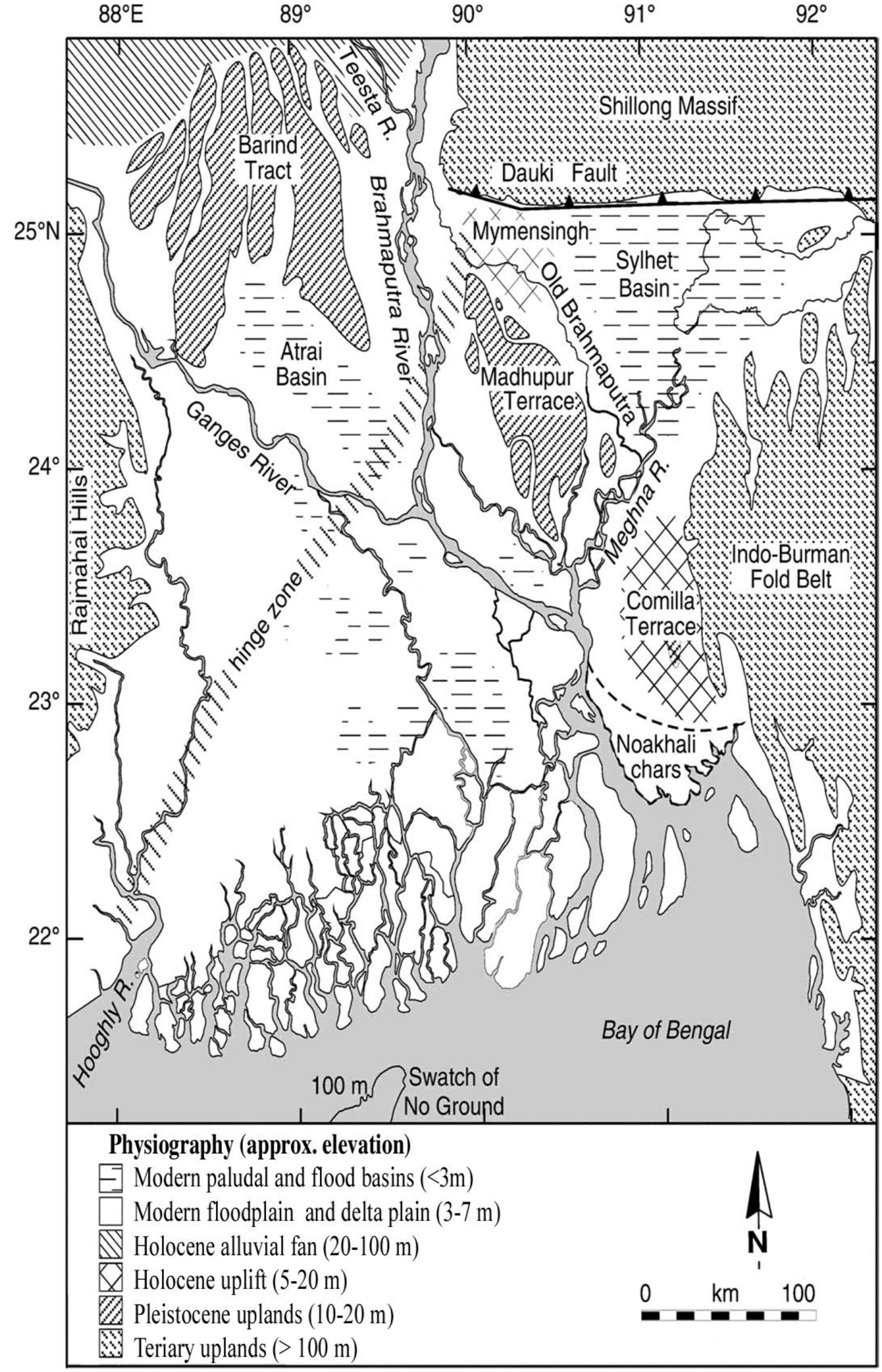

Figure 4.1: Map of the Bengal basin showing physiography and geology of the Ganges–Brahmaputra alluvium and its surrounding area (Source: Goodbred et al., 2003).

4.2.2 Soil Sampling

Soil samples were collected on one-minute latitude and longitude intervals. Hence, a total of 268 soil samples were collected on a one-minute regular grid throughout the study area. GPS Magellan (Model 320) was used to identify the exact coordinates. Details on soil sampling are given in Chapter 3 (Section 3.1.1).

4.2.3 SOC Analysis

SOC in soils was determined by the dichromate oxidation method (Nelson and Sommers, 1982), as described in Chapter 3 (Section 3.3).

4.2.4 Geostatistics

Geostatistical methods such as semivariogram construction, kriging, and mapping have been widely applied in the study of SOC distributions (Bond-Lamberty et al., 2006; Loescher et al., 2014). The semivariogram is a mathematical description of the relationship (structure) between the variance of pairs of observations (data points) and the distance separating the observations (h). It describes the between–population variance within a distance class (y-axis) according to the geographical distance between pairs of populations (x-axis) (Fig. 4.2). The semivariographic model can be described through different parameters: the sill, the nugget variance, the scale, and the range (Fig. 4.2). The most important part of a semivariogram is its shape near the origin until the range, as the closest points or group of pairs are given more weight in the interpolation process. The sill corresponds to the model asymptote (scale and the nugget variance) and should be equal to the variance of the data set. The range is the value of h at which y attains the maximum value where the sill occurs and so represents the separation distance over which no more spatial dependence is apparent.

Nugget represents the undetectable measurement error, inherent variability or the variation within the minimum sampling distance. Samples separated by distances smaller than the range are spatially related, whereas samples separated by larger distances are not spatially related. Four representative groups of pairs are enough to represent a relevant semivariogram with a significant R^2 and a good ‘nugget-to-sill’ ratio (Dinel and Nolin, 2000). Directional dependence has to be tested in the spatial autocorrelation.The isotrope (no directional dependence) or anisotrope (directional dependence) characteristic of the semivariogram has to be determined. If no anisotropy is found, it means that the value of the variable varies similarly in all directions and the semivariance depends only on the distance between sampling points (Emery, 2006).

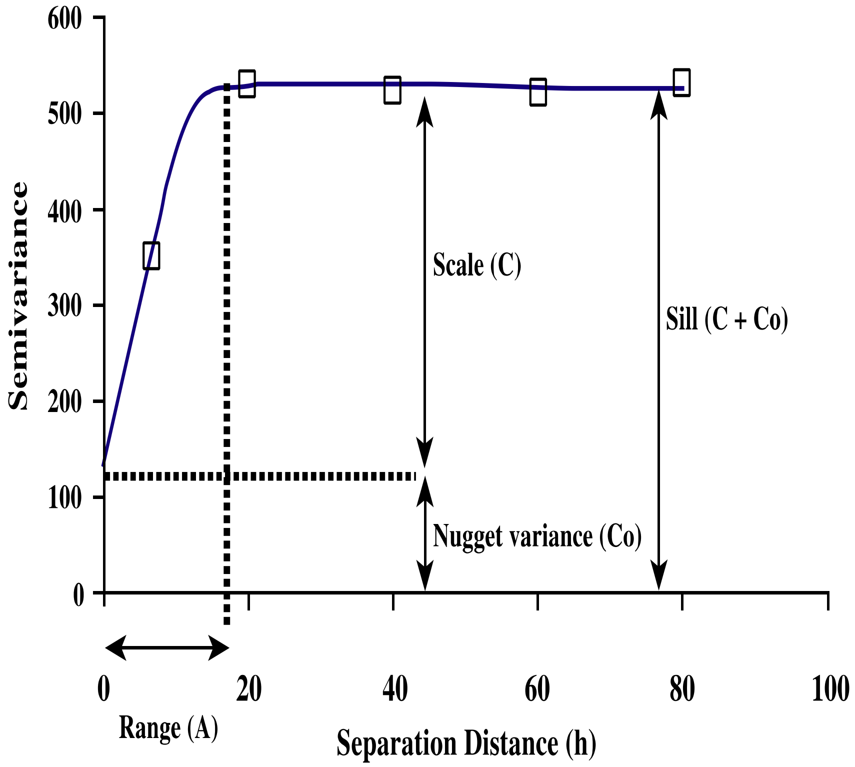

Figure 4.2: An ideal semivariogram model and its parameters

Finally, the best semivariogram model (spherical, linear etc.) and its parameters (nugget, sill, scale, range, etc.) have to be determined in order to validate the modeling of the spatial autocorrelation through the semivariogram parameter optimization. Mabit and Bernard (2007) noted that two major indicators can be used: the coefficient of correlation and the nugget to sill ratio (Co/C+Co), which tends to 1. It means the Co (the nugget) should tend towards 0. Some authors also use the nugget-to-sill ratio (Co/(Co+C), which should tend towards 0. If the nugget-to- sill ratio is less than 25%, then the variable can be considered to have a strong spatial dependence. If this ratio is between 25% and 75%, the spatial dependence will be considered as moderate and if the ratio equals or exceeds 75% then the spatial dependence will be considered as weak (Cambardella et al., 1994). Some software like GS^+ takes into account the distance between the group of pairs and the fitted model called the residual sum of squares (RSS). The RSS is very useful as it allows the comparison of the different semivariograms tested. Lowest RSS is also an indicator of spatial relationships. To summarize, the coefficient of regression (R^2) should be greater than 0.8 and the scale to sill ratio should be close to 1, meaning that the nugget variance has to be as close as possible to the origin (Cambardella et al., 1994; Duffera et al., 2007). Thus, the semivariogram with the best RSS reduction has to be selected to represent the autocorrelation between the data.

4.2.5 Data Interpolation

Kriging is based on the assumption that the parameter being interpolated can be considered as a localized variable, the regionalised variable theory (Matheron, 1963). It is assumed that, given an adequate population, variables will exhibit a degree of continuity within a finite region. It is also a key assumption that the regionalized variables are subject to a statistically normal distribution. Krig interpolation provides an optimal interpolation estimate from observed values and their spatial relationships (Wackernagel, 1995). Kriging uses nearby points weighted by distance from the interpolate location and the degree of autocorrelation or spatial structure for those distances, and calculates optimum weights at each sampling distances (Isaaks and Srivastava, 1989). On the other hand, other interpolation techniques e.g., Inverse Distance Weighted (IDW), and triangulation with linear interpolation are used when the spatial structure is weak (Mabit and Bernard, 2007). IDW also called Inverse Distance to a Power is a weighted average interpolator which assigns more weight to nearby samples for estimating the attributes of the variables at unsampled locations. Thus the weights are inversely proportional to a power of the distance. The weights assigned to the data points are fractions and the sum of all the weights is equal to 1. The value of the power is frequently set to 2 (Isaaks and Srivastava, 1989).

4.2.6 Methods

SOC variability was tested within the sub-sites where a classical statistical analysis was used. This illustrates the trends and the overall variation of the SOC variables. This test includes descriptions of the minimum, maximum, mean, skewness, kurtosis, standard deviation (SD), coefficient of variations (CVs), histogram and Q-Q plots. All the above analyses were done using the statistical package SPSS version 20.0 (SPSS Ins., Chicago, IL, USA). Geostatistical analysis, construction of semivariogram, and spatial structure of SOC variability were performed with GS$^+$ version 10.0 (Gamma Design Software, Plainwell, Michigan, USA). Spatial interpolation through kriging and IDW (details are given in section 3.3.1.1) were done with the GIS software ArcGIS version 9.3 (ESRI Inc., Redlands, California, USA).

4.3 Results and Discussion

4.3.1 Classical Statistics

Classical statistics of the SOC dataset of the four sub-sites are summarized in Table 4.2. Mean contents of SOC across the four sub-sites of the two alluviums were different and ranged from 0.69 to 1.14%. From the Table 4.2, it may be noted that Delduar and Fultala sub-sites have very similar mean SOC and Melandah and Mirpur sub-sites have similar mean SOC as well. SOC variation is higher in the Delduar and Fultala sub-sites than the other two sub-sites. Co-efficient of variation (CV) across the four sub-sites varies from 30.9 to 47.8% indicating a moderate variability in SOC. CV values also indicate the trends of mean SOC across the four sub-sites i.e., Delduar and Fultala sub-sites have similar CV whereas Melandah and Mirpur sub-sites have similar CV. Overall, the extent of SOC variability across the sub-sites of the Brahmaputra and the Ganges alluvium soils can be considered as moderate. The moderate CV of SOC across the study sites may be due to the heterogeneity of topographic land units and soil types (Liu et al., 2006).

Table 4.2: Summary statistics of SOC contents in the four sub- sites of the Brahmaputra and the Ganges Alluviums

	SOC (%)			
Variables	Delduar	Melandah	Fultala	Mirpur
Mean	1.14	0.75	1.13	0.69
Minimum	0.40	0.40	0.30	0.38
Maximum	2.60	1.35	2.30	1.39
SD	0.553	0.246	0.511	0.214
CV(%)	47.8	32.8	45.1	30.9
Skewness	0.30	0.27	0.44	0.25
Kurtosis	0.59	0.53	0.858	0.49

SD= Standard Deviation, CV= Coefficient of Variation,

It is important to test whether the SOC contents followed a normal distribution or not. To test this, two methods were used. First, the histograms of SOC across the sub-sites were plotted with a normal distribution curve (Figs. 4.3-4.6). This shows that SOC is positively skewed across the three sub-sites except at Fultala. Second, a Quantile-Quantile (Q-Q) plot was used, which also shows that the SOC is normally distributed only in the Fultala sub-site with a straight line (Fig. 4.5). From these tests, it is important to note that SOC datasets do not fall on a straight line in the sub-sites of Delduar, Melandah, and Mirpur; thus Fultala is the only sub-site where SOC is normally distributed.

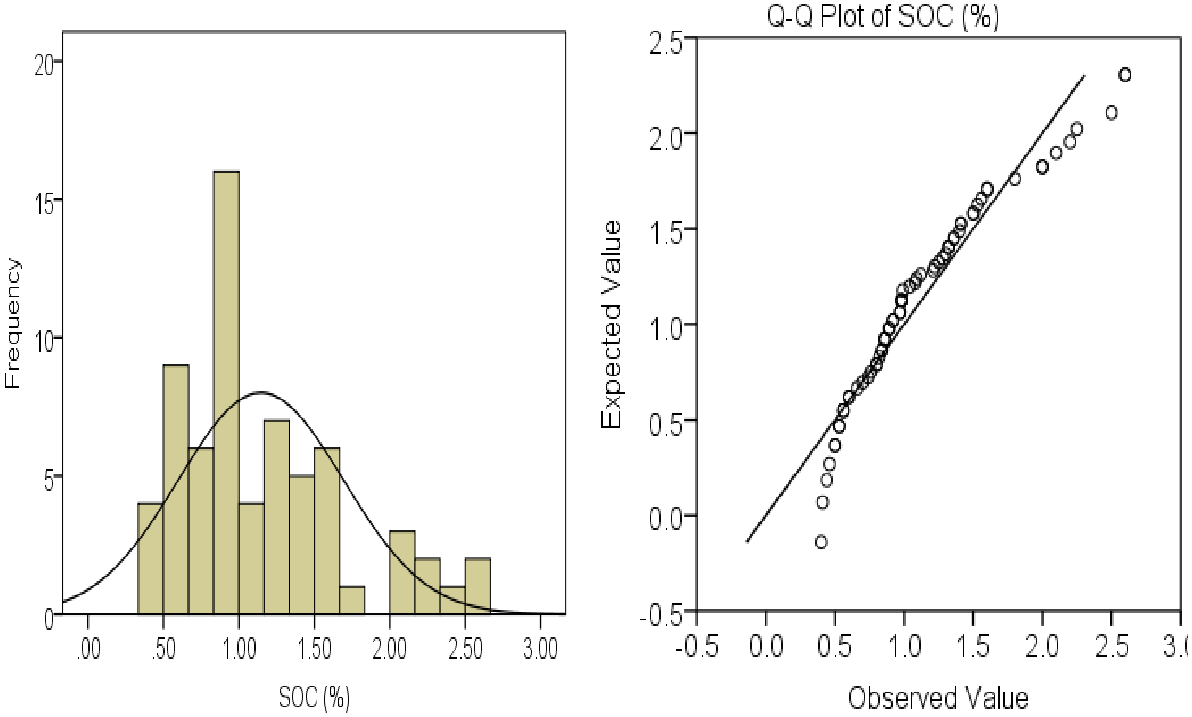

Figure 4.3: Histogram and Q-Q plot of SOC (%) in the Delduar sub-site across the Brahmaputra Alluvium

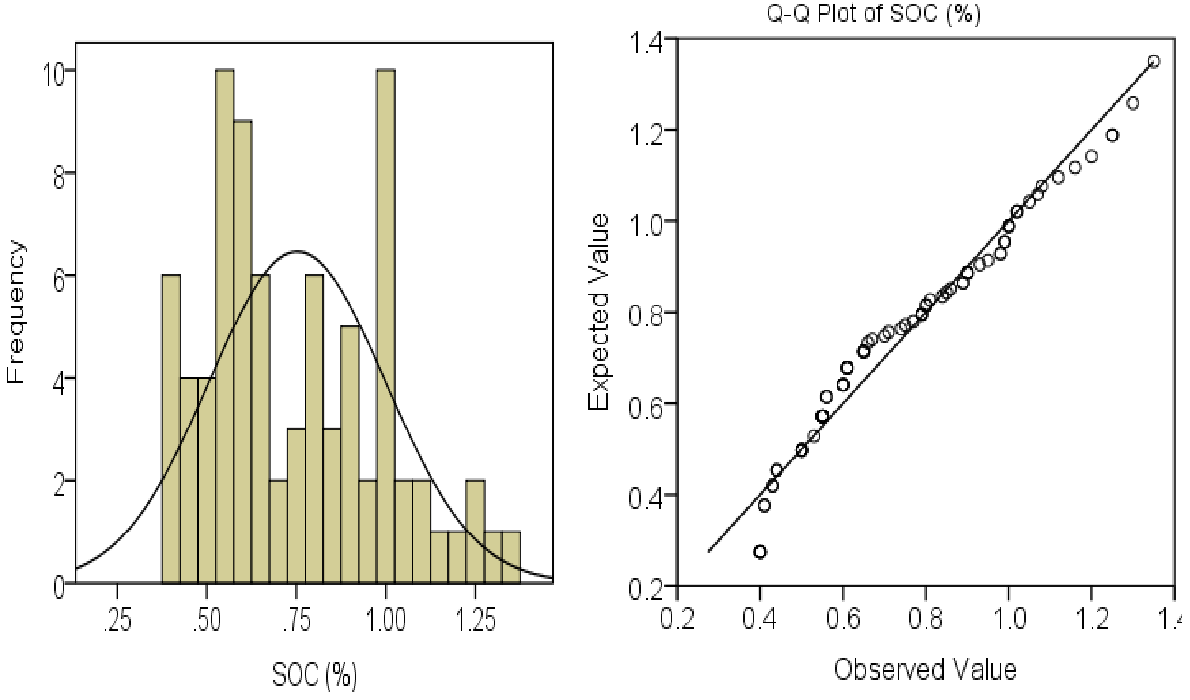

Figure 4.4: Histogram and Q-Q plot of SOC (%) in the Melandah sub-site across the Brahmaputra Alluvium

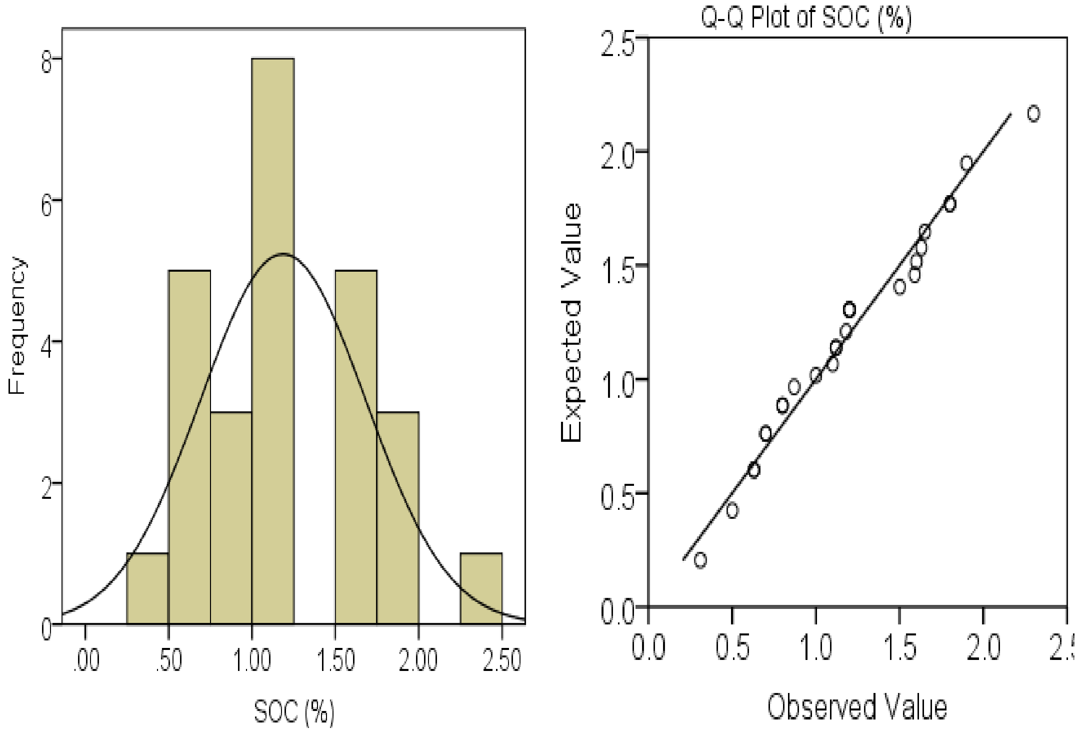

Figure 4.5: Histogram and Q-Q plot of SOC (%) in the Fultala sub-site across the Ganges alluvium

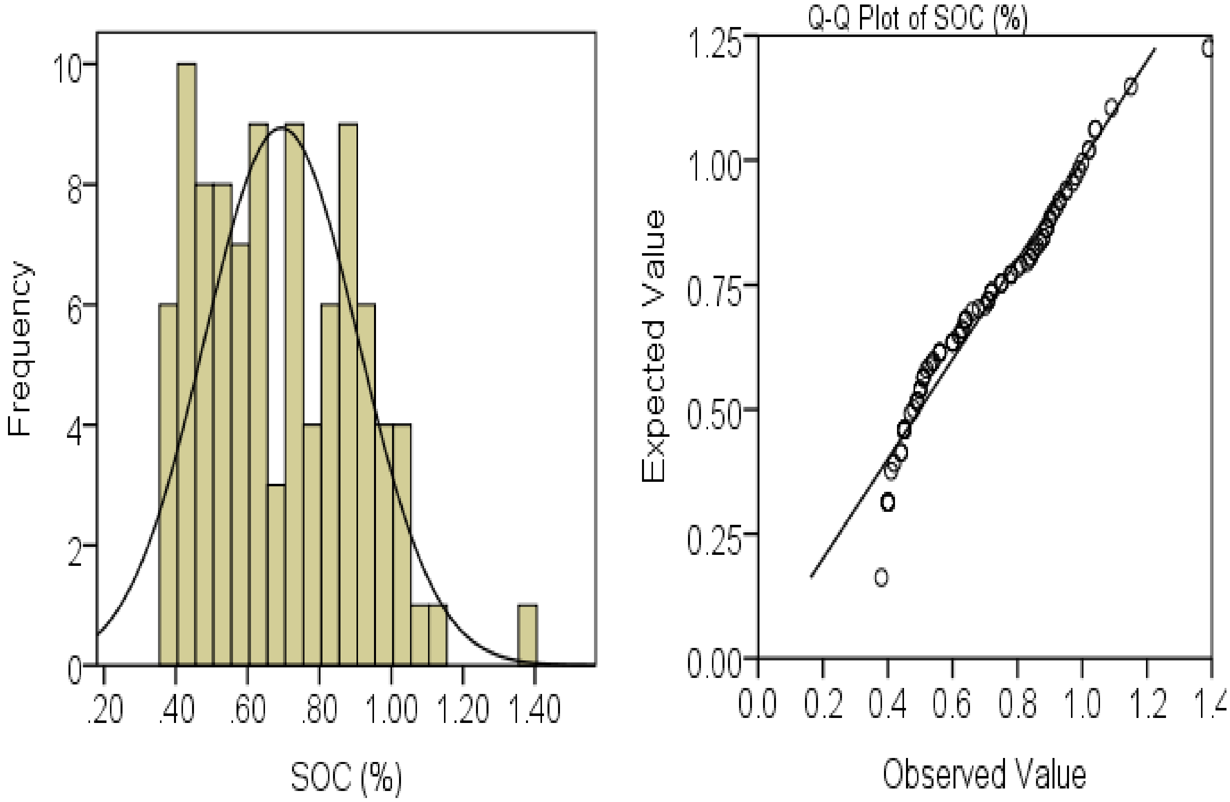

Figure 4.6: Histogram and Q-Q plot of SOC (%) in the Mirpur sub-site across the Ganges alluvium

4.3.2 Geostatistics and Spatial Structure of SOC Variability

In recent years, spatial dependence models of geostatistics have gained popularity as they allow the quantification of landscape spatial structure from point-sampled data. One such model that has received much attention and is used here is the semivariogram (Cressie, 1993). The semivariogram reveals the randomness and structural aspects of the spatial dispersion of a given variable and is a plot of the average squared differences between the values of a spatial variable at pairs of points separated by a lag distance (Davidson and Csillag, 2003). The empirical semivariogram describes the overall spatial pattern of sample data (Fortin, 1999) and a variety of theoretical semivariogram models can be used to describe spatial structure of a landscape attribute. These then provide powerful capabilities that can be used to analyze realistically the complex spatial relationship in any ecological systems. Thus, the understanding of the spatial variability of SOC levels between and within farms is very important for refining the farm management practices and implementing precision farming. The spatial dependence of SOC was determined by the semivariogram analysis. In the current study, the tested SOC in each sub-sites was modeled with linear, spherical, Gaussian or exponential semivariograms with a nugget effect.The values of the different semivariogram parameters i.e., nugget (Co), sill (C+Co), range (Ao), and nugget/sill ratio are given in Table 4.3. Generally, the nugget effect can be defined as an indicator of continuity at close distances.

Table 4.3: Parameters of the semivariogram models estimated for the SOC contents across the study sites

Sub sites	Model	Nugget (Co)	Sill (C+Co)	Co/C+Co	Range (Ao) (m)	RSS*	R^2
Delduar	Spherical	0.037	0.330	0.113	0.02	0.006	0.233
Melandah	Linear	0.067	0.067	1.00	0.10	0.005	0.138
Fultala	Gaussian	0.064	0.296	0.216	0.03	0.001	0.946
Mirpur	Exponential	0.029	0.058	0.499	0.07	0.002	0.055

*RSS= Residual Sum of Squares

The semivariogram for SOC across the four sub-sites are shown in Figs. 4.7-4.10.The semivariogram of the Fultala sub-site appears to have strong structure and a gradual approach to the range, with the Gaussian model providing the best fit. It shows a nugget (Co) of 0.064; a sill (C+Co) equal to 0.296; range (Ao) equal to 0.03; coefficient of determination (R^2) of 0.946; a residual sum of squares (RSS) equal to 0.001. This semivariogram appears to exhibit a pure nugget effect, possibly because of too sparse a sampling to adequately capture autocorrelation. On the other hand, the other three sub-sites (Delduar, Melandah and Mirpur) show similarity to the Fultala sub site regarding the nugget effect, sill, range and RSS. However, the coefficient of determination (R^2) clearly shows that SOC datasets at these three sub-sites do not adequately fit to any of the semivariogram models. The lowest RSS value is one of the criteria of selecting the best fitted models (Robinson and Metternicht, 2006). In the case of Fultala, R^2, RSS and nugget-to-sill ratio reveal that at this sub site SOC is strongly spatially dependent (Table 4.3). The other sub sites i.e., Delduar, Melandah, and Mirpur, show a weak spatial dependency as they have R^2<0.5.

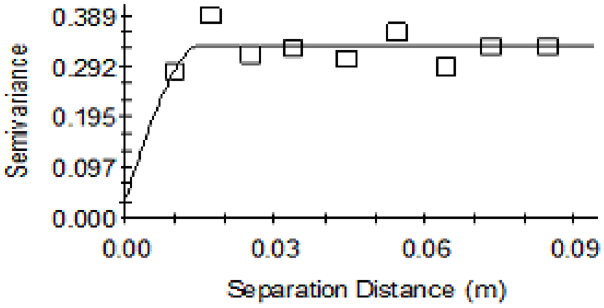

Figure 4.7: The semivariogram model of SOC at the Delduar sub-site of the Brahmaputra alluvium

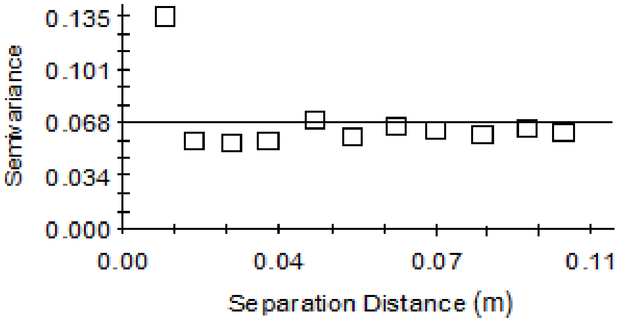

Figure 4.8: The semivariogram model of SOC at the Melandah sub-site of the Brahmaputra alluvium

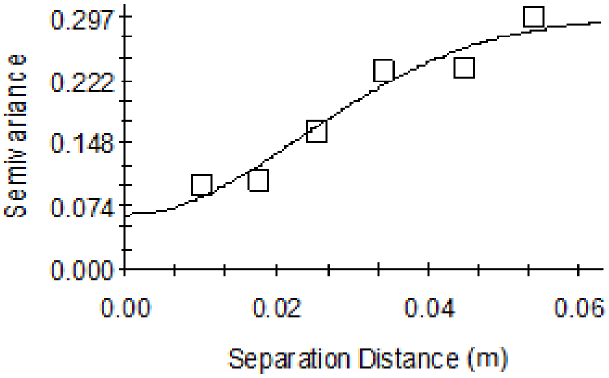

Figure 4.9: The semivariogram model of SOC at the Fultala sub-site of the Ganges alluvium

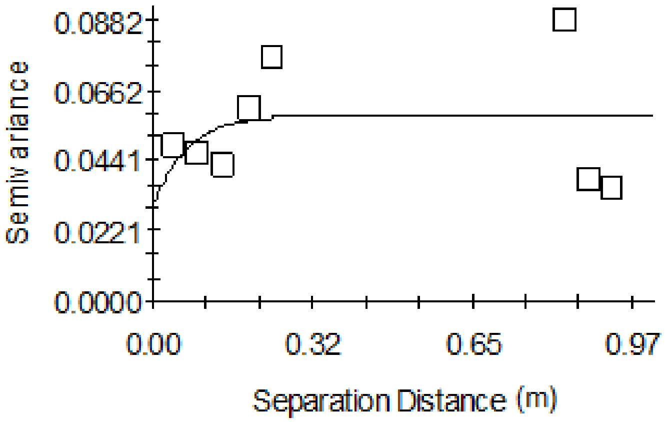

Figure 4.10: The semivariogram model of SOC at the Mirpur sub-site of the Ganges alluvium

Besides, the SOC semivariograms indicated a smaller nugget effect (Co) in the study sites, implying that they had lower undetectable experimental error, short range variability, and random and inherent variability of SOC concentrations (Schlesinger, 1996; Liu et al., 2006). In the current study, the isotrope or omnidirectional semivariogram characteristics have been found in the Delduar, Melandah, and Mirpur sub-sites; this means that no directional dependence occurs in the study sites. If no anisotropy is found, it means that the value of the variable varies similarly in all directions and the semivariance depends only on the distance between sampling points (Burgos et al., 2006; Emery, 2006). On the other hand, anisotropic characteristics have been found in the Fultala sub-site which means that the covariance between the SOC values depends both on the direction and distance of the sampling sites. Cambardella et al. (1994) noted that the spatial variability of soil properties may be affected by both intrinsic i.e., soil forming factors such as parent materials and extrinsic factors i.e., soil management practices such as fertilization. They also added that strong spatial dependency of SOC can be attributed to intrinsic factors whereas weak spatial dependency can be attributed to extrinsic factors.Thus, the strong spatial dependence of SOC across the Fultala sub-site may be attributed by the structural or intrinsic factors which is governed by the larger resolution sampling design.This structural or intrinsic factors are the topographic units, SOC contents, mineral composition and soil type etc. The possible causes of the spatial variability in SOC may be the topographic land units and soil types, though other factors like land use and management are also associated. The spatial variation in SOC may be partly attributed to the complex topography in the landscape (Liu et al., 2006). The Fultala sub-site occupies three diverse physiographic units, Ganges tidal floodplain i.e., saline soils, peat soils with high SOC contents and non-saline soils. Due to its inherent low fertility nature (FRG, 2012), this sub-site bears a relatively low cropping intensity. Hence, tillage and crop management activities are much lower than any other sites.

As a result, the spatial structure of SOC in the Fultala sub-site is not influenced by the soil fertilization and cultivation practices. As such, the spatial dependence remains strong in this sub-site. On the other hand, agricultural activities (such as tillage, irrigation practices; and land use intensification by higher cropping intensity), are the random factors which prevail across the other three sub-sites. Thus, it would appear that the lack of spatial dependence of SOC in the three sub sites. This is possibly attributed due to extrinsic factors of soil fertilization, which weakened their spatial correlation after a long history of cultivation. The weak spatial dependence of SOC across the Delduar, Melandah and Mirpur sub-sites is likely attributed by the human activities such as tillage, cropping system management, irrigation practices, land use cover, manure and fertilizer, crop residue management and cropping intensity etc. (Kilic et al., 2004).

4.3.3 Spatial Interpolation and Cross Validation of SOC

In order to apply agricultural practices precisely and appropriately, it is important to investigate the spatial distribution of SOC across the four sub-sites. The parameters derived from the geostatistical models were used for kriging and inverse distance weighted (IDW) i.e., spatial interpolation by which spatial distribution maps of SOC across the study sites were produced (Figs. 4.11-4.14). The maps of SOC distribution clearly show how the predicted values are spatially distributed. The interpolated krig map for Fultala (Fig. 4.11) showed strong spatial dependence. SOC concentration in this sub-site decreased from south to north, which was apparently related to the nature of soil and topographic conditions. On the other hand, weighted interpolation SOC maps were prepared for the other three sub-sites (Figs. 4.12-4.14) which showed weak spatial dependence. It may be noted that weighted interpolation is used where data have weak spatial dependence or no spatial dependence. IDW is based on values at nearby locations weighted only by distance from the interpolation location, Bulls eye effect was found in this IDW datasets. Thus, IDW helps to compensate for the effects of data clustering, assigning individual points within a cluster less weight than isolated data points or treating clusters more like single points. IDW-interpolated maps for the other three sub-sites indicate that the spatial structure is dispersed due to the continuous management of the soil resources i.e., a weak SOC spatial dependency. Besides, it should be mentioned that the SOC were concentrated in some particular areas or land types of the Delduar, Melandah and Mirpur sub-sites which may be due to their local variability of land types and differences in land management practices and intensities. Thus, land management activities by the local stake holders enhance the isotrope semivariances of SOC in these sites. Similar spatial distribution observations have been made for some soil properties of Bangladesh (Rahman et al., 2005).

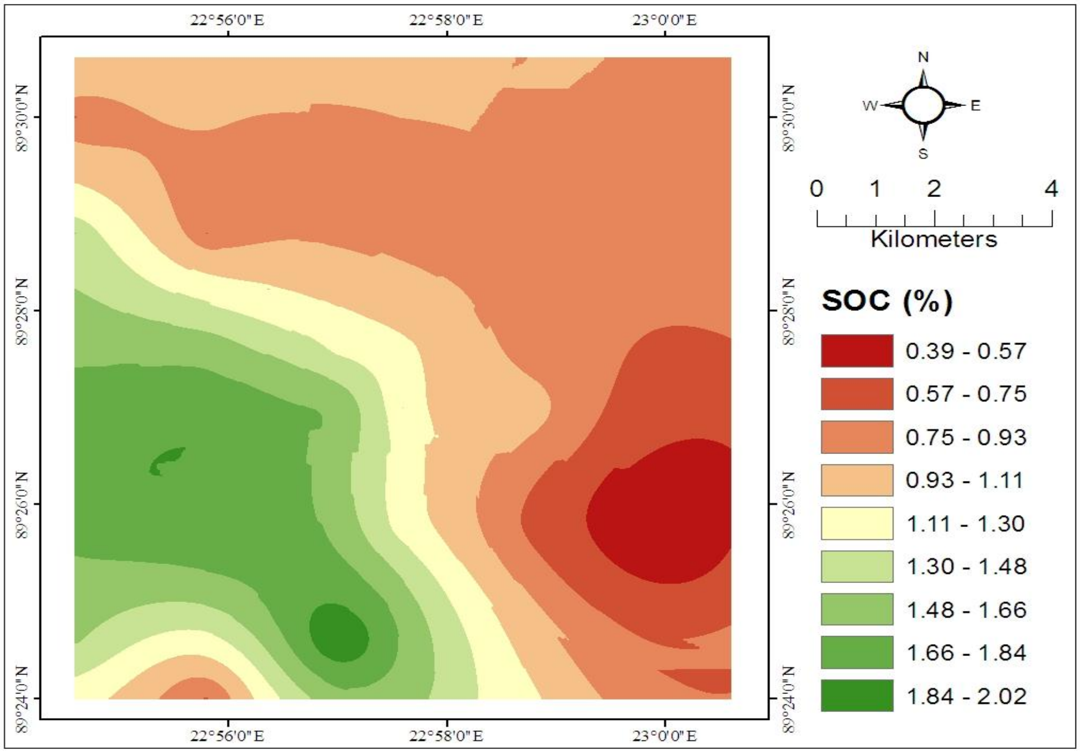

Figure 4.11: Distribution of SOC contents (%) in the Fultala sub-site using Kriging

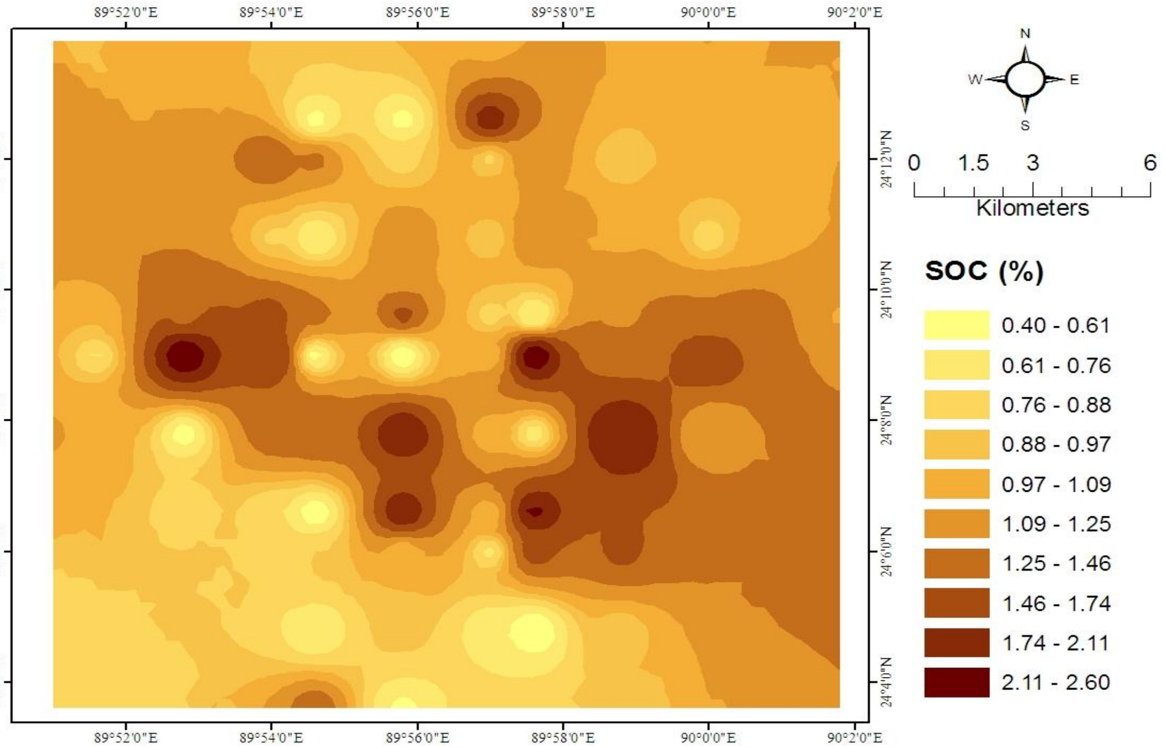

Figure 4.12: Distribution of SOC contents (%) in the Delduar sub-site using IDW

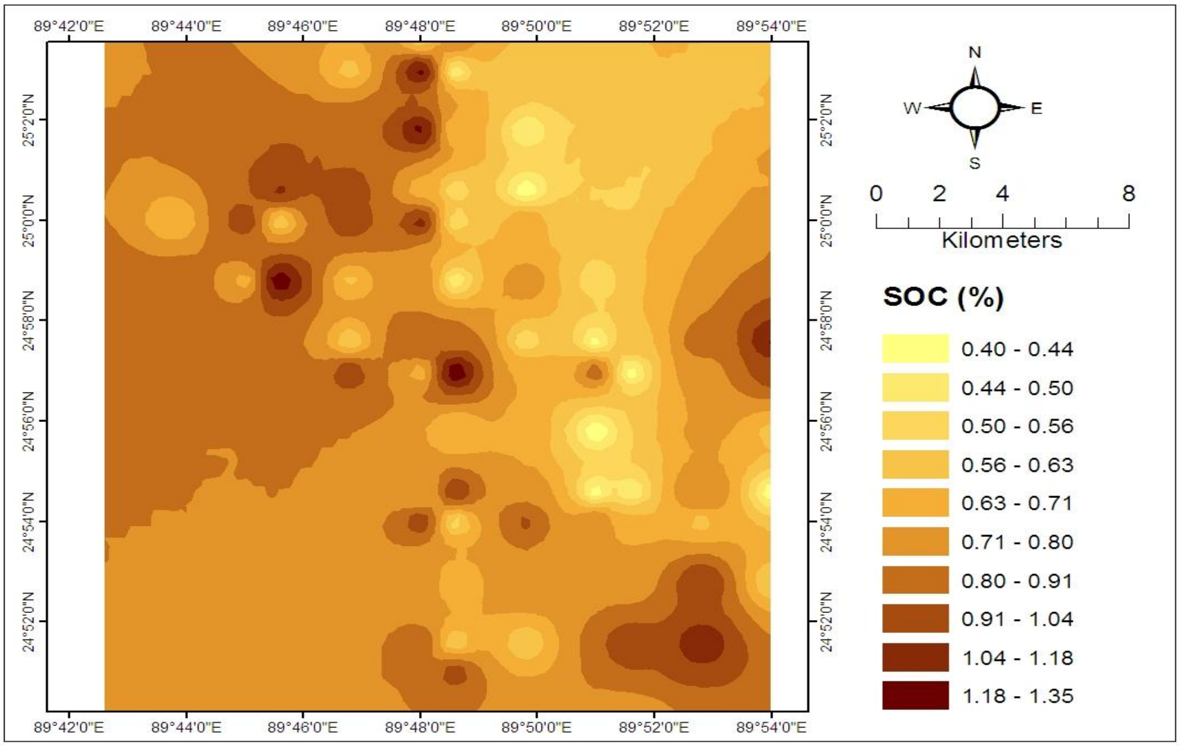

Figure 4.13: Distribution of SOC contents (%) in the Melandah sub-site using IDW

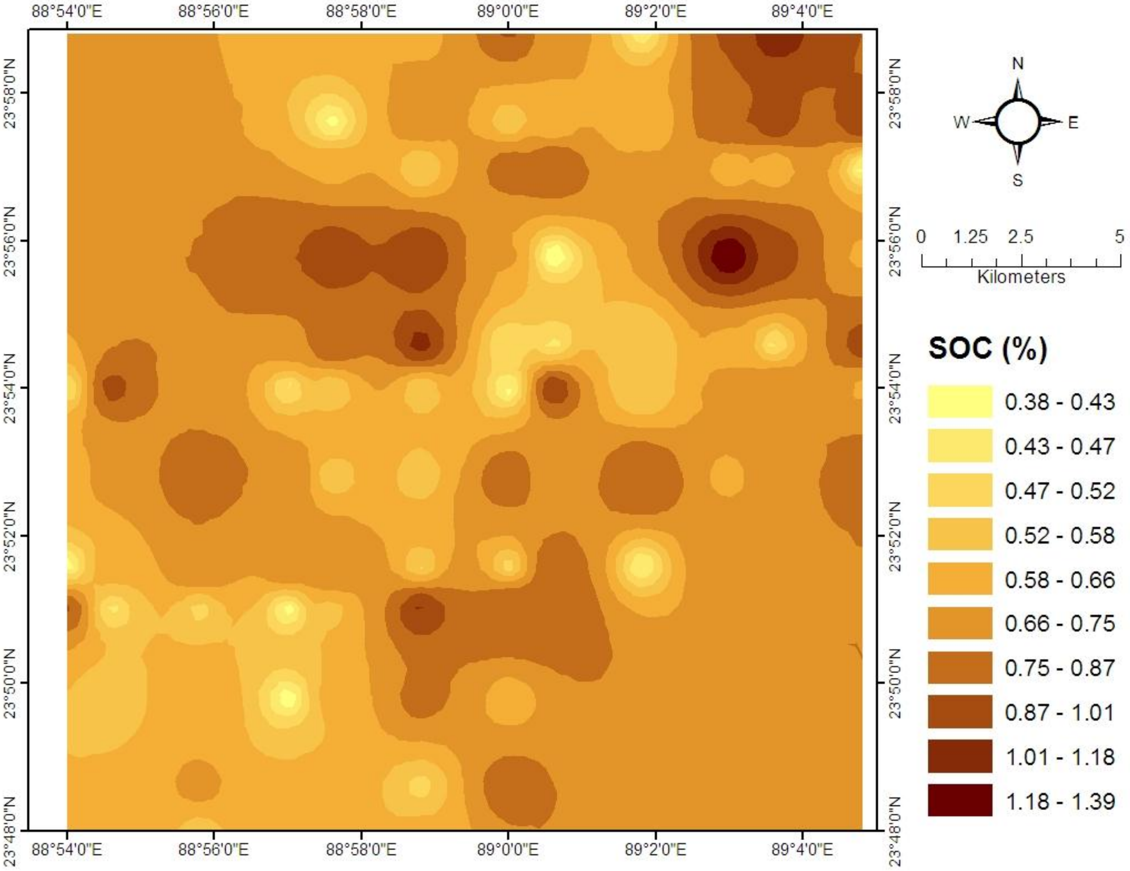

Figure 4.14: Distribution of SOC contents (%) in the Mirpur sub-site using IDW

It is a common practice to use cross-validation to validate the accuracy of an interpolation (Voltz and Webster, 1990). Cross validation is achieved by eliminating information, generally one observation at a time, estimating the value at that location with remaining data and then computing the difference between the actual and estimated value for each data location (Robinson and Metternicht, 2006). Cross validation is an excellent scheme for solving the inconvenience of redundant data collection (Webster and Oliver, 2007), and hence all of the collected data can be used for estimation. The mean error should ideally be zero, assuming the interpolation method is unbiased (Robinson and Metternicht, 2006). Cross validation analysis was used to evaluate the effectiveness of ordinary kriging and IDW interpolations. The cross validation is determined by coefficient of correlation between the measured values and the cross validation values, which were predicted, based on the semivariogram and neighbor values (Robertson, 1987). For an acceptable cross-validation, the regression coefficient (r^2) that measures the goodness of fit for the least squares model describing the linear regression equation needs to be as close as possible to 1 (Mabit and Bernard, 2007).

In the current study, during kriging, the number of closest samples chosen was 15 for all the sites. The best found kriging parameters for the Fultala sub-site were selected from the cross validation results (Table 4.4). For SOC, the lowest root mean square error (RMSE) was found with a neighborhood of 15 points. The mean error (ME) suggests that the predictions are completely unbiased because the ME value is close to. Robinson and Metternicht (2006) noted that the mean error (ME) should ideally be zero, if the interpolation method is unbiased. They also reported that RMSE would be less than 1 which is also recorded from the current interpolations. On the other hand, the precision of IDW is also affected by the choice of the number of the closest samples used for estimation; hence, this number is 15. The best weighting parameter was found to be for Delduar, Melandah and Mirpur (Table 4.4). This suggests that the weights diminish slowly from the sample point over the chosen radius. IDW, the power of one was the best choice (over powers of two, three and four), which is possibly due to the relatively low skewness inherent soil properties (Kravchenko and Bullock, 1999).

Table 4.4: Parameters of cross validation from the Kriging and IDW interpolation across the study sites

Sub sites	Neighbors	Power	Mean Error (ME)	Root mean square error (RMSE)
Fultala	15	-	-0.01193	0.02002
Delduar	15	1	0.0172	0.5744
Melandah	15	1	0.004427	0.274
Mirpur	15	1	0.001995	0.2293

In this study, the weak spatial dependent sites possess a relatively flat topography (only 2 m elevation variation), the SOC distribution should not only be linked to water erosion processes, but also to tillage erosion. Indeed, widespread adoption of mechanized agriculture that promotes more intensive continuous tillage accelerates SOC oxidation (Polyakov and Lal, 2008) and predisposes soils to increased erosion (Rasmussen et al., 1998). Tillage, especially the conventional 30-cm deep tillage, is one of the major practices that affects SOC. Tillage thus accelerates runoff during the rainy season and destroys natural soil aggregates. This traditional tillage does not leave any residues on the soil surface to reduce rainfall erosivity. Thus, conventional tillage disturbs on soil porosity, aeration and reduces the decomposition of organic matter that exacerbates the soil pulverization during the dry periods which are also reported by Bot and Benites (2005) in case of conventional tillage. Interpolated values of SOC in the surface layer (0-30 cm), obtained by kriging ranged from 0.39 to 2.02% in the Fultala sub-site (Fig. 4.12). The highest SOC tended to occur in the Fultala sub-site, where the landscape is diverse with low cropping intensity. This sub-site belongs to the south-western coastal plain of Bangladesh where the major land use is the rice-shrimp integrated farming (Fig. 4.12). This topographic diversity mainly causes high variability in SOC. On the other hand, SOC interpolated by IDW ranged from 0.40 to 2.60% in the Delduar sub-site, 0.40 to 1.35% in the Melandah sub-site and 0.38 to 1.39% in the Mirpur sub-site respectively (Figs. 4.13-4.15). The lower SOC levels in these sub-sites may be attributed to more intensive cropping with HYV rice.

4.3.4 Potential limitations of spatial interpolation methodology

The interpolation methodology employed and results may have been influenced by several potential limitations. Most important among these limiations is grid size. While some variables may inherently have weak spatial structure (crucial for interpolation), it i.e., spatial structure tends to become weak with increasing grid size. Clearly sample size i.e., grid size affects the reliability of the interpolation methods. The larger the sample size from which the variogram is computed, the more precise is the estimate. In the present study, sampling grid is much wider e.g., 1600 m distance covers one sample which is not highly precise, and this may have been the reason for the weak SOC spatial structure/dependence observed for 3 of the 4 sites investigated.

The nature of physical surface can also influence spatial dependence of SOC and hence its interpolation. The study sites are widely variable with diversified land types e.g., HL, MHL, MLL and LL. Such variability in land types is likely to weaken SOC spatial structure by soil erosion from higher lands (e.g., HL, MHL) and deposition in lower lands (e.g., MLL and LL), which may influence the interpolation processes.

The physical and geographic barriers that exist in the landscape, like waterbodies, settlements and woodlands present a particular challenge when mapping using interpolation. In the study sites, a lot of features such as settlements, ponds, woodlands and industry exist within the sampled landscape; they create barriers and a sudden interruption in the interpolation process.

4.4 Conclusions

Understanding the spatial variability of soils is important to best manage and target precision agricultural practices. Geostatistical analyses coupled with geographic information systems (GIS) are effective tools in assessing the spatial variability and mapping of SOC. This study showed that SOC concentrations in the Fultala sub site have strong spatial dependence. This strong spatial dependence may be attributed mainly due to the structural factors of soils such as topographic land units, soil types, and diverse physiography, though other factors may have also influenced this. The other three sub-sites (Delduar, Melandah, and Mirpur) showed weak spatial dependence. Agricultural activities such as tillage, cropping system management, land use intensification by high inputs, etc. are the random factors that prevail at these sub-sites, which may be responsible for the weak spatial dependence after a long history of agricultural use. Thus, it is possible to make an accurate estimation of SOC carbon loss or storage at the study sites by comparing these SOC maps with subsequent SOC measurements. Moreover, this spatial information can be used to design and implement effective measures in terms of soil and water management, based on the quantitative spatial variability of SOC associated with topographical nature, and land use and soil types. Clearly, the sites where SOC loss is intensive, a pragmatic policy may be adopted to maximize SOC sequestration Therefore, the spatial variability of SOC can help better manage agricultural land by targeting management practices appropriate to the SOC levels.

CHAPTER 5

Soil Organic Carbon in the Brahmaputra and the Ganges Alluvium: Storage, Distribution, and Controlling Factors

5.1 Introduction

Carbon sequestration potential of soils is one of the inventories of soil organic carbon (SOC) stock and its contents (Eswaran et al., 1993; Houghton, 1995; Batjes, 1996). Moreover, it is important to investigate the impact of the key factors of climate, hydrology, parent material, soil fertility, biological activity, vegetation, and land cover-all of which control the levels of SOC in soils in order to identify optimal strategies for land management (Jenny, 1980). Any land management decisions should be directed at enhancement of SOC stocks in soils and so offer a potential mitigation of climate change while fostering the main soil functions (e.g., Nannipieri et al., 2003). Spatial and temporal patterns of SOC are a function of soil redistribution, vegetative productivity, mineralization of SOC, landscape position and management (Gregorich et al., 1998; Sauerbeck, 2001; West and Marland, 2003; Jacinthe et al., 2004). Water, tillage, and erosion contribute significantly to the redistribution of soil and SOC across the landscape, with both soil and SOC being redeposited within the field as well as being moved off the field (Harden et al., 1999; Smith et al., 2001; McCarty and Ritchie, 2002; Ritchie and McCarty, 2003). Understanding the patterns and processes involved in SOC redistribution across agricultural landscapes is the key to understanding the potential for SOC sequestration in agricultural systems as well as SOC distribution patterns on the landscape. Most studies have concentrated on the field scale using grid sampling and various mapping techniques to study the relationship between soil redistribution and SOC (VandenBygaart, 2001; Hao et al., 2001; Pennock and Frick, 2001; Ritchie and McCarty, 2003).

Many factors such as topography, land use, soil texture, field management, and vegetation may influence the spatial variability of SOC (Tan and Lal, 2005; Liu et al., 2006; Wang et al., 2010; Chuai et al., 2011). SOC content of surface soils is sensitive to human interference and changes in land use and soil management to protect or increase the existing soil carbon pool by sequestration of carbon from the atmosphere could become crucial in terms of future policies to mitigate the global greenhouse effect (IPCC, 2000). Therefore, it is critical to understand how SOC varies in response to factors such as topography, land use, and soil texture, when evaluating the role of terrestrial ecosystem processes in alternating the global carbon cycle and carbon accumulation in the atmosphere (Jiao et al., 2010). Wang et al. (2010) found that the influence of soil texture on SOC was more important where there was significant positive correlation between SOC and clay or silt content but negative correlation between SOC and sand content. Land use changes have profound influences on the physical, chemical, and biological environment of soils (Buschbacher et al., 1988; Solomon et al., 2000). Soils can be a source or sink for atmospheric carbon depending on land use and management (Mishra et al., 2010). It has been reported that about one fourth of anthropogenic CO_2 emissions are due to land use changes, especially deforestation, and the rest are due to fossil fuel burning in the past 20 years (Barnett et al., 2005). Long-term experimental studies have confirmed that SOC is highly sensitive to land use changes from native ecosystems, such as forest or grassland, to agricultural systems, resulting in the loss of organic carbon (Conant and Paustian, 2002; Jiao et al., 2010).

The present research was undertaken with the following objectives: (i) assessing distribution of SOC across the alluviums as well as the inundation land types (ii) whether the inundation land types or cropping intensity had an impact on SOC.

5.2 Materials and Methods

268 soil samples were collected on a regular grid from the four sub-sites: Delduar, Melandah, Fultala and Mirpur, using one-minute latitude and longitude intervals (representing a distance of 1600m between grid points) following a random grid sampling strategy. A portable GPS (Global Positioning Systems-Magellan, Model 320) was used to identify the sampling location in the field. The sampling sites exclude settlements, industry, woodlands, water-bodies and infrastructures, as the focus of this work was land that is used for agricultural purposes. This sampling strategy ensured that four land types (HL, MHL, MLL and LL) received fair representation, proportionate to their area within the sampling sites/landscapes. This work considered across two major alluviums – the Brahmaputra and the Ganges, as much of the agricultural land in Bangladesh belongs to these two alluviums. Soil texture and drainage conditions of the soils were measured in the field according to the guidelines of FAO (2006). In the field, soil texture was determined by the feel method. The soil is rubbed between thumb and fingers, preferably while wet. Sand feels gritty and its particles can be easily seen with the naked eye. The silt when dry feels like flour or talcum powder and is slightly plastic when wet. Clayey materials feel very plastic and exhibit stickiness when wet and are hard under dry conditions. Information on land types, land use, and cropping intensity were recorded during the field work.

5.2.1 Soil Organic Carbon Analysis

Organic carbon in soils was determined by the dichromate oxidation method of Walkley-Black (Nelson and Sommers, 1982), as in Chapter 3.

5.2.2 Data Analysis

SOC data analysis was done using SPSS version 20.0. SOC data distribution across the alluviums (as well as the land types) was assessed by boxplots analysis. SOC and cropping intensity (CI), SOC and land type's variability were tested by using one-way analysis of variance (ANOVA). SOC variability within the land types was also tested by Post hoc and Tukey's multiple comparison tests.

5.3 Results and Discussion

5.3.1 SOC Distribution across the Alluviums

The SOC distribution across the alluviums shows that mean SOC in the Brahmaputra alluvium is about 0.80 % (8.0 kg/m^2) in the 0-30 cm soil depths whereas SOC in the Ganges alluvium is about 0.60 % (6.0 kg/m^2) in the same depths (Fig. 5.1). So, it is observed that SOC distribution is low in both of the alluviums. Estimates of critical levels of SOC are available (Greenland., 1975), considered as 2% of SOC as the minimum requirement for maintenance of satisfactory soil aggregate stability and above which no further increase in productivity are achieved (Janzen et al., 1992), the quantitative basis for such thresholds is limited (Loveland and Webb, 2003). Janseen and de Willigen (2006) reported 6 g/kg of SOC as the minimum limit to prevent collapse of soil structure. Karim and Iqbal (2001) also noted that a good soil have an organic carbon content of more than 2% but in Bangladesh, most soils have less than 1%, and some soils have even less than 0.60%. Brahmaputra alluvium possesses slightly higher SOC than the Ganges alluvium at 0-30 cm soil depths and shows symmetric distribution i.e., most SOC values occur at or near 0.80%. On the other hand, SOC distribution in the Ganges alluvium is positively skewed i.e., most SOC values are below 0.60% (Fig. 5.1). These differences might be due to the differences in land management activities and/or cropping intensity over the two alluviums or due to their inherent dissimilarities.

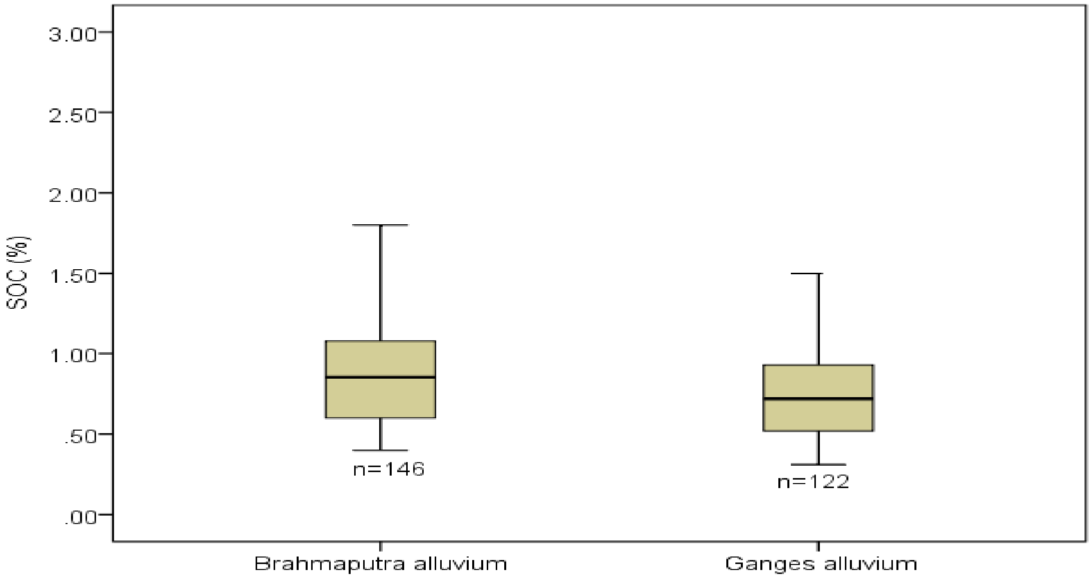

Figure 5.1: Boxplots showing SOC distribution across the alluviums of the study sites

5.3.2 SOC Distribution across the Inundation Land Types of the Alluviums

SOC distribution under different land types were examined using boxplot analysis. SOC ranges from 0.50 to 1.45% depending on the land types across the alluviums. SOC varies from 0.52 to 1.45 % across the land types of the Brahmaputra alluvium, whereas SOC ranges from 0.50 to 1.35 % across the land types of the Ganges alluvium. It was seen that the SOC variability was higher across the MLL and LL types than HL and MHL types in both the alluviums (Fig. 5.2). It appears that inundation land types may be an influential factor here, as SOC across the inundation land types follows the following decreasing order as <LL<MLL<MHL<HL (Fig. 5.2). Agriculture in Bangladesh is practiced mainly on the HL and MHL sites, often with the application of adequate quantities of chemical fertilizers instead of farmyard manures or other organic fertilizers. The HL and MHL sites are used for intensive cropping with intensive tillage. Their topographic position makes them more suitable for intensive agriculture. The higher SOC contents in the MLL and LL sites compared to HL and MHL sites may be attributed due to their topographic position as well as lower cropping intensity and management (Mia, 1995; Ritchie et al., 2007; FRG, 2012). Topographic land type affects soil properties mainly through its effects on water movements. In fact, in terrain depressions, soils are moister because they receive runoff, sediments including organic matter, and seepage from the surrounding, leading to a higher SOC concentration than in drier upland soil (Yoo et al., 2006). On the contrary, soils on steep slopes tend to lose organic carbon because the topsoil is constantly eroded. Xie et al. (2007) reported that the average area-weighted total SOC density in paddy soils e.g., MLL and LL soils were higher than HL and MHL sites. Therefore, the spatial distribution of topographic attributes that characterize the flow paths can help in capturing the soil variability and in predicting soil

properties (Moore et al., 1993; Florinsky and Kuryakova, 1996). Ritchie et al. (2007) also noted that upland sites have significantly less SOC than soils in deposition areas.

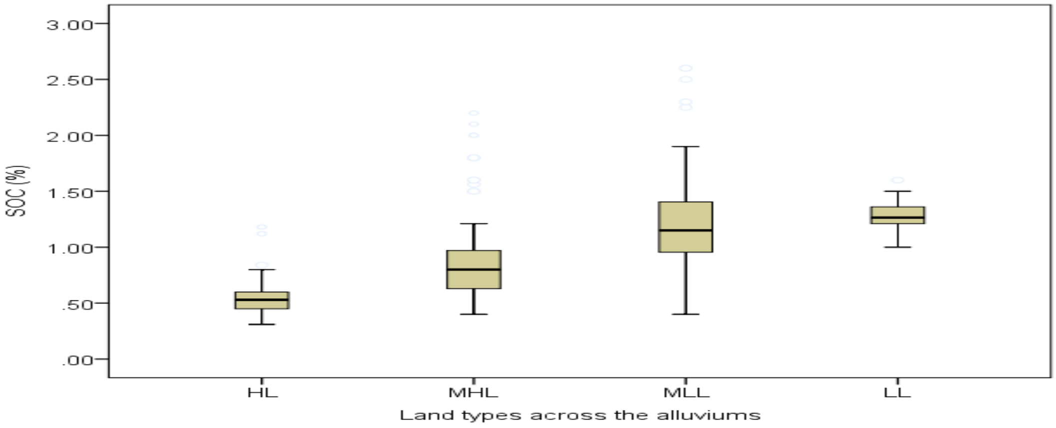

Figure 5.2: Boxplots showing SOC distribution across the land types of the alluviums

5.3.3 Land Use and Cropping Intensity on SOC

Cropping intensity (%) across the land types varies 240 to 330% in the HL sites, 200 to 240% in the MHL sites, 120 to 200 % in the MLL sites and 80 to 90 % in the LL sites. Thus, there is a higher cropping intensity exists in the HL and MHL sites and a lower cropping intensity in the MLL and LL sites (Fig. 5.3) mainly due to the nature of flooding depths. Descriptive statistics of the current SOC and CI revealed that the SOC content is higher (1.30%) in the lower cropping intensity sites. SOC content is lower (0.55%) in the higher cropping intensity sites. One-way ANOVA test of SOC and CI revealed that the SOC within the CI groups vary significantly ($p<0.001$, F ratio= 23.57). This is clear evidence of SOC being intimately related to the cropping intensity. Thus, SOC is lower in the higher cropping intensity sites i.e., HL and MHL sites. On the other hand, SOC is higher in the lower cropping intensity sites i.e., MLL and LL sites. Due to their inundation nature of land, the HL and MHL favours for growing 3 to 4 crops a year, whereas LL and MLL favours only 1 or 2 crops in a year. Thus, it may be said that intensive cropping promotes SOC contents to be low which is true for the HL and MHL sites. A similar observation was made by Song et al. (2005). Cui et al. (2003) reported that SOC tended to decline in response to increased tillage and a reduction in natural organic debris input caused by agriculture. A similar situation prevails in Bangladesh, where crop residues are widely used as fuel and fodder and usually not returned to the soil.

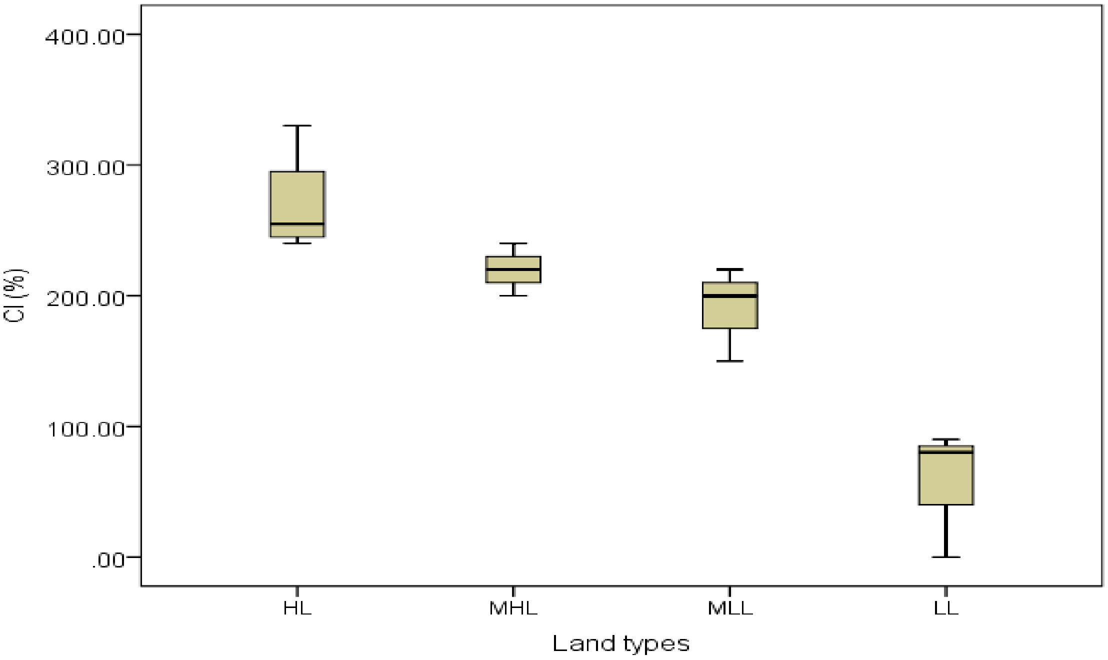

Figure 5.3: Boxplots showing variability pattern of cropping intensity across the alluviums

In the HL and MHL sites across the alluviums, perennial crops along with other crops such as modern varieties of rice cultivars and vegetables have been grown year round. The other major crops are wheat, pepper, potatoes, pulses, tobacco, and mustard, high yielding 'boro' and transplanted 'aman' rice (Table 5.1). In a cropping season, three or four cropping patterns are common in the HL and MHL sites across the alluviums, thereby intensifying the land cover and land use by doubled or tripled crops. In the MLL and LL sites across the alluviums, high yielding rice crops mainly dominates with lower cropping intensities (Table 5.2). UNCD (1992) reported that the cropping intensity varies from 100 to 300 percent, depending upon the quality of land across the Hindu Kush- Himalayan (HKH) region. Sitaula et al. (2004) also reported that HKH region presents particularly complex land use and land cover change processes in the fragmented and diverse socio-economic and agro-ecological subunits. Thus, the intensification of vegetable crops, high yielding rice cultivars and other perennial crops are reported in the HL and MHL sites of the two alluviums. Winter crops and vegetables are specifically grown under intensive management in the HL and MHL sites where as MLL and LL sites are being used mainly for high yielding rice cultivars under anaerobic submerged conditions.

Table 5.1: Land use/cover across the HL and MHL sites of the Brahmaputra and the Ganges alluvium

Land units	Land-use in the Brahmaputra alluvium	Land-use in the Ganges alluvium
Highland (HL)	Sugarcane/Pineapple/Banana; Sugarcane/Banana/Potato/Wheat; Potato/Jute-Transplanted aman rice; Mustard/Wheat/Fallow; Wheat/Mustard/ Transplanted aman rice; Mustard/Potato/Cowpea-Mixed aus and Aman rice; Mustard/Cowpea/Pulses/ Transplanted aman rice; Potato/Tobacco- Transplanted aman rice;	Homestead vegetables; Banana/Sugarcane/Betel nut/Date tree/Coconut; Jute/ Transplanted aman rice; Transplanted aman rice-Fallow/Rabi crops; Tobacco/Wheat/Maize-Transplanted Aman rice; Maize/Wheat/Jute/Vegetables; Wheat/Mustard/Maize/Vegetables-Fallow; Wheat/Mustard/Kharif vegetables;
Medium highland (MHL)	HYV Boro rice-Transplanted aman rice; Mustard/Potato/Cowpea-Mixed aus and aman rice; Mustard/Potato/Pulses/HYV Boro-Transplanted aman rice; Mustard/Cowpea/Pulses-T. Aman rice; Wheat- Transplanted aman rice; Potato-Jute- Transplanted aman rice; Wheat/Jute- Transplanted aman rice; Potato/Pulses-Boro rice; Potato/Tobacco- Transplanted aman rice; Wheat/Pepper/Mustard- Transplanted aman rice;	HYV Boro rice-Transplanted aman rice; Mustard/Cowpea-HYV Boro rice-Transplanted aman rice; Tobacco-Transplanted aman rice; Tobacco/Pulses-Transplanted aman rice; Tobacco/Wheat/Jute/Pulses-Transplanted aman rice; Mustard/Potato/Pulses/HYV Boro-Transplanted aman rice; Wheat/Pepper/Mustard- Transplanted aman rice;

Table 5.2: Land use/cover across the MLL and LL sites of the Brahmaputra and the Ganges alluvium

Land units	Land use in the Brahmaputra alluvium	Land use in the Ganges alluvium
Medium Lowland (MLL) and Lowland (LL)	Mustard/Cowpea/Pulses-HYV Boro rice; HYV Boro Rice-Fallow; HYV Boro rice-Deep transplanted aman rice; HYV Boro rice-Fallow	HYV Boro rice-Transplanted aman rice; HYV Boro rice-Fallow; Shrimp/Hogla (Fencing plant); Shrimp/HYV Boro rice

In Bangladesh, pressure from an increasing population has forced the production of two to four crops every year on the same land of HL and MHL sites resulting in a very short fallow period for agricultural use. This very short fallow period is not sufficient for the land to regain its natural attributes (Hussain et al., 2002), which are essential for its good health or biophysical conditions and productive capacity. Use of chemical fertilizers instead of organic manures or fertilizers negatively impacts the biophysical conditions of the lands specifically the HL and MHL types. Technological developments e.g., the release of short duration cultivars also influences the cropping intensity (CI) in the above land types. Farmers are easily motivated to cultivate these cultivars or varieties in between the major crops within a cropping season. Decrease in the depth and duration of inundation level also enhances the cropping intensity especially in the HL and MHL sites (Brammer, 2002). The farmer's awareness programme by the department of agricultural extension (DAE) of Bangladesh promotes such intensification by providing various incentives to increase the CI. With the advent of modern electronic technologies, i.e., mobile phone, smart phone, and other electronic devices, it becomes very easy to advertise the seeds/fertilizers/varieties which play a role in increasing cropping intensity. Local farmers lack awareness of the capability of soil quality but they only want to grow more food by increasing the cropping intensity. Also, modern rice varieties were developed by Bangladesh Rice Research Institute (BRRI), which are of a short duration, encourage farmers to cultivate multiple rice crops in a cropping season.

5.3.4 Impacts of Inundation Land Types and Cropping Intensity on SOC

The influence of inundation land types on SOC was tested using a one-way ANOVA which shows that SOC across land type varies significantly ($p<0.001$, $F = 40.51$) for the study sites. Further post hoc tests show that SOC differences between the HL and MHL (least significant difference, LSD = 0.103), HL and MLL (LSD = 0.128), HL and LL (LSD =0.230), MHL and MLL (LSD = 0.110), and MHL and LL (LSD = 0.221) types were statistically significant ($p = 0.05$). However, the SOC in the MLL and LL sites was similar (LSD =0.234). Tukey's multiple comparison test on the SOC data also revealed that, except between the MLL and LL sites, SOC comparisons across all other land types were statistically significant ($p<0.01$). From this analysis, it is clear that SOC is lower in the HL and MHL than in the MLL and LL land types. In the HL sites, CI varied from 240-330 % where the mean SOC content is 0.56%. In the MHL sites, CI varied from 200-240% and the mean SOC content is 0.84%. In the MLL sites, CI varied from 120-200% and the average SOC content is 1.26%. In the LL sites, CI varied from 80-90% whereas the mean SOC content is 1.30%. Clearly there is an intrinsic link between inundation land type and CI, as SOC declines with increasing CI. The trend in SOC variation across the land types (LL>MLL>MHL>HL) is thus at least partly driven by CI, which is highest in HL<MHL<MLL<LL (Fig. 5.4). So, the above datasets reveal that SOC is decreasing in the HL and MHL sites with the increasing trends of CI whereas SOC is not declining in the MLL and LL sites with the slow increment of CI. Therefore, it may be said that inundation land types had impacts on the SOC and CI in the study sites. This statement coincides with the findings of Jian-bing et al. (2008) where they noted that SOC variability depends on topographic variability and land use. This is consistent with the findings of other researchers (Bationo et al., 1995; Pagiola, 1995; Patil, 2011) where intensive cultivation of crops was found to accelerate the SOC declines. Wang et al. (2008) noted that upland eroding areas have significantly less SOC than soils in deposition areas. Here, HL and MHL sites may be regarded as the upland erosion areas which have less SOC than soils of the deposition areas i.e.,

MLL and LL sites. Micro topography and vegetation are the dominant factors of SOC variability in small-scale units (Wang et al., 2001).

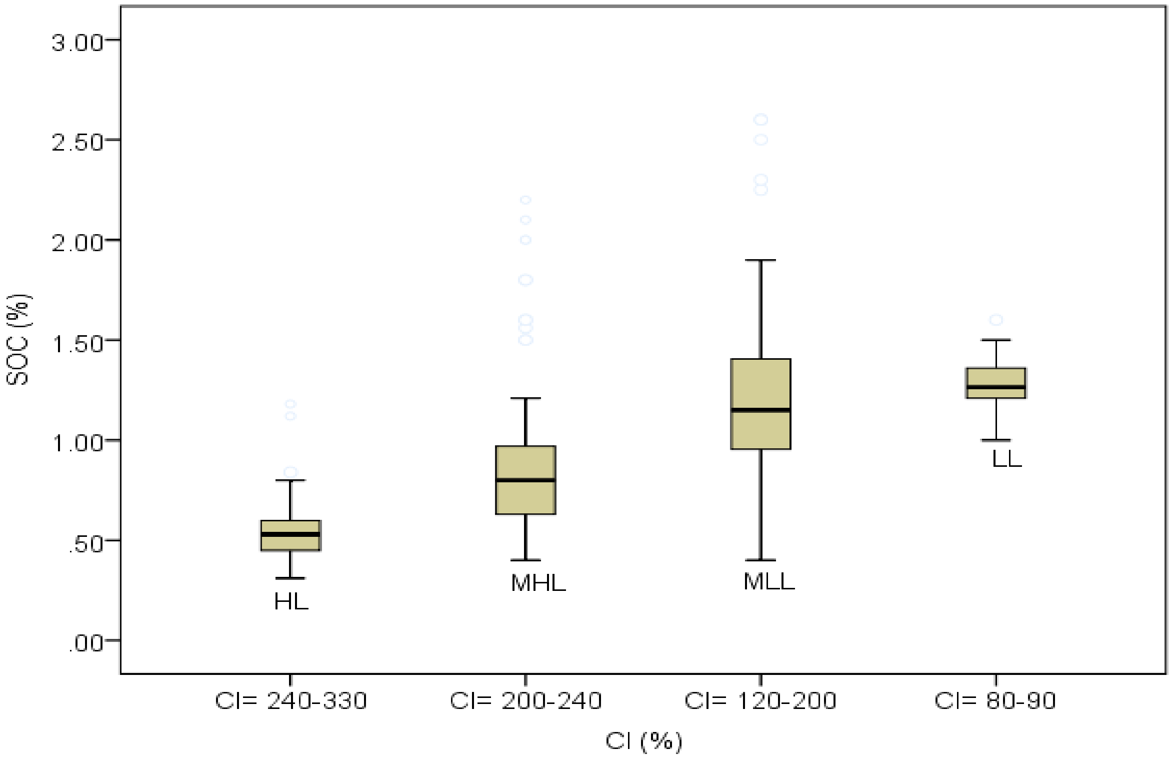

Figure 5.4: Boxplots showing SOC and CI variability pattern across the land types of the study sites

SOC storage strongly depends on land-cover types (Chaplot et al., 2010; Martin et al., 2011). Jobbagy and Jackson (2000) and Yang et al. (2007) reported that land cover significantly affected the distribution of SOC. In the current study, MLL and LL have the highest SOC, which is most likely related to lower cropping intensity with lower decomposition rate of SOC and high soil moisture contents which is in consistent with the findings of Taggart et al. (2012). Conversely, there was notable low SOC content in the HL and MHL, which might be the result of continuous cultivation (Song et al., 2005). Brammer (2002) reported that inundation land level conversion is taking place in some places of Bangladesh due to the decrease in flooding depth; former LL into MLL, MLL into MHL, and MHL into HL in a more or less systematic way. These observations imply that the implementation of an effective plan for land management, conservation, and restoration is required for increasing local level C sequestration and reducing the C budget. Vegetation and topographic control on the spatial variability of SOC was reported by Queslati et al. (2013). Intensive agricultural activities (e.g., tillage) have resulted in enhanced soil mineralization (Lal, 2002), which has led to low SOC in the HL and MHL sites.

Soil texture is closely related to the soil water holding capacity and the decomposition rate of organic carbon, which indicates a key role in the spatial distribution of SOC (Chaplot et al., 2010). In the current HL and MHL sites, soil texture varies from silt loam to silty clay loam or silty clay. On the other hand, in the MLL and LL sites soil texture varies from silty clay loam to clay. So, MLL or LL soil contains more clay than other land types. This soil textural condition governs the soil drainage as well as land cover and land use (FAO, 2006). Chaplot et al. (2010) and Mao et al. (2015) noted that a spatial pattern of SOC storage depends on the textural conditions at a small scale level. This result supports the observation by Jobbagy and Jackson (2000) that clay content is the best predictor of SOC in the lower inundation sites than the higher inundation sites. Thus, this inundation level controls soil textural as well as drainage conditions by controlling their biophysical activities. So, it is seen that HL, MHL types have higher cropping intensity and contains less SOC, whereas LL and MLL types bears lower cropping intensity and contains high SOC. So, it may be said that inundation land types are related to soil texture, drainage as well as land cover and land use or cropping intensity. So, SOC variability or distribution depends on land level, soil texture, land cover, cropping intensity, soil tillage and soil management etc. Similar observations have also been reported by Venteris et al. (2004), Smith (2005), Davidson and Janssen (2006), and Chaplot et al. (2010).

5.4 Conclusions

The SOC distribution over the two alluviums is low, reflecting the intensification of agriculture and land management practices in Bangladesh since the late 1970s. Increasing food demand due to a growing population is the main driver for the widely seen expansion and intensification of agriculture, where multiple crops (2-4) are grown with little or no crop residue or organic amendment. Cropping intensity, in turn, is influenced by land inundation. The lands that are not flooded or are flooded to a lesser extent have considerably higher cropping intensity (such as the HL and MHL types in this study) than lands which are regularly flooded to a greater extent (such as the MLL and LL). These differences in the extent of land inundation are clearly reflected in SOC distribution across the land types, as the SOC levels in the HL and MHL were significantly lower than those in the MLL and LL types, primarily because of the lower cropping intensity in the latter land types. However, in much of Bangladesh cropping intensity is intrinsically linked with inundation land type. SOC depletion as seen in the high cropping intensity sites is a major cause of stagnation in crop productivity, and poses a serious threat to food security in Bangladesh.

CHAPTER 6

Soil Organic Carbon Dynamics in the Agricultural Soils

6.1 Introduction

The terrestrial biosphere can act either as a source or a sink for atmospheric CO_2, and has been considered to hold the key to the ∼2 Gt C $year^{-1}$ discrepancy that persists in estimates of the global carbon cycle designated by the Intergovernmental Panel on Climate Change as 'residual terrestrial uptake' (IPCC, 2000). Both the vegetation and the soil may play a part in the residual terrestrial uptake. Therefore, a new challenge in the context of climate change mitigation is the management of terrestrial ecosystem to conserve existing carbon stocks and to remove carbon from the atmosphere by adding it to its terrestrial stocks (Malhi et al., 1999). Documentation of the results of such management is part of the national greenhouse gas inventory process (IPCC, 1997) that is mandated by the framework convention on climate change. Changes in land use in the last few centuries have been phenomenal. In this regard, Richards (1990) noted that in the past 300 years:

> "… the world's forests and woodlands diminished by 1.2 billion ha, or 19% of the (year) 1700. Grasslands and pastures have declined by 580 million ha, or 8% of the (year) 1700 estimate. Croplands brought into cultivation show a net increase of 1.2 billion ha, or a 466% increase in less than three centuries. … Agricultural expansion and depletion of forests and grasslands were greater in absolute terms over the 35 years, between 1950 and 1985, than in the 150 years between 1700 and 1850."

In the last two centuries, land use change has been a significant source of atmospheric CO_2 through conversion of natural vegetation to farming (Esser, 1987; Houghton, 1999; Lal, 1999; Smith et al., 2000). In the terrestrial ecosystems, the SOC pool is greater (about twice) than living vegetation (Post et al., 1990; Lal, 1999). Because soil organic carbon has generally a slower turnover rate, it may be preserved for a longer time (IGBP, 1998). The huge carbon pool of soils and significant changes of SOC related to land use suggest a considerable potential to enhance the rate of carbon sequestration in soils through land use and management activities, and thereby to decrease the atmospheric CO_2 level (Paustian et al., 1997; Janzen et al., 1998; Lal and Bruce, 1999; Post and Kwon, 2000). A number of efforts have been made to determining the changes in SOC storage induced by land use at regional (Mann, 1986; Esser, 1995; Fearnside and Barbosa, 1997; Houghton, 1999; Smith et al., 2000) and global (Houghton et al., 1987; Esser, 1987; Houghton, 1999) scales. However, because of the high inherent natural variability in the world's soils and variable dynamics of carbon loss under different land uses, accurate estimates of the historic loss are usually hampered by the lack of the baseline data on soils (Lal, 1999). More exact estimates on the size of the current SOC storage and the human-induced changes at regional scale are needed, especially based on greater data density with direct field measurements (Bruce et al., 1999). This would provide a basis for a better understanding of the future carbon fluxes between the terrestrial ecosystem and the atmosphere.

In Bangladesh, agricultural land use planning in terms of crop selection needs to consider the frequency and extent of land inundation. Brammer (1996) outlined that the inundation land types have an important influence on the physical and biological environmental conditions, as well as on land use and agricultural potentials. FAO-UNDP (1988) also reported that inundation lands are crucial for land use planning when they are precisely categorized for agricultural development in Bangladesh and other countries. Land use dynamics in Bangladesh began in the early 1960s with the beginning of the green revolution, but visible changes occurred from the 1970s. During the 1980s, rice production technologies such as high yielding cultivars, fertilizers, seeds, and farm machinery were implemented, driving the process of changes in land use, cropping intensity and cropping patterns.

The expansion of high yielding rice cultivar was found increasing at a considerably rate with the increasing availability of modern inputs. Rahman (2010) reported that expansion of areas under high yielding cultivars with irrigation facilities in Bangladesh initiated the agricultural expansion. Thus, over the years, cropping patterns as well as cropping intensity have changed significantly due mainly to the changes in flooding depths and extent, and the general intensification of farming systems. These changes in land use and/or cropping pattern, directly or indirectly, are likely to have impacts on soil quality, particularly SOC (Post and Kwon, 2000). Thus, land use and management are the important determinants of SOC stock. Soil organic carbon changes at farm levels over time are vital to assess the influence of change in land use and management practices, and to clearly define the mechanisms and processes of soil degradation or resilience (Li, 1995). In Bangladesh, the high population pressure (more than 160 million) has forced the production of two or three crops a year on the same land, resulting in a very short fallow period. This short fallow period leaves little or no time for the land to regain all its natural attributes, which are essential for its biophysical conditions (Hussain et al., 2002). Such intensive land use could cause widespread land degradation due to loss of SOC and its associated influences on soil structure and fertility, which are gradually likely to aggravate with time due to ever-increasing population pressure.

The main aims of this chapter were (i) to identify the land use as well as cropping intensity (CI) changes over the period 1989-92 to 2012, and (ii) to estimate the SOC loss or sequestration over this period of time (1989-92 to 2012) by comparing the historical SOC measurements (1989-92) with their current (2012) measurements.

6.2 Materials and Methods

One hundred ninety composite soil samples were collected from the same four sub-sites under the Brahmaputra and the Ganges alluviums, which were previously sampled by Soil Resource Development Institute (SRDI) of Bangladesh during 1989-92. The land and soil resource utilization guide (LSRUG) maps of SRDI were used in the field for revisiting the sampling sites. It may be mentioned that LSRUG reports of SRDI contains the historical SOC and cropping intensity (CI) datasets. The four sub-sites were Delduar, Melandah, Fultala, and Mirpur under the two major alluviums of Bangladesh – the Brahmaputra and the Ganges. These sites fall under the diverse agro-ecological regions of Bangladesh. A list of agro-ecological regions under the studied sub sites along with the sampling information are presented in Table 6.1. It should be mentioned that Delduar and Melandah sub-sites fall under the Brahmaputra River alluvium which were previously sampled during 1990-1991 and were re-sampled in March 2012 so that changes over time in cropping intensity (CI) and soil organic carbon (SOC) can be estimated. Similarly, the sub-sites Fultala and Mirpur fall under the Ganges River alluvium which were previously sampled during 1989-1992 and were re-sampled in April, 2012. The changes in SOC were assessed by the paired t-Test in IBM SPSS statistics version 20.0, and boxplot analysis as well. The SOC dynamics were assessed by comparing the present and previous SOC of individual sites, sub-sites, and individual land types, etc.

Table 6.1: Sampling information across the study sites under the Brahmaputra and the Ganges alluviums

Sites	Sub-sites	Agro-ecological regions	Sampling year		Number of samples*
			This work	Previous study	
Brahmaputra Alluvium	Delduar	Old and Young Brahmaputra floodplains	2012	1990	36
	Melandah	Old and Young Brahmaputra floodplains	2012	1991	60
Ganges Alluvium	Fultala	Ganges river and tidal floodplains, and Gopalganj-Khulna peat basins	2012	1989	28
	Mirpur	Ganges river floodplains	2012	1992	66
	Total number of soil samples		-	-	190

*190 samples were taken total by revisiting the previous sampling locations

6.3 Results and Discussion

6.3.1 Changes in Land Use and Land Cover

Change in crops or cropping patterns in Bangladesh started in the early sixties with the beginning of the green revolution, but visible changes occurred in the 1970s onward. Over the years, cropping patterns have changed significantly due to changes in non-economic and economic factors. During the late 1960s and throughout the 1970s, breakthroughs in rice production technologies occurred, setting in motion changes in land use, cropping intensity, and cropping patterns. Rahman (2010) reported that technological development and expansion of modern crop varieties, increase in the use of chemical fertilizers, extension of irrigation facilities, high demand for food, and all these factors accelerated the changes in cropping patterns and cropping intensity. Thus, with the introduction of irrigation facilities, high yielding cultivars and flood protection measures in some areas, most farmers have switched from single crop to double or triple crops with higher cropping intensities as seen in the study sites (Tables 6.2-6.3). Traditional varieties of crops were replaced by the new high yielding varieties increasing the number of crops as well as cropping intensity specifically in the HL (high land) and MHL (medium high land) sites. On the other hand, MLL (medium low land) and LL (low land sites) sites due to their inundation level are limited to one to two crops i.e., relatively lower cropping intensity. It is important to note that number of crops or cropping pattern have also increased by 2-3 times in the HL and MHL units compared to 1989-92, whereas, the cropping pattern almost remains the same in the MLL and LL sites (Tables 6.2-6.3), with the only difference being local or traditional rice varieties being replaced by high yielding rice cultivars in these sites specifically those grown under submerged rice conditions (Tables 6.2-6.3). Similar observations have been reported by Karim and Iqbal (2001). Smith et al. (2000) reported that changes in SOC in agricultural soils are influenced by land use, management practices, and soil characteristics. Brammer (2002) noted that the introduction and expansion of high yielding cultivars of rice or other crops, extension of irrigation facilities, construction of flood control dams and thus changes in inundation lands especially in the Ganges and the Brahmaputra alluviums were the major factors responsible for changes in cropping patterns and cropping intensity.

Table 6.2: Changes in land use/cover in the studied sites under the Brahmaputra alluvium

Sub-sites	Land types	Land use *(1989-92)	Present land use (2012)
Delduar	High land (HL)	1. Sugarcane	1. Sugarcane/Pineapple/Banana
		2. Winter vegetable crops-Fallow	2. Potato/Jute-Transplanted aman rice
		3. Aus rice/Jute-Winter crops	3.1 Mustard-wheat-Fallow
			3.2 Potato/Jute-Transplanted aman rice
			3.3 Mustard/Potato/Cowpea-Mixed aus and Aman rice
			3.4 Mustard/Cowpea/Pulses-T. aman
	Medium high land (MHL)	1 Aus rice/Jute- Winter rabi crops	1.1 HYV *Boro* rice-Transplanted.*aman* rice
			1.2 Mustard/Potato/Cowpea-Mixed *Aus* and *Aman* rice
			1.3 Mustard/Pulses/HYV *Boro*- Transplanted *aman* rice
			1.4 Mustard/Cowpea/Pulses-T. aman
		2. *Aman* rice-Mustard-**HYV Boro rice	2.1 Mustard/Potato- HYV *Boro* rice-Transplanted *aman* rice
			2.2 Wheat-Transplanted *aman* rice
			2.3 Potato/Jute-Transplanted aman rice
			2.4 Potato/HYV Boro-Transplanted aman rice
	Medium lowland (MLL) and Lowland (LL)	1 Mixed aus and Broadcast *Aman* rice/*Aus* rice	1. Mustard/Cowpea/Pulses-HYV Boro rice
		2 HYV Boro rice-Fallow	2.1 HYV *Boro* rice-Fallow
			2.2 HYV *Boro* rice-Deep Transplanted *aman* rice
Melandah	Highland (HL)	1 Sugarcane	1.1 Sugarcane/Banana/Potato/Wheat
			1.2 Banana
		2 Aus rice/Jute-Winter vegetables	2. Wheat/Pepper/Mustard-Transplanted aman rice
		3 Broadcast aman rice-Fallow	3.1 Potato/Tobacco-Transplanted aman rice
			3.2 Boro-Transplanted aman
	Medium highland (MHL)	1 Aus rice/Jute-Transplanted aman rice	1. HYV Boro rice-Transplanted aman rice
		2 Transplanted aus rice-Fallow	2. Wheat/Jute-Transplanted aman
		3 Transplanted aman rice-Fallow	3.1 Potato/Pulses-Boro rice; Boro-Transplanted aman
			3.2 Wheat/Pepper/Mustard-Transplanted aman rice
		4 Broadcast aman rice-Fallow	4.1 Pepper/HYV Boro-Transplanted aman rice
			4.2 Potato/Tobacco-T.aman rice
	Medium lowland (MLL) and Low land (LL)	1 Mixed Broadcast aus and aman rice-Winter crops	1.1 HYV Boro rice-Deep transplanted aman rice
			1.2 HYV Boro rice-Fallow
		2 Grazing/Fallow	2.1 HYV Boro rice-Fallow

* According to previous database of 1989 and 1992; Note: Italics indicates the local name of the crops

** HYV= High Yielding Varieties or cultivars

Table 6.3: Changes in land use/cover in the studied sites under the Ganges alluvium

Sub-sites	Land types	Land use *(1989-92)	Present land use (2012)
Fultala	High land (HL)	1. Aus rice/Jute-Vegetables	1.1 Date tree; Coconut; Betel nut 1.2 Homestead vegetables
		2. Aus rice/Jute-Transplanted aman	2.1 Banana/Vegetables
		3. Aus rice/Jute/Vegetable-Rabi crops	3.1 Jute-T. Aman 3.2 Transplanted aman rice-Fallow/Rabi crops
	Medium high land (MHL)	1. Aus rice/Jute-Transplanted aman rice/Rabi crops	1. HYV Boro rice –Transplanted aman rice
		2. Aus rice/Jute-Transplanted aman rice-Fallow	2. HYV Boro rice-Transplanted aman rice
		3. Transplanted aman-Fallow	3. HYV Boro rice-Transplanted aman rice
		4. Transplanted aman rice-HYV Boro rice/ Rabi vegetable crops	4. Mustard/Cowpea-HYV Boro rice-Transplanted aman rice
	Medium lowland (MLL) and Lowland (LL)	1. Mixed aus rice and Broadcast aman rice-Fallow/Rabi vegetable crops	1. HYV Boro rice-Transplanted aman rice
		2. Mixed aus rice and aman rice-Fallow	2.1 Shrimp/Hogla (Fencing plant)
		3. Broadcast aman rice-Fallow	3.1 HYV Boro rice-Fallow 3.2 Shrimp
Mirpur	Highland (HL)	1. Sugarcane	1. Tobacco/Wheat/Maize-Transplanted aman rice
		2. Transplanted aman rice-Rabi pulses/Fallow	2.1 Sugarcane 2.2 Maize/Wheat/Jute/Vegetables
		3. Aus rice/Jute-Rabi vegetable crops	3.1 Wheat/Mustard/Maize/Vegetables-Fallow 3.2 Wheat/Mustard/Kharif vegetables
	Medium highland (MHL)	1. Aus rice/Jute-Transplanted aman rice-Fallow	1.1 Tobacco-Transplanted aman rice 1.2 HYV Boro rice-Transplanted aman rice
		2. Transplanted aman rice-Fallow	2.1 HYV Boro rice-Transplanted aman rice
		3. Transplanted aus rice-Transplanted aman rice-Fallow	3.1 Tobacco/Pulses-Transplanted aman rice 3.2 HYV Boro rice-Transplanted aman rice
		4. Aus rice/Jute-Transplanted aman rice-Rabi crops	4.1 Tobacco/Wheat/Jute/Pulses-Transplanted aman rice 4.2 HYV Boro rice-Transplanted aman rice
	Medium lowland (MLL)	1. Mixed Broadcast aus rice and Transplanted aman rice-Rabi vegetables/Fallow	1. HYV Boro rice-Fallow

* According to previous database of 1989 and 1992; Note: Italics indicates the local name of the crops

** HYV= High Yielding Varieties or cultivars

Thus, the intensification of vegetable crops, high-yielding rice cultivars, and other perennial crops are commonly grown in the HL and MHL sites. Winter crops and vegetables are specifically grown under intensive management in the HL and MHL sites where as MLL and LL sites are being used for high yielding rice cultivars under submerged conditions. Thus, the number of crops with modern cultivars has enhanced higher cropping intensity (CI) in the HL and MHL sites compared to the MLL and LL sites.

6.3.2 SOC Dynamics

SOC sampled in the 2012 across all 4 sub-sites varies from 0.31 to 2.60 % and the overall mean is 0.84±0.469% (n = 190). SOC in the same soils during the previous study period (1989-92) ranged from 0.23 to 2.78 % and the overall mean was 0.97± 0.559% (n= 190) (Table 6.4). SOC in the Brahmaputra alluvium in the 2012 sampling varies from 0.40 to 2.60 %, with an overall mean of 0.92±0.521% (n = 96). SOC in the same soils during the year 1989-92 sampling varied from 0.46 to 2.78 % and the mean was 1.09± 0.622 % (n = 96). On the other hand, SOC in the Ganges alluvium varies from 0.31 to 2.30 %, with an overall mean of 0.76±0.397 % (n = 94). SOC in the same soils during the 1989-92 sampling varied from 0.23 to 2.03 % and the mean SOC was 0.85±0.458% (n = 94) (Table 6.4). A comparison of the present (2012) and previous (1989-92) samples, using the paired t-test showed that SOC has declined significantly ($p<0.001$) in the two alluviums over the two sampling periods. It provides a clear evidence of SOC declining considerably in the Brahmaputra alluvium and the Ganges alluvium during the 1989-92 to 2012 period (Table 6.4). Similarly, SOC declined during this period significantly ($p<.001$) at all four sub sites (Delduar, Melandah, Fultala, and Mirpur). A similar analysis (paired t-Test) was used to compare the SOC measured in 2012 with past SOC levels across the land types, i.e., HL, MHL, MLL and LL sites which also revealed that SOC has declined significantly ($p<0.001$) in the HL and MHL sites. In the MLL and LL sites, SOC in fact has increased significantly ($p<0.05$) (Table 6.4). The depletion of organic carbon in Bangladesh is mainly caused by low organic residues input and high cropping intensity (CI). Crop residues and livestock manures are widely used as fuel since firewood is in short supply. The hot humid climatic conditions also encourage rapid mineralization of organic matter.

Table 6.4: Statistics of the paired SOC (%) values of the four sub- sites

Parameters of SOC statistics	Time level	N	Mean	SD*	P**
Whole study site	2012	190	0.842	0.469	
	1989-92		0.978	0.559	<.001
Brahmaputra alluvium	2012	96	0.921	0.521	
	1989-92		1.099	0.622	<0.001
Ganges alluvium	2012	94	0.762	0.397	
	1989-92		0.855	0.458	<0.001
Delduar sub-site	2012	36	1.228	0.684	
	1989-92		1.502	0.811	<0.001
Melandah sub-site	2012	60	0.739	0.260	
	1989-92		0.860	0.276	<0.001
Fultala sub-site	2012	28	1.135	0.511	
	1989-92		1.311	0.518	<0.05
Mirpur sub-site	2012	66	0.603	0.178	
	1989-92		0.661	0.248	<0.05
Highland (HL) sites	2012		0.553	0.174	
	1989-92	51	0.641	0.274	<.001
Medium highland (MHL)	2012	98	0.823	0.422	<.001
	1989-92		1.066	0.589	
Medium lowlands (MLL)	2012	34	1.301	0.593	<0.05
	1989-92		1.258	0.601	
Lowlands (LL)	2012	07	1.041	0.255	<0.05
	1989-92		0.854	0.258	

*SD= Standard deviation; **P values comes from paired T-test

The results of this study suggest that changes in land use have had impacts on the SOC levels. This is consistent with other observations (Post and Kwon, 2000). In our study, the average SOC depletion has taken place in the HL and MHL sites rather than the MLL and LL sites. This is due to a greatly reduced input of crop residues due to the increased CI. The conversion of land use from traditional to high-yielding crops, gown 2-3 times a year, reduces the SOC mainly through reducing biomass inputs into the soil, increasing soil erosion and accelerated decomposition of SOC. Similar findings have been reported by other works (Martinez-Mena et al., 2002; Almagro et al., 2010). Furthermore, it is well known that the magnitude of SOC loss increases with tillage or cultivation (Celik, 2005; Martinez-Mena et al., 2008). A further point to note here is that HL and MHL sites are more susceptible to soil erosion than MLL and LL, which could also be responsible for SOC reduction in them and its accumulation in the latter group land types (Lal, 2004b), a fact corroborated by Liu et al. (2005). Thus it can be said that low contents of SOC in the HL and MHL sites may be attributed due to their high land use intensity and low organic residue inputs as well their erosion susceptibility.

6.3.3 SOC Temporal and Spatial Variability

SOC variability was assessed using the boxplot analysis. SOC variability or change was identified among the alluviums, the individual sub- sites and land types respectively. The results show that SOC variation is low in the present (2012) SOC dataset, whereas SOC variation was high in the previous (1989-92) dataset of the whole study site (Fig. 6.1). It means that not only SOC has decreased its variability has also decreased. This is because the rate of SOC decline or decreases at low SOC levels and at certain low levels SOC stops declining, reaching the so-called “system equilibrium.” The SOC in the 2012 sampling averaged to 0.70%, whereas earlier (1989-92) it was 0.95%—a decline of about 26%.

SOC distribution across the alluvium shows that SOC has decreased in the Brahmaputra alluvium site and the boxplot shows that its distribution changed from positively skewed to symmetric (Fig. 6.2). Likewise, SOC has decreased in the Ganges alluvium and the distribution changed from symmetric to positively skewed (Fig. 6.2). The boxplot analysis (Fig. 6.2) further shows that previously (1989-92) SOC in the Brahmaputra alluvium averaged to 0.95% while its measurements in 2012 averaged to 0.75%. The rate of decrease of SOC is about 21%. Previously measured SOC in the Ganges alluvium averaged to 0.75% and it decreased to 0.60 % during 1989-92 to 2012 period, by about 20% (Fig. 6.2).

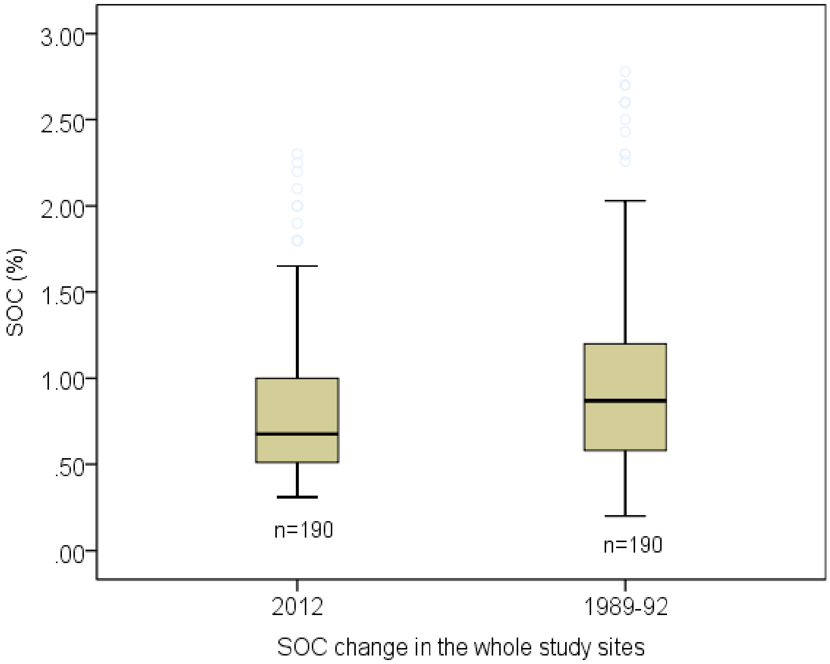

Figure 6.1: Boxplots showing SOC change during 1989-92 to 2012 in the whole study site

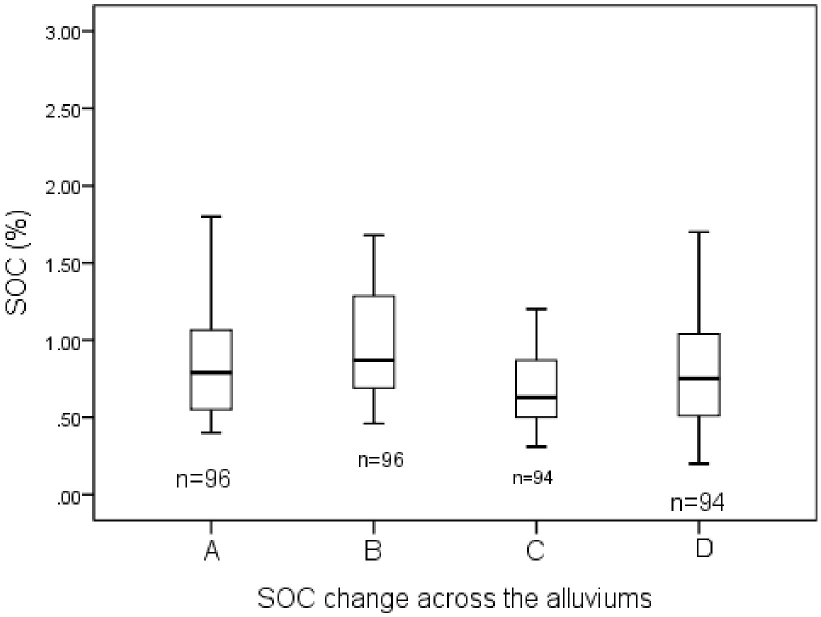

Figure 6.2: Boxplots showing SOC change measured in 1989-92 and 2012 across the alluviums (A and B: SOC at 2012 and 1989-92 in the Brahmaputra alluvium respectively; C and D: SOC at 2012 and 1989-92 in the Ganges alluvium respectively)

SOC variation is higher in the previous (1989-92) sampling than that in the present (2012) SOC in the Delduar sub-site, though the SOC is positively skewed in both instances (Fig. 6.3). The SOC measured in 2012 averaged to 1.00% whereas it was 1.30 % in 1989-92, a decrease of about 23% during the 1989-92 and 2012 sampling period. The average SOC measured in 2012 is lower in the Melandah sub-site soils than its previous counterpart (1989-92).

The boxplot of the SOC datasets show that the SOC distribution has become positively skewed while it was negatively skewed at sub- site during 1989-92 (Fig. 6.3). The mean SOC of present dataset is 0.70% whereas it was 0.90% in 1989-92. So, the rate of decrease of SOC is about 23% in the Melandah sub- site. SOC average is lower in the present dataset (2012) than the previous SOC dataset (1989-92) of the Fultala sub- site. The boxplot indicates that SOC distribution in the present dataset is approximately symmetric whereas SOC distribution was negatively skewed in the previous SOC dataset (Fig. 6.3). The mean SOC of the present dataset at this sub-site is 1.20 % whereas it was 1.50% in 1989-92, a decrease of 20%. The boxplot of SOC dataset show that SOC is approximately symmetric, with low average and low variation in the Mirpur sub-site for the both times but the present SOC show lower variation than the previous one (Fig. 6.3). The present SOC average is 0.55%, whereas it was 0.70% in 1989-92, a decrease of 21% in the Mirpur sub- site. From the above analysis, it is clear that SOC has been decreased in all 4 sub-sites. The sub sites belong to a diverse agro-ecological zone and possess very dynamic physiographic units as the SOC pattern is heterogeneous. Due to their topographic variability, cropping nature is also diverse. In most cases, the soils are used for the cultivation of three or four crops without any fallow periods.

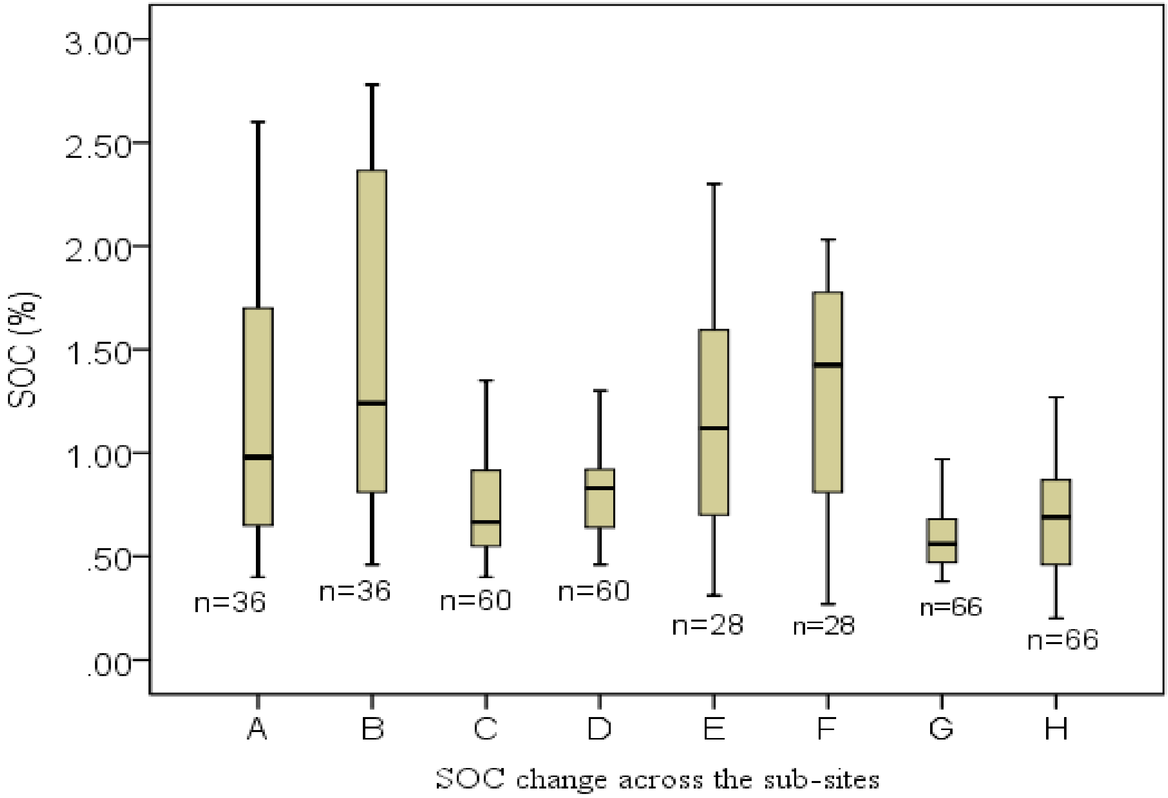

Figure 6.3: Boxplots showing SOC change during 1989-92 and 2012 across the sub-sites.
(A and B: SOC at Delduar in 2012 and 1989-92 respectively; C and D: SOC at Melandah in 2012 and 1989-92 respectively; E and F: SOC at Fultala in 2012 and 1989-92 respectively; G and H: SOC at Mirpur in 2012 and1989-92 respectively)

The CI in the Delduar sub-site increased from 180 to 270 %, Melandah sub-site from 165 to 245%, Fultala sub- site from 130-180%, and Mirpur sub-site 130 to 230%. Clearly, cropping intensity increased substantially in all sub-sites except Fultala (Fig. 6.4) where it increased, but only moderately. The Fultala sub-site belongs to the coastal salinity prone area (Brammer, 1996; FRG, 2012). CI in this area remains relatively moderate, because crop production in this site is hampered by the expansion of salinity. Nonetheless, it would appear that increased CI across the sites is a contributory factor for the SOC decline observed.

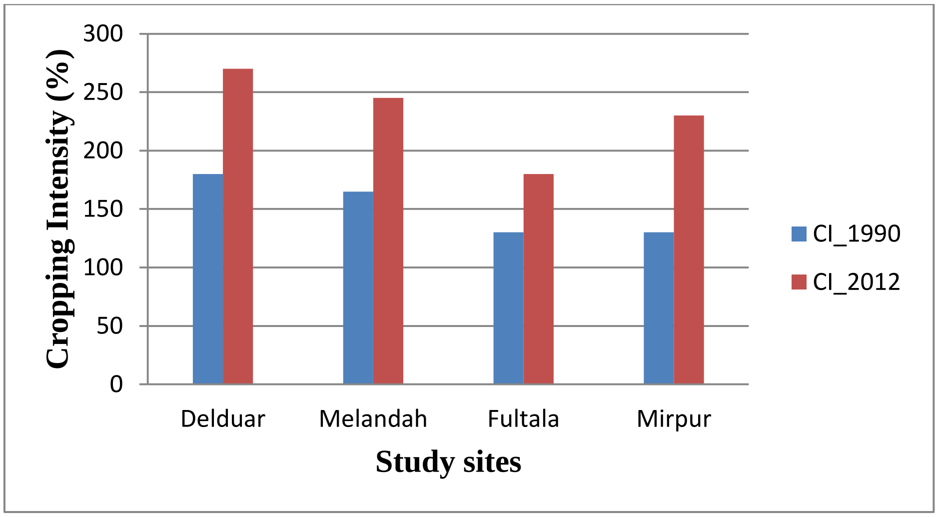

Figure 6.4: Changes in cropping intensity between 1989-92 and 2012 in the study sites

SOC variation across the HL sites measured in 2012 is low and is positively skewed and whereas in the previous HL datasets (1989-92) it was positively skewed or approximately symmetric (Fig 6.5). Here SOC decreased from 0.64% (mean) to 0.55%, a decline of about 17%. Variation in the present (2012) SOC of MHL sites is much higher than seen for HL sites (Fig 6.5). The present SOC in the MHL is 0.82% whereas it was 0.96% in 1989-92. Here SOC decreased from 0.96% (mean) to 0.82%, a decline of about 14%. Present SOC variation in the MLL sites (2012) is higher than the previous SOC (1989-92) in these land types (Fig. 6.5). The average SOC in the MLL sites is 1.30% whereas it was 1.25% in 1989-92, reaming largely similar over the study period (1989-92 to 2012). The present SOC variation in the LL sites (2012) is low (Fig 6.5). The present SOC in the LL sites is 0.94% whereas it was 0.50% in 1989-92 – a drastic increase of is about 88% in the LL sites. From the boxplot SOC analysis, it is clear that SOC has decreased in the HL MHL sites and increased in the MLL and LL sites. Lal (2004) noted that SOC loss due to agricultural activities in Bangladesh between 1967 and 1995 was 16.2 Mg C/ha, with a range of 3.8 to 30.5 Mg C/ha. For a land area of 3 Mha, the total SOC loss was estimated to be 42.8 Tg C within a 27-year period. This decline was attributed to removal of crop residue and changes in cropping systems etc. Cai (1996) and Lal (2002) reported that rice cultivation enhances SOC sequestration at the rate of 0.2-0.3 Mg/ha/year, which is also seen in this study (MLL and LL units where rice cultivation is common). The incorporation of rice residues and continuous flooding has become common in tropical areas, which promotes C sequestration. Long-term experiments in the Philippines (Pampolino et al., 2008) and China (Zhang and He, 2004) showed that continuous cultivation of irrigated rice with balanced fertilizer on submerged soils increased SOC. Minasny et al. (2012) noted that SOC content in the top soils (0-15 cm) increased with the continuous rice cropping in Indonesia (Java) and South Korea. Wu et al. (2003) reported that non-irrigated cultivated soils experienced a significant C loss, ranging from 40% to 10% relative to their non-cultivated counterpart.

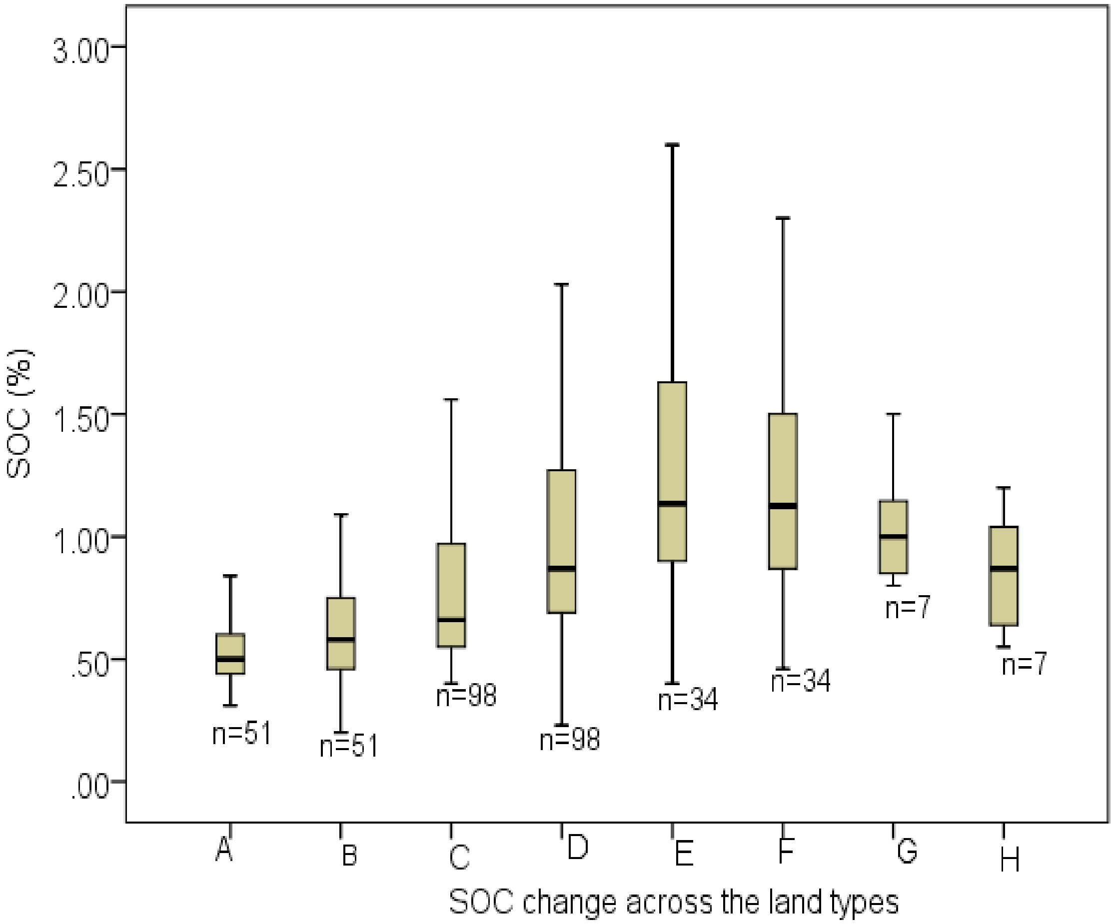

Figure 6.5: Boxplots showing SOC change during 1989-92 and 2012 across the land types of the study sites (A and B: SOC in 2012 and 1989-92 in the highland sites respectively; C and D: SOC in 2012 and 1989-92 in the medium highland sites respectively; E and F: SOC at 2012 and 1989-92 in the medium lowland sites respectively; G and H: SOC in 2012 and 1989-92 in the lowland sites respectively)

6.3.4 Concept of SOC equilibrium

SOC equilibrium means that SOC remains stable when land use, land management, and environmental properties (such as climate, CO_2 concentration or nitrogen deposition) do not change either. Stevenson (1982) proposed an equation, which is most appropriate to explain the SOC equilibrium situation in the HL and MHL sites of Bangladesh. The equation is $dc/dt= -kC+A$. Where, dc/dt= rate of SOC change, k= decomposition constant, C= SOC content at a time t, A= Accretion constant. The magnitude of A depends on land use and management. So, the difference between kC and A that determines the rate of SOC change. On the other hand, Lal (1998) noted that soil degradation processes decrease SOC and increase the magnitude of decomposition constant k, and, in contrast, soil restorative processes increase SOC and decrease the magnitude of k. In Bangladesh, agricultural land use practices that increase k due to the effects of continuous cultivation, residue removal in most cases of the HL and MHL types, low input subsistence agriculture, excessive tillage etc. The rate of sequestration in the soils of Bangladesh is very slow in most cases because of their low SOC contents. If the soil is continuously cultivated (Bangladesh situation), its SOC content declines until an equilibrium level (Ce) is achieved. The magnitude of Ce depends on the climate, land use and cropping pattern etc. The equation is $C= Ce + (Co-Ce)e^{-rt}$ Where C= SOC constant at time t, r = fraction of C decomposed /year, t= time in years, Ce= equilibrium level, Co-Ce= difference in SOC=gaseous emission into the atmosphere and losses due to soil erosion and leaching as dissolved and particulate carbon. In Bangladesh, SOC has perhaps declined to an equilibrium level, and further decline may not occur unless land use intensity changes further.

Several studies have reported that the rate of SOC change in various agricultural soils of Canada has nearly reached equilibrium after several decades of cultivation (Liang and MacKenzie, 1992; Monreal and Janzen, 1993; Nyborg et al., 1995). Janzen et al. (1998) inferred that the loss of SOC as a result of conversion to arable agriculture has diminished to low levels in many agricultural soils in Canada. They also stated that the current changes in SOC dynamics are largely a function of current management practices. A study also showed that conversion of forest lands to permanent cropping decreases the SOC stocks rapidly in the initial years and at slower rate thereafter, approaching a new equilibrium after 30 to 50 years (Mann, 1986; Balesdent et al., 1988; Arrouays et al., 1995; Nieder and Benbi, 2008). Arrouays and Pelissier (1994) demonstrated that SOC storage in the 0-50 cm layer soil horizon declined by about 50% after 35 years of intensive corn cropping in temperate soils. Decline in OC in the tropical soils due to continuous cultivation has also been reported in some studies (Brown and Lugo, 1990; Lugo and Brown, 1993). Bernoux et al. (2006) suggested that any modification of land use or land management can induce variations in SOC stocks, even in agricultural systems that are perceived to be in a steady state.

6.3.5 Challenges and limitations to SOC sequestrations

Despite the potential, and the dire need for improving soil quality, enhancing SOC pool in the soils of Bangladesh remains a challenge for agricultural scientists, land managers and policy makers. Major impediments to SOC sequestration are social and economic conditions, which ultimately related to: (i) continuous increment in cropping intensity; (ii) removal of crop residues for fodder, fuel, and other purposes; (iii) use of crop residues and manure for household cooking as fuel rather than a soil amendment; (iv) low external input of chemical fertilizers and organic amendment causes depletion of the SOC pool because nutrients harvested in agricultural products are not replaced; (v) excessive tillage rather than conservation tillage which makes topsoil degradation through erosion and enhanced mineralization; (vi) little or no fallow periods; and (viii) crop rotations often do not have nitrogen fixing legumes.

6.4 Conclusions

Estimating C change or dynamics in agricultural soils is vital to assess the sequestration or loss in an ecosystem. The findings revealed that loss of SOC is more prominent in the HL and MHL sites where SOC sequestration takes place in the MLL and LL sites. SOC in the HL and MHL sites reaches an equilibrium state or steady state within 20-25 years. The reason for such losses of SOC in the HL and MHL sites are at least partly due to intensive cropping with improper management. This SOC depletion causes low productivity, which is considered one of the most serious threats to the sustainability of agriculture in Bangladesh. Policies based on recommended management practices (RMPs) should be formulated for soil carbon sequestration. The RMPs should include use of cover crops, manure and compost, better crop residues management, liming and balanced fertilizer, etc.

CHAPTER 7

Soil Organic Carbon and Total Nitrogen Storage and Distribution in the Agricultural Soils as Affected by Soil Depths and Inundation Land Types

7.1. Introduction

The biogeochemical cycles of carbon and nitrogen in terrestrial ecosystems have received increasing attention worldwide over the past few decades because the emission of their oxides contributes greatly to global warming (Fu et al., 2010). As soils contain significantly more carbon than is present as CO_2 in the atmosphere, the stability of this soil store, particularly under changing temperature and other climatic factors, is a major source of uncertainty in future climate change predictions (Giardina and Ryan, 2000; Fang et al., 2012; Knorrs et al., 2005; Davidson and Janssen, 2006). Soil is a major pool of carbon and nitrogen and plays an important role in their global cycles (Batjes, 1996). The loss of C and N via the emissions of greenhouse gases, GHGs (CO_2, CH_4 and N_2O) from soil to the atmosphere by natural or anthropogenic processes is a contributory factor to global warming. Consequently, sequestration of soil organic carbon (SOC) and conservation of total nitrogen (TN) are of increasingly scientific and political interests worldwide. SOC and TN, often tightly coupled, are controlled by a number of natural and anthropogenic factors, including climate, vegetation, topography, parent material, intrinsic soil properties, land use and management practices (Homann et al., 1995). A better understanding of SOC and TN contents and their relationships with these controlling factors is critical to evaluate soil C and N pools as well as potentials for C sequestration and N conservation to offset anthropogenic greenhouse gas emissions.

SOC is one of the main factors affecting soil quality and agricultural productivity. Being a source as well as storage of plant nutrients, SOC plays an important role in terrestrial C cycle (Freixo et al., 2002). Land use has a significant effect on SOC storage, since it affects the amount and quality of litter input, litter decomposition rate, and stabilization of SOC (Bronson et al., 2004). Information on global and regional SOC pool in topsoil is generally available for a variety of land use and climatic conditions (Batjes, 1996). However, study on SOC and TN storage in soils as affected by inundation land is very scanty, particularly in Bangladesh. It is widely accepted that SOC is largely concentrated in the top 30 cm of the soil, but there is a growing evidence that deeper soil horizons have the capacity to sequester high amounts of SOC (Jobbagy and Jackson, 2000; Swift, 2001) and that this should be considered for SOC emission-storage analysis.The importance of SOC sequestration in sub-soils mitigating the greenhouse effect is related to the fact that subsoil SOC occurs in fairly stable and highly recalcitrant forms to biodegradation (Batjes, 1996; Kogel-Knabner, 2002; Nierop and Verstraten, 2003). SOC surveys usually consider a fixed soil depth, typically 1 meter. Global surveys based on vegetation units (Post et al., 1982) and soil taxonomic units (Eswaran et al., 1993; Batjes, 1996) indicate that soil store 1500-1600 Pg C in the top one meter. However, soil carbon can be underestimated in its global budgets by fixing a lower boundary at 1m depending on the vertical distribution of SOC.

SOC content exhibits considerable variability spatially, both horizontally according to land use and vertically within the soil profile (Dhakal et al., 2010). The SOC diminishes with depth regardless of vegetation, soil texture, and clay size fraction (Trujilo et al., 1997). Soils of the world are potentially viable sinks for atmospheric carbon and may significantly contribute to mitigate the global climate change (Lal et al., 1998). However, the assessment of potential carbon sequestration in soil requires estimating carbon pools under existing land uses and its depth wise distribution in the soil profile. Minimizing soil disturbance generally leads to soil organic carbon accumulation, while high-intensity/frequency of cultivation causes decline in SOC (Bajracharya et al., 1998).

Climate, topography and soil properties are considered as main environmental controls of SOC and TN (Hontoria et al., 1999). Climate is known as the primary driver for vegetation type, plant growth and litter decomposition (Perry, 1994), and thereby influencing SOC loss-gain balance (Rustad and Fernandez, 1998). Topographical factors, such as elevation, slope and horizon depth influence SOC levels by controlling soil water balance and thus plant litter production and decomposition, as well as soil erosion and geologic deposition processes (Birkeland, 1984). Among soil properties, soil water regime, which integrates soil and climatic characteristics and topographical features, may be a critical factor determining SOC contents (Grigal and Ohmann, 1992). Soil pH influences SOC and TN by regulating microbial activities and higher pH value has a negative effect probably because of accelerated decomposition of SOC (Motavalli et al., 1995). Soil texture impacts not only SOC inputs indirectly by influencing vegetation productivity via water availability and soil fertility (Schimel and Parton, 1986), but also through the role of clay in the protection of SOC from decomposition (Bationo et al., 2005). It is well known that higher SOC and TN are found in finer textured soils and clay content has been recognized as a key factor controlling soil C and N dynamics (Homann et al., 2007).

The objectives of this study were: (i) to understand some soil properties across the land types of eight profiles of the two alluviums highlighting the relationships between the SOC and TN; (ii) to estimate the SOC and TN distribution and storage across the study sites; and (iii) to assess the impact of land types and soil depths on SOC and TN distribution and storage.

7.2. Materials and Methods

Two catena were selected across the two alluviums based on the land types for the current study. Fortyeight soil samples from the eight profiles of the major two catena at different soil depths (0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, 80-100 cm and 100-120 cm) were collected. Prior to analysis, the soil samples were air-dried and gently disaggregated. The soil samples were then gently ground using a mortar and pestle and passed through 2 mm sieve and mixed thoroughly. The samples were then preserved in sealed plastic containers for laboratory analysis. An outline of the site characteristics of the land types are presented in Table 7.1. The HL in the both alluviums occurs in the upper parts of the catena. The morphological properties (color, texture, drainage, structure, consistence, nature and distribution of roots) of the HL sites are similar in both alluviums (Table 7.1) except pH. The pH in the Brahmaputra alluvium (BA) site is slightly acidic to neutral whereas in the Ganges alluvium (GA), it is neutral to alkaline. The MHL in the both alluviums occur in the middle part of the catena. The morphological properties of the MHL sites in both alluviums are similar except inundation depth (Table 7.1). The MLL sites in both alluviums occur in the lower middle part of the catena. The morphological properties of the MLL sites of both alluviums are more or less similar except the inundation depth (Table 7.1). The LL in the both alluviums occurs in the lower part of the catena. The morphological properties of the LL sites of the both alluviums are more or less same except the inundation depth also (Table 7.1).

Table 7.1: Morphological characteristics of the inundation land types of the eight profiles of the Brahmaputra and the Ganges alluvium

Land types	Characteristics	Brahmaputra alluvium	Ganges alluvium
	Location	24˚08’ N and 89˚ 58’ E	23˚ 49’ N and 89˚ 00’ E
HL	Topographic position	Upper part of the ridges of a catena under the Brahmaputra alluvium	Upper part of the ridges of a catena under the Ganges alluvium
	Soil color	Olive grey to grey with olive brown in the lower depths (60-120 cm).	Olive brown in the 0-60 cm depth and light olive brown in the lower depths (60-120 cm)
	Texture	Silt loam	Silt loam
	pH	6.0 to 6.9	7.5 to 7.9
	Drainage	Imperfectly drained	Imperfectly drained
	Structure	Varied from angular blocky to prismatic	Prismatic except in the plough layer
	Consistence	Friable under moist conditions	Friable in the 0-60 cm and slightly friable in the 60-120 cm under moist conditions
	Soil series	Sonatala series (Aeric Endoaquepts)	Sara series (Aeric Endoaquepts

MHL	Location	24˚ 06’ N and 89˚ 56’ E	23˚ 51’ N and 89˚ 01’ E
	Topographic position	Middle part of the ridges	Middle part of the ridges
	Soil color	Light grey to grey	Light grey to grey
	Texture	Silty clay to silty clay loam	Silty clay to silty clay loam
	pH	6.5 to 7.2	6.9 to 7.6
	Drainage	Imperfectly drained	Imperfectly drained
	Structure	Prismatic to angular blocky, except in the 0-20 cm where it is massive	Prismatic to angular blocky, except in the 0-20 cm where it is massive
	Consistence	Friable under moist conditions	Friable under moist conditions
	Soil series	Silmandi series (Aeric Endoaquepts)	Ishurdi series (Aeric Endoaquepts)
MLL	Location	25˚00’ N and 89˚ 45’ E	23˚56’ 88˚59’
	Topographic position	Moderately lower part of the ridges	Moderately gentle lower part of the ridges
	Color	Grey to dark grey with light olive brown in the lower depths (60-120 cm)	Grey to dark grey with light olive brown in the lower depths (60-120 cm)
	Texture	Clay to silty clay loam	Clay to silty clay loam
	pH	6.5 to 7.0	6.5 to 7.8
	Drainage	Poorly drained	Poorly drained
	Structure	Angular blocky except in the 0-20 cm depths	Angular blocky except in the 0-20 cm depths
	Consistence	Sticky plastic to slightly sticky under moist conditions	Sticky plastic to slightly sticky under moist conditions
	Soil series	Ghatail soil series (Typic Endoaquepts)	Gheor soil series (Typic Endoaquepts)
LL	Location	24˚08’89˚55’	23˚56’ 88˚59’
	Topographic position	Lower part of the ridges of the Brahmaputra alluvium	Lower part of the ridges of the Ganges alluvium
	Color	Grey to dark grey with light olive brown in the lower depths (60-120 cm)	Light grey to dark grey with light olive brown in the lower depths (60-120 cm)
	Texture	Clay to silty clay loam	Clay to silty clay
	pH	6.5 to 7.0	6.5 to 7.9
	Drainage	Poorly drained	Poorly drained
	Structure	Angular blocky except in the 0-20 cm	Angular blocky except in the 0-20 cm
	Consistence	Sticky plastic to slightly sticky under moist conditions	Sticky plastic to sticky under moist conditions
	Soil series	Balina series (Typic Endoaquepts)	Garuri series (VerticEndoaquepts)

Morphological characteristics of the inundation land types were studied in the field using the guidelines of FAO (2006). Soil pH was determined in soil-water suspension (1:2.5 w/v) using a pre-calibrated pH meter following the procedure of Page et al. (1982). SOC was determined by following the method of Walkley and Black (Nelson and Sommers, 1982) and the Kjeldahl method (Bremner and Mulvaney, 1982) was used for total soil nitrogen (TSN) determination. The particle size analysis of soils was carried out by the hydrometer method as described by (Gee and Bauder, 1986). Soil bulk density was determined by using the core method as described by Blake and Hartge (1986). Details of the above methods were given in Chapter 3 (Section 3.3). It may be noted that the bulk density and SOC concentration (%) are the two prerequisites for estimating SOC stock or storage. Thus, the SOC and TN storage were calculated using the following equations (Batjes 1996; Chen et al. 2007; Zhang et al. 2013).

Total Soil Organic Carbon (TSOC) = $SOC_i \times B_i \times D_i$ Eq. (i)

Total Soil Nitrogen (TSN) = $TN_i \times B_i \times D_i$ Eq. (ii)

Where, equation (i) represents TSOC; SOCi is the SOC content on the i^{th} layer (g/kg);
Equation (ii) represents TSN; TN_i is the total nitrogen content on the i^{th} layer (g/kg);
B_i is the bulk density of the i^{th} layer (g/cc), and D_i is the depth of the i^{th} layer (cm).

Data is reported as mean± standard deviation. Two-way analysis of variance (ANOVA) was employed to assess the effects of land types and soil depths on SOC and TN storage or concentrations. One-way ANOVA was used to examine the effect of soil depths on SOC and TN storage. Regression analyses were used to test the relationships between SOC and TN storage at 0-20 cm depths, 0-60 cm depths, and 0-120 cm depths. All statistical analyses were conducted using SPSS, version 20.0.

7.3 Results and Discussion

7.3.1 Soil Properties across the Alluviums

The soil pH across the land types of the Brahmaputra alluvium (BA) ranged from 5.6 to 7.0 with a mean value of 6.6 (Table 7.2), whereas soil pH in the Ganges alluvium (GA) varied from 6.1 to 7.6 with a mean value of 7.06 (Table 7.3). The higher pH in the Ganges alluvium than the Brahmaputra alluvium is consistent with the findings of Ali et al. (2003) for agricultural soils in Bangladesh. The reason of higher soil pH in the Ganges alluvium than the Brahmaputra alluvium is due to the calcareous nature of the soils. The organic carbon (OC) content in the soils of the Brahmaputra alluvium ranged from 0.18% to 1.82% with a mean value of 0.66% (Table 7.2) whereas, OC varied from 0.14% to 1.81% with a mean value of 0.52 % in the soils of Ganges alluvium (Table 7.3). The OC content is slightly higher in the soils of Brahmaputra alluvium which may due to the nature of their biophysical conditions. The higher OC in the surface layer is due to relatively greater biomass inputs in the form of manure and crop residues. The SOC content is higher in the lowland sites than the other land types in the both alluviums. TN contents across the land types of the Brahmaputra alluvium (BA) ranged from 0.03% to 0.18% with a mean value of 0.088% (Table 7.2) whereas, TN varied from 0.03 % to 0.20% with a mean value of .066% in the land types of Ganges alluvium (GA) (Table 7.3).

The C: N ratio in the surface soil (0-20 cm) was slightly higher than the subsurface horizons. Cultivation and residue input affects the C: N ratio in the surface soils. As a result, The C: N ratio in the surface soils tend to be higher than those less cultivated horizons. In the current study, the C: N ratio ranged from 6 to 10 across the two alluviums (Tables 7.2-7.3). This is relatively low variation in the C: N ratio, which may be due to the similar climatic conditions and similar agricultural management techniques adopted by the farmers. The bulk density in the four profile of the BA varied from 1.18 to1.32 g/cc where the mean value was 1.24 (Table 7.2). On the other hand, the bulk density in the four profile of the GA varied from 1.15 to 1.33 g/cc where the mean value was 1.23 (Table 7.3). The bulk density in the surface layer is relatively low and it increases gradually and becomes low in the depth of 100-120 cm, across the land types. The bulk density of the surface soil is low because the surface soils are ploughed intensively with subsequent disturbances where most of the aggregates or clods are destroyed. Silt content in the soils of BA soils ranged from 39% to 72% with a mean value of 58% (Table 7.2) whereas in GA soils it ranged from 42% to 70% with a mean value of 58% (Table 7.3). Silt is the dominant size fraction in the study sites. Clay content in the BA soils ranged from 10% to 48% with a mean value of 30% (Table 7.2), whereas in the GA soils it ranged from 10% to 53% with a mean value of 30% (Table 7.3). On the other hand, the sand content in the soils of BA ranged from 5% to 26% with a mean value of 12% (Table 7.2), whereas sand contents in the soils of GA ranged from 6% to 24% with a mean value of 8% (Table 7.3). The sand contents seem to be relatively low across the eight land types of the two alluviums.

Table 7.2: Soil properties of the inundation land types across the four profiles of the Brahmaputra alluvium

Land types	Depths (cm)	pH (H_2O)	Organic carbon %	Total N %	*C/N ratio	Sand %	Silt %	Clay %	Bulk Density g/cc
Highland (HL)	0-20	6.20	0.71	0.10	7	10	64	26	1.20
	20-40	6.60	0.46	0.075	6	12	64	24	1.22
	40-60	6.60	0.40	0.076	6	14	66	20	1.22
	60-80	6.70	0.36	0.070	6	16	72	12	1.24
	80-100	6.70	0.30	0.050	6	20	68	12	1.24
	100-120	6.90	0.26	0.050	6	26	64	10	1.18
Medium high land (MHL)	0-20	6.05	0.88	0.09	9	6	64	30	1.22
	20-40	6.60	0.63	0.08	8	8	64	28	1.24
	40-60	6.75	0.54	0.07	8	10	66	24	1.24
	60-80	6.81	0.40	0.06	7	16	62	22	1.24
	80-100	6.84	0.25	0.03	7	21	59	20	1.20
	100-120	6.80	0.18	0.03	6	22	64	14	1.20
Medium Low land (MLL)	0-20	6.03	1.05	0.12	9	5	47	48	1.24
	20-40	6.80	0.68	0.08	8	7	58	35	1.28
	40-60	6.93	0.60	0.08	7	9	57	34	1.28
	60-80	6.99	0.51	0.07	7	12	56	32	1.30
	80-100	7.00	0.41	0.06	7	15	55	30	1.30
	100-120	7.00	0.33	0.06	6	17	61	22	1.20
Lowland (LL)	0-20	5.6	1.82	0.18	10	6	39	55	1.22
	20-40	6.0	1.60	0.17	9	5	45	50	1.26
	40-60	6.2	1.0	0.14	7	5	45	50	1.26
	60-80	6.5	0.91	0.13	7	7	52	45	1.32
	80-100	6.8	0.90	0.12	7	7	49	44	1.32
	100-120	7.0	0.71	0.11	6	8	50	42	1.20
Mean ± SD		6.60± 0.38	0.66± 0.40	0.08± 0.03	7.16± 1.16	11.83 ±6.09	57.95± 8.54	30.37± 13.31	1.24± 0.04

*C/N ratio was rounded to the nearest complete figure.

Table 7.3: Soil properties of the inundation land types across the four profiles of the Ganges Alluvium

Land types	Depth (cm)	pH (H_2O)	Organic carbon %	Total N %	*C/N ratio	Sand %	Silt %	Clay %	Bulk Density g/cc
Highland (HL)	0-20	6.98	0.80	.084	9	8	62	30	1.20
	20-40	7.20	0.38	.048	8	10	70	20	1.21
	40-60	7.26	0.30	.042	7	15	65	20	1.22
	60-80	7.31	0.28	.042	6	19	66	15	1.23
	80-100	7.30	0.21	.030	7	20	68	12	1.20
	100-120	7.30	0.20	.030	6	24	66	10	1.15
Medium high land (MHL)	0-20	6.30	1.0	0.12	8	6	49	45	1.20
	20-40	6.77	0.51	.071	7	9	52	39	1.23
	40-60	6.80	0.40	.050	8	11	57	32	1.24
	60-80	7.09	0.31	.050	6	14	59	27	1.25
	80-100	7.01	0.20	.030	6	19	57	24	1.20
	100-120	7.05	0.14	.022	6	21	59	20	1.18
Medium Low land (MLL)	0-20	6.70	1.4	0.14	10	5	42	53	1.22
	20-40	7.20	0.61	0.07	9	7	53	40	1.25
	40-60	7.40	0.50	0.07	8	8	57	35	1.28
	60-80	7.40	0.38	0.06	8	10	60	30	1.28
	80-100	7.60	0.21	0.03	7	13	57	20	1.28
	100-120	7.60	0.20	0.03	7	16	64	20	1.20
Lowland (LL)	0-20	6.1	1.81	0.20	9	4	55	50	1.25
	20-40	6.7	0.79	0.09	9	5	45	50	1.28
	40-60	6.8	0.61	0.08	8	7	53	40	1.33
	60-80	7.1	0.50	0.08	8	8	57	35	1.33
	80-100	7.1	0.39	0.06	7	10	60	30	1.21
	100-120	7.4	0.39	0.06	7	10	60	30	1.21
Mean ± SD		7.06 ± 0.37	0.52 ± 0.40	0.06 ± 0.04	7.54 ± 1.14	11.62 ± 5.65	58.04 ± 6.89	30.29 ± 12.12	1.23 ± 0.04

*C/N ratios were rounded to nearest complete figure

A positive relationship was found between OC and TN contents in the soils of BA (r= 0.95) (Fig. 7.1) and GA (r= 0.98) (Fig. 7.2) respectively. From the above data, it is important to note that there is a strong correlation between OC and TN which indicates that the bulk of soil N is tied up in the SOC pool across the study sites. Manu et al. (1991) and Bationo et al. (2005) noted that there is a strong correlation of OC with TN in soils**.** Esteban et al. (2000) noted that land use is a major determinant of SOC and TN distribution besides climate. Land use is governed by the inundation or topographic land levels. Thus topographic land types may act as the drivers of SOC and TN distribution. Lower SOC and TN in the HL and MHL sites depend on the variation of land types as well as land use and may be attributed as the result of decreased organic residues inputs. This is supported by Liu et al. (2012), who reported that net losses of SOC and TN occur due to the change in land use, which resulted in decreased organic inputs. As reported by Cambardella and Elliot (1992), changes in land use and management practices may alter the distribution of SOC and TN among labile and stable pools with kinetically different turnover pools. They also reported intensive cultivation reduces the SOC and TN because of the destruction of soil aggregates by intensive levels of tillage.

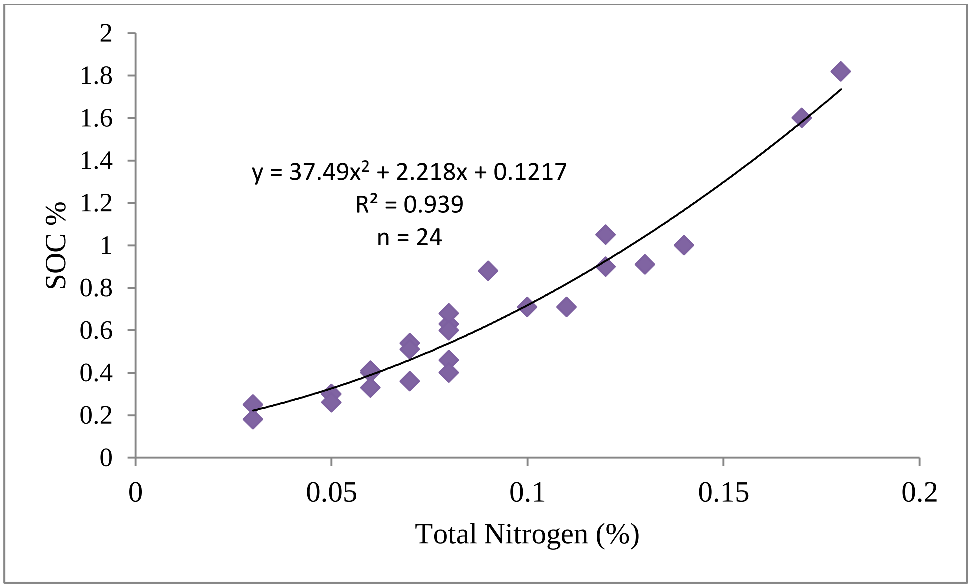

Figure 7.1: Relationship of SOC and TN across the land types of the four profiles of the Brahmaputra alluvium

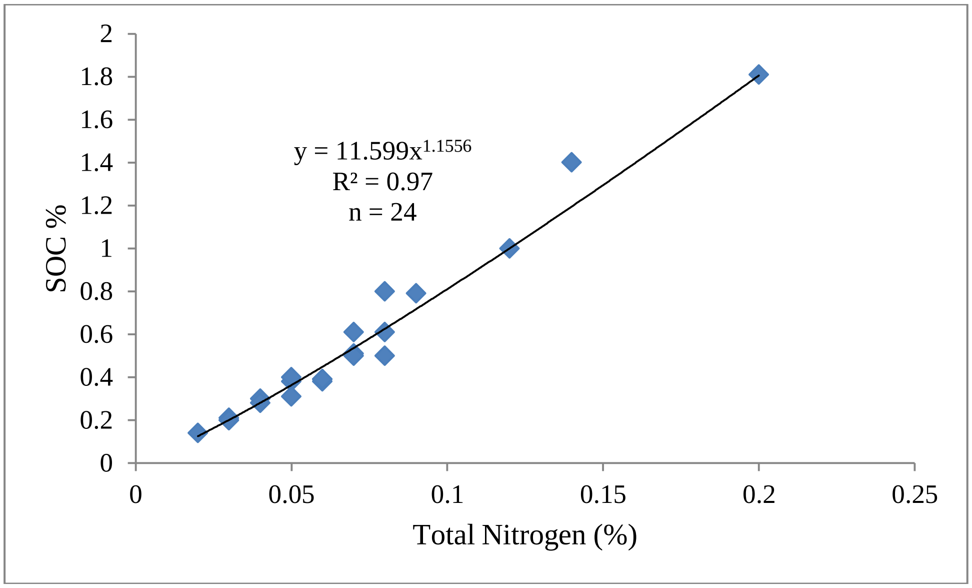

Figure 7.2: Relationship of SOC and TN across the land types of the four profiles of the Ganges alluvium

Clay and silt play an important role in stabilizing organic compounds (Bationo and Buerkert, 2001). Among these, clays are an important component in the direct stabilization of organic molecules (Amato and Ladd, 1992; Feller et al., 1996). Batjes (1996) and Liu et al. (2011) reported that clay has the stabilizing effect where SOC can be trapped in their small spaces between clay particles, making them inaccessible to micro-organism and thereby slowing decomposition. In addition, clay offers chemical protection to organic carbon through adsorption on to clay surfaces, which again prevents organic matter from being decomposed. In the current study, a positive relationship was found between SOC and clay contents in the soils of BA (r = 0.87) (Fig. 7.3) and GA (r = 0.82) (Fig. 7.4), whereas a negative correlation was found between SOC and sand contents in the soils of BA (r= -0.78) (Fig 7.5) and GA (r = -0.73) (Fig. 7.6). David et al. (2003) reported that the clay fraction of surficial sediments, Smectite is diagnostic with high values (~39%) in the Ganges and low values (~3%) in the Brahmaputra alluvium. In contrast, the Brahmaputra alluvium contains more kaolinite (29% vs. 18%), illite (63% vs. 41%), and chlorite (3% vs. 1%) than the Ganges alluvium.

Plante et al. (2006) found a significant relationship between clay and SOC contents where the amount of clay increased, the amount of C retained in soil also increased. Similar observations of SOC and clay interrelations were observed by other workers (Burke et al., 1989; Arrouays et al., 2006). Further, Kogel-Knabner et al. (2008) reported that clay protects SOC from decomposition by developing stable-clay organic complex. From the above analysis, it is clear that soils with high clay content tend to have higher SOC than soils with lower clay content.

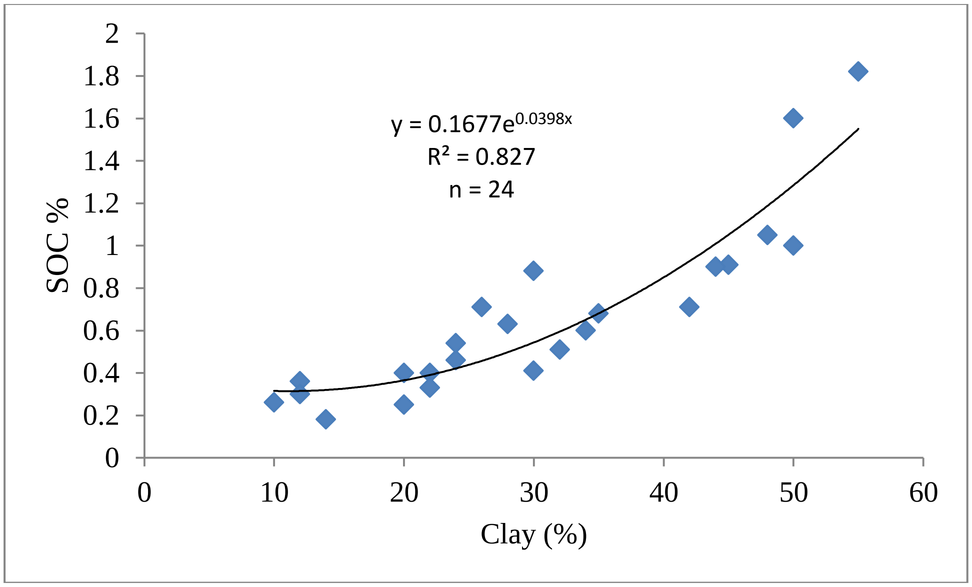

Figure 7.3: Relationship of SOC and clay across the land types of the four profiles of the Brahmaputra alluvium

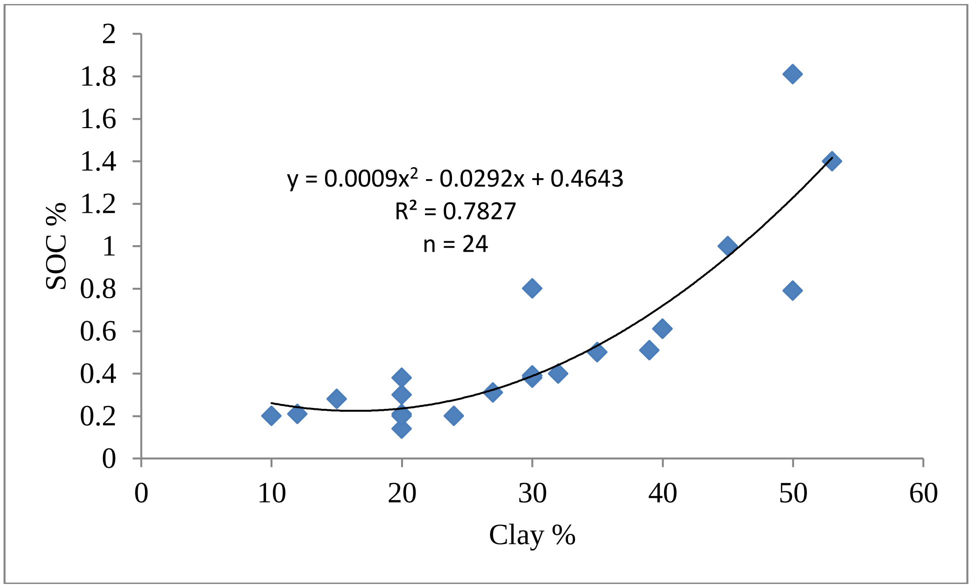

Figure 7.4: Relationship of SOC and clay across the land types of the four profiles of the Ganges alluvium

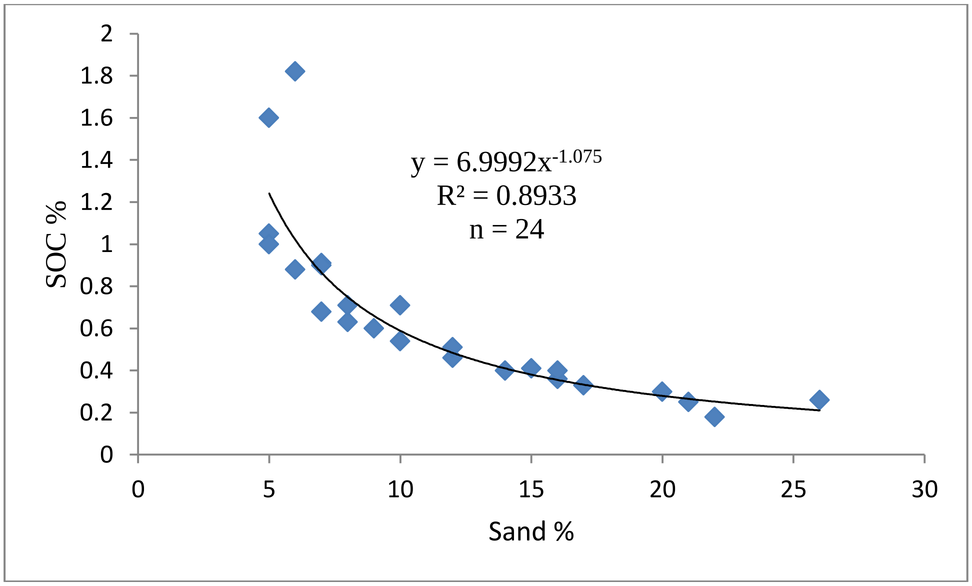

Figure 7.5: Relationship of SOC and sand across the land types of the four profiles of the Brahmaputra alluvium.

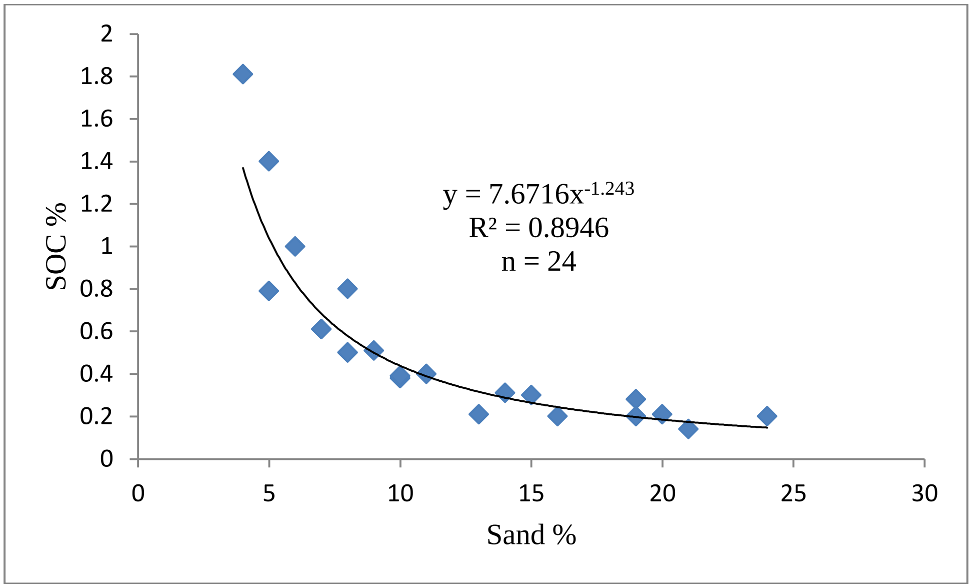

Figure 7.6: Relationship of SOC and sand across the land types of the four profiles of the Ganges alluvium

7.3.2 SOC Contents at Different Soil Depths across the Inundation Land Types

The highest SOC concentration was found in the topsoil (0-20 cm) across the eight land types of the two alluviums (Table 7.4). SOC concentration depends on the balance between OC input and loss from soils (Zhuang et al., 2007). Topsoil layer (0-20 cm) is tilled and receives greater residue inputs which are subsequently mineralized. Thus this layer possesses higher SOC than the other soil layers (20-120cm). Chaplot et al. (2010) reported that the topsoil layer may be able to sequester atmospheric CO_2 and thus mitigate climate change where more biophysical activities take place. Xiao-Wei et al. (2012) noted that surface soils are rich in SOC due to being covered by highly productive vegetation or subject to long-term use of organic fertilizers or flooding conditions. SOC in the top soil layer (0-20 cm) varies significantly ($P<0.001$) when tested using Tukey's Honestly Significant Difference (HSD). Besides, SOC concentration showed a decreasing trend from the top soil layer to the bottom layer for all land types of the two alluviums (Table 7.4).

The mean SOC concentration across the Brahmaputra alluvium (BA) varies from 0.41% (4.15 g/kg) to 1.15 % (11.56 g/kg) (Table 7.4). Lowland sites of BA show the highest SOC concentration than the HL and MHL sites. The mean SOC concentration across the Ganges alluvium (GA) varies from 0.36% (3.61 g/kg) to 0.74% (7.48 g/kg) (Table 7.4) where low land sites show the highest SOC concentration than the HL and MHL sites (Table 7.4). Among the two alluviums, the Brahmaputra alluvium (BA) contains more SOC than the Ganges alluvium (GA). Low land (LL) sites contain a higher SOC concentration in both the alluviums than the other land types (HL and MHL) (Table 7.4). Thus, lowland (LL) and even medium lowland (MLL) types of the both alluviums contain higher SOC due to the nature of inundation depths. On the other hand, the HL and MHL types lose their SOC due to the increased decomposition being not inundated, erosion, and more intensive tillage (Houghton, 1991; Ritchie et al., 2007). Roose and Barthes (2001) noted that SOC is lost in the higher topography, through erosion, runoff and leaching where erosion and runoff contribute a large portion of carbon losses and these are highly accelerated in cultivated land as compared to undisturbed land.

Table 7.4: Soil organic carbon (SOC) distribution (%) at different soil depths across the eight land types of the alluviums

Depths	Brahmaputra Floodplains				Ganges Floodplains			
(cm)	HL	MHL	MLL	LL	HL	MHL	MLL	LL
0-20	0.71	0.88	1.05	1.82	0.80	1.0	1.4	1.81
20-40	0.46	0.63	0.68	1.60	0.38	0.51	0.61	0.79
40-60	0.40	0.54	0.60	1.0	0.30	0.40	0.50	0.61
60-80	0.36	0.40	0.51	0.91	0.28	0.31	0.38	0.50
80-100	0.30	0.25	0.41	0.90	0.21	0.20	0.21	0.39
100-120	0.26	0.18	0.33	0.71	0.20	0.14	0.20	0.39
Mean± SD	0.41± 0.16	0.48± 0.25	0.59± 0.25	1.15± 0.44	0.36± 0.22	0.42± 0.31	0.55± 0.44	0.74± 0.54

7.3.3 TN Contents at Different Soil Depths across the Inundation Land Types

The highest TN concentration was found in the topsoil (0-20 cm) across the eight land types like SOC. TN concentration across the four land types of Brahmaputra alluvium (BA) varied from 0.03 to 0.18% (0.30 to 1.8 g/kg) where the MLL/LL types contains the highest TN concentration and the HL and MHL contains the lowest TN concentration. TN concentration across the land types of the Ganges alluvium (GA) varied from 0.02 to 0.20% (0.22 g/kg to 2.0 g/kg) where MLL and LL sites contains highest TN concentration and the HL and MHL sites contains the lowest TN concentrations which are consistent with their SOC levels. MLL and LL types contain higher TN concentrations than the HL and MHL land types across the alluviums (Table 7.5). Among the two alluviums, BA contains more TN than the GA as reported for SOC. TN in the top layer varies significantly ($P<0.001$) when tested using Tukey’s Honestly Significant Difference (HSD). TN concentration showed a decreasing trend downward from the top soil layer (0-20 cm) across the land types of the two alluviums.

Table 7.5: Total nitrogen (TN) distribution (%) at different soil depths across the eight land types of the alluviums

Depths	Brahmaputra alluvium				Ganges alluvium			
(cm)	HL	MHL	MLL	LL	HL	MHL	MLL	LL
0-20	0.10	0.09	0.12	0.18	0.08	0.12	0.14	0.20
20-40	0.07	0.08	0.08	0.17	0.04	0.07	0.07	0.09
40-60	0.07	0.07	0.08	0.14	0.04	0.05	0.07	0.08
60-80	0.07	0.06	0.07	0.13	0.04	0.05	0.06	0.08
80-100	0.05	0.03	0.06	0.12	0.03	0.03	0.03	0.06
100-120	0.05	0.03	0.06	0.11	0.03	0.02	0.03	0.06
Mean ± SD	0.07 ± 0.01	0.06 ± 0.02	0.07 ± 0.02	0.14 ± 0.02	0.04 ± 0.01	0.05 ± 0.03	0.06 ± 0.04	0.09 ± 0.05

The above result showed that the effect of land types and soil depths across the study sites on SOC is significant (Table 7.6) indicating both land types and soil depths are important factors influencing the SOC distribution across the inundation land types. A similar observation of the effect of topographic land condition and soil depths on SOC have been made by others (Chen et al., 2007; Fang et al., 2012; Fu et al., 2010).

Land types and soil depths exhibited a significant effect on SOC and TN concentration as tested by two-way ANOVA. The SOC and TN contents varied significantly (P<0.001) across the land types as well as soil depths (Table 7.6). Land types and soil depths showed a significant effect on TN concentration (P<0.001) (Table 7.6), and the distribution of TN in soil was similar to SOC.

Table 7.6: Two-way ANOVA for the effect of land types and soil depths on SOC and TN

		Soil Organic carbon (SOC)		Total nitrogen (TN)	
Parameters	df	F	P	F	P
Land types	7	34.949	<0.001	31.710	<0.001
Soil depth	5	18.865	<0.001	27.808	<0.001

The current study shows that the highest SOC and TN concentration were found in the top soil layer (0-20 cm) in all the profiles across the alluviums. This layer is the most important part of the profile where maximum pedogenic activities take place. The high residue inputs in the surface soils may contribute to the increased SOC and TN distribution (Wu et al., 2004; Liu et al., 2005). SOC and TN is less variable in the deeper soil layers (60-120 cm) across the land types, than the 0-60 cm layer, which suggests that SOC and TN remained relatively stable in the soil depths between 60-120 cm. The study also shows that SOC and TN were found variable within 0-60 cm depths across the land types where most physical and chemical activities taken place. The SOC and TN contents across the land types decreased with increasing depths (Tables 7.4-7.5). On the other hand, the lowest SOC and TN were found in the HL and MHL sites and the highest SOC and TN were found in the LL sites across the two alluviums. A moderate level of SOC and TN was found in the MLL types (Tables 7.4 -7.5).

The above results agreed with other findings (Chen et al., 2007), indicating that both topographic nature and land use influence the SOC as well as TN contents. The lower SOC in the HL and MHL sites may be attributed to the reduced residue input in the soil and extensive soil erosion because of their higher elevation in the landscape and also due to intensive tillage, which is common in such land types. Guo and Gifford (2002) reported that plant roots also play an essential role in influencing SOC and TN distribution. Wei et al. (2009) revealed that distributions of fine roots are lower in higher topographic level than lower topographic level due to differences in vegetation. Similarly, LL and MLL types provide fine root system under anaerobic rice-rice cultivation with even residue decomposition which may also be responsible for higher SOC and TN contents in the MLL and LL types. The SOC and TN contents of the MLL and LL sites were higher than those of other land types, which may be attributed due to their inundation nature as well as their nature of farming. The topographic nature and anaerobic farming systems in the MLL and LL types may have greatly reduced the nutrients losses from reduced soil erosion. Erosion and leaching are more prevalent in the HL and MHL types because their drainage. SOC and TN losses are more prevalent in the HL and MHL sites due to the processes of erosion and runoff. Roose and Barthes (2001) noted that erosion and runoff contribute a large portion of C losses and these are highly accelerated in the cultivated land than the uncultivated soils.

7.3.4 SOC and TN Storage at Different Soil Depths for Different Inundation Land Types

The average amounts of SOC storage varied from 1.70 kg/m^2 to 4.52 kg/m^2 in the 0-20 cm layer, 0.97 kg/m^2 to 2.52 kg/m^2 in the 20-60 cm layer and 0.33 kg/m^2 to 2.40 kg/m^2 in the 60-120 cm layer across the two alluviums of the eight profiles (Table 7.7). On the other hand, SOC storage across the inundation land types of the BA varied from 6.03 to 17.46 kg/m^2. SOC storage across the inundation land types of the GA varied from 5.20 to11.37 kg/m^2 (Table 7.7). Similar observations have been reported by several studies regarding the SOC storage. Tarnocai (1997) reported that average SOC content in the surface soils in Canada ranged from 4.9 to 18.7 kg/m^2. Sakin (2012) also reported that SOC content varies from 3.57 kg/m^2 to 6.47 kg/m^2 in the Harran plain soils in Southeastern Turkey. In the present study, compared with the HL and MHL sites, the SOC storage in the MLL and LL sites was higher across the two alluviums. The SOC storage decreases with increasing depths across the different land types.

Table 7.7: Soil organic carbon storage (kg/m^2) at different soil depths across the land types of the two alluviums

Depths (cm)	Brahmaputra alluvium				Ganges alluvium			
	HL	MHL	MLL	LL	HL	MHL	MLL	LL
0-20	1.70	2.14	2.60	4.44	1.92	2.40	3.41	4.52
20-40	1.12	1.56	1.74	4.03	0.91	1.25	1.52	2.02
40-60	0.97	1.33	1.53	2.52	0.73	0.99	1.28	1.62
60-80	0.89	0.99	1.32	2.40	0.68	0.77	0.97	1.33
80-100	0.74	0.60	1.06	2.37	0.50	0.48	0.53	0.94
100-120	0.61	0.43	0.79	1.70	0.46	0.33	0.48	0.94
Total	6.03	7.05	9.04	17.46	5.20	6.22	8.19	11.37
Mean ± SD	1.00± 0.38	1.17± 0.63	1.50± 0.63	2.91± 1.07	0.86± 0.54	1.03± 0.74	1.36± 1.08	2.91± 1.07

TN storage in the soils was similar to SOC (Table 7.8). The average amounts of TN storage varied from 0.20 kg/m^2 to 0.50 kg/m^2 in the 0-20 cm layer, 0.10 kg/m^2 to 0.42 kg/m^2 in the 20-60 cm layer and 0.07kg/m^2 to 0.34 kg/m^2 in the 60-120 cm layer across the alluviums of the eight profiles (Table 7.8). The TN storage across the inundation land types of the BA ranged from 0.85 to 2.12 kg/m^2. TN storage across the inundation land types of the GA varied from 0.65 to1.44 kg/m^2 (Table 7.8). Similar observations have been reported by several studies. Carter et al. (1998) reported that TN in Canada farming soils ranged from 0.36 to 1.05 kg/m^2 and the TN storage in the MLL and LL sites were higher than those HL and MHL soils. They also noted that TN storage also varied with the increasing depths across different land types. Liu et al. (2012) also reported that the average densities of SOC and TN at a depth of 1m were about 7.72 kg/m^2 and 0.93 kg/m^2, respectively, in the northeastern margin of the Qinghai-Tibetan Plateau. The above situation regarding SOC and TN contents are consistent with Bangladesh situation because plateau margin occupies alluvial characteristics similar to the alluvial soils of Bangladesh.

Table 7.8: Total nitrogen storage (kg/m^2) at different soil depths across the land types of the two alluviums

Depths (cm)	Brahmaputra alluvium				Ganges alluvium			
	HL	MHL	MLL	LL	HL	MHL	MLL	LL
0-20	0.24	0.21	0.30	0.44	0.20	0.28	0.34	0.50
20-40	0.19	0.19	0.21	0.42	0.11	0.17	0.17	0.24
40-60	0.19	0.17	0.20	0.35	0.10	0.12	0.17	0.21
60-80	0.17	0.14	0.18	0.34	0.10	0.12	0.15	0.21
80-100	0.12	0.07	0.15	0.31	0.07	0.07	0.07	0.14
100-120	0.11	0.07	0.14	0.26	0.07	0.07	0.07	0.14
Total	1.02	0.85	1.18	2.12	0.65	0.83	0.97	1.44
Mean ± SD	0.17± 0.04	0.14± 0.06	0.19± 0.05	0.35± 0.06	0.10± 0.04	0.13± 0.07	0.16± 0.09	0.23± 0.13

The effect of soil depths on SOC and TN storage in soils are presented in Table 7.9. Soil depths had significant influence ($P<0.05$) on SOC and TN storage as assessed by a one-way ANOVA study.

Table 7.9: One-way ANOVA for the effect of soil depths on SOC and TN storage in soils

Depths (cm)	df	Soil Organic carbon (SOC) F	Soil Organic carbon (SOC) P	Total nitrogen (TN) F	Total nitrogen (TN) P
0-20	8	28.034	<0.05	17.308	<0.05
20-60	8	6.281	<0.05	6.179	<0.05
60-120	8	8.446	<0.05	8.560	<0.05

F and P values, from one-way ANOVA; df is degrees of freedom;
All values show significant at $P<0.05$

The relationships between SOC and TN storage among the topsoil (0-20 cm) and deeper layers (0-60 cm), and (0-120 cm) are shown in Figs. 7.7-7.10. All the changes in SOC and TN storage with increasing depths were evaluated using regression equations. The relationships of SOC storage between the soil depths 0-20 cm and 0-60 cm (Fig. 7.7), and 0-20 cm and 0-120 cm (Fig. 7.8) show strong correlations ($r = 0.92$ and 0.85 respectively). Likewise, the relationship of TN storage between the soil 0-20 cm and 0-60 cm depths (Fig. 7.9) and 0-20 cm and 0-120 cm depths (Fig. 7.10) show strong correlations ($r = 0.86$ and 0.80 respectively).

In this study, mean SOC and TN storage calculations also showed that SOC was higher in the surface soil (0-20 cm depth) than that in the deeper layers (Tables 7.7-7.8). This is consistent with the findings of Zhang et al. (2011). On the other hand, SOC and TN storage was higher in the LL and MLL sites than that in the HL and MHL sites (Tables 7.7-7.8) across the alluviums, which indicates that the topographic variability as well as their water recession conditions are related to carbon loss or sequestration. Ritchie et al. (2007) reported that topographic patterns and processes involved in SOC redistribution across agricultural landscapes are the key to understanding the potential for SOC dynamics. In the present study, SOC and TN storage was higher in the surface level (0-20 cm) than the deep layers (60-120 cm) across the study sites.

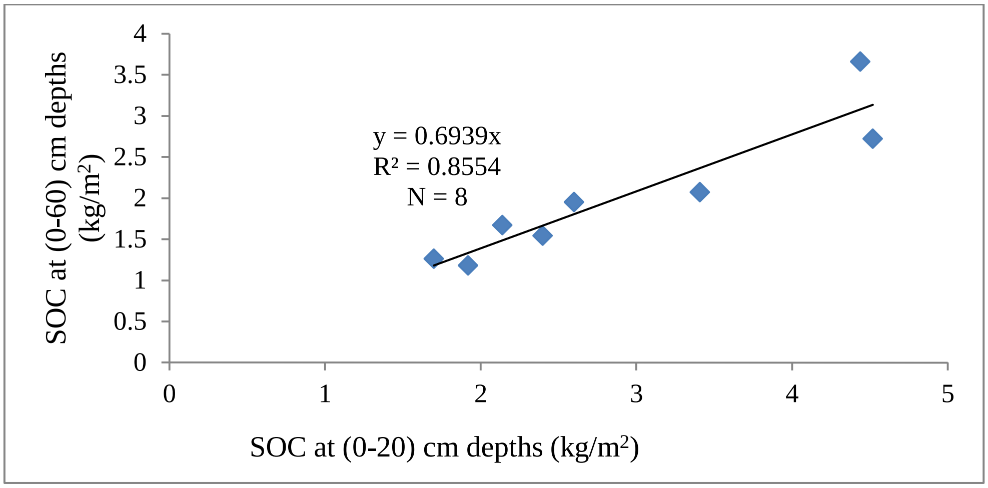

Figure 7.7: Relationship of SOC storage between the soil depths 0-20 cm and 0-60 cm in the eight profiles of the two alluviums

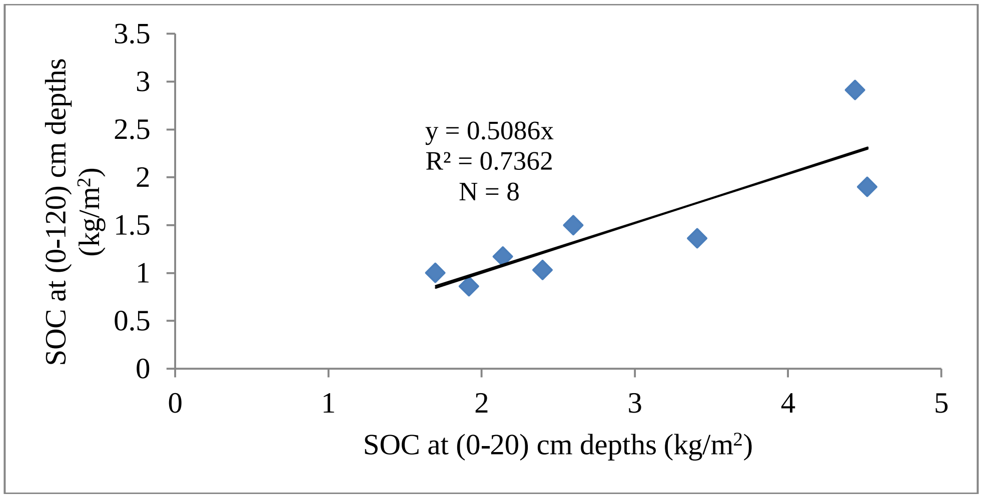

Figure 7.8: Relationship of SOC storage between the soil depths 0-20 cm and 0-120 cm in the eight profiles of the two alluviums

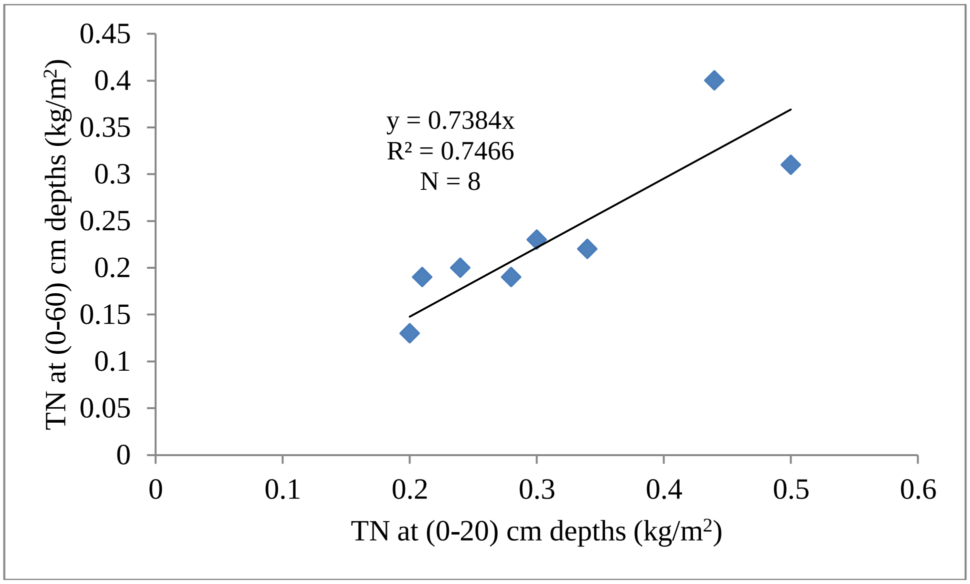

Figure7.9: Relationship of TN storage between the soil depths 0-20 cm and 0-60 cm in the eight profiles of the two alluviums

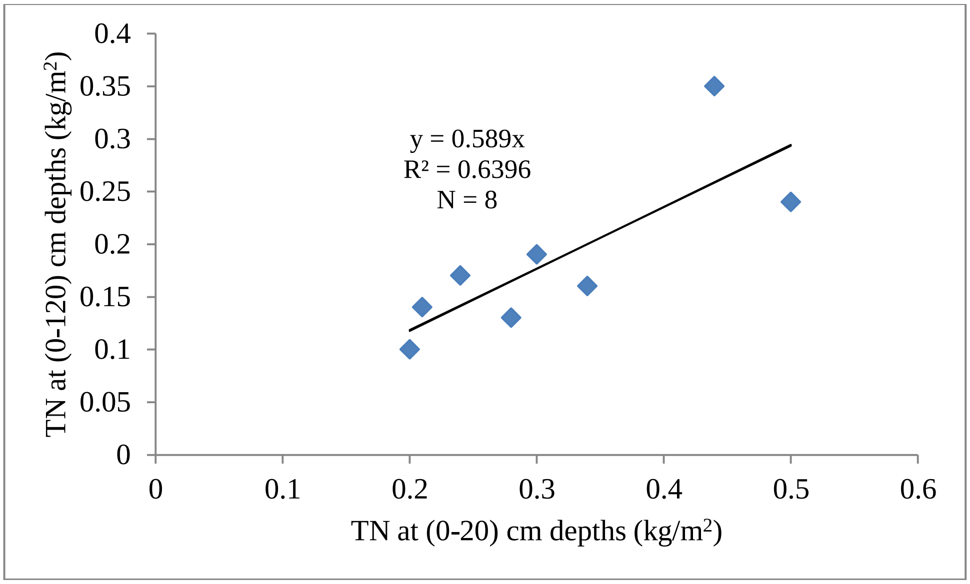

Figure 7.10: Relationship of TN storage between the soil depths 0-20 cm and 0-120 cm in the eight profiles of the two alluviums

On the other hand, mean SOC and TN storage was higher in the Brahmaputra alluvium (BA) than the Ganges alluvium (GA). SOC storage increases as it progresses from HL towards LL across the land types of BA and GA (Fig. 7.11); similarly, TN storage increases from HL to towards LL across the land types of BA and GA (Fig. 7.12). The low SOC in the soils of HL and MHL sites is linked to the removal of crop residues, deterioration of soil aggregation due to intensive tillage (e.g., Gregorich et al., 1998; Six et al., 1998; Balesdent et al., 2000; Stoate et al., 2001; Hamza and Anderson, 2005).

The highest SOC densities were found in MLL and LL sites in each alluvium where these lands are utilized by irrigated paddy cultivation. Higher SOC densities in flooded paddy soils agrees well with previous studies (Jia-Guo et al., 2010) and is explained by natural fertility of wetlands and other lowlands and by the long-term use of organic fertilizers and flooding, which provide a strong supply of organic carbon (OC) with lower decomposition rates (Fu et al., 2001; Wang et al., 2003).

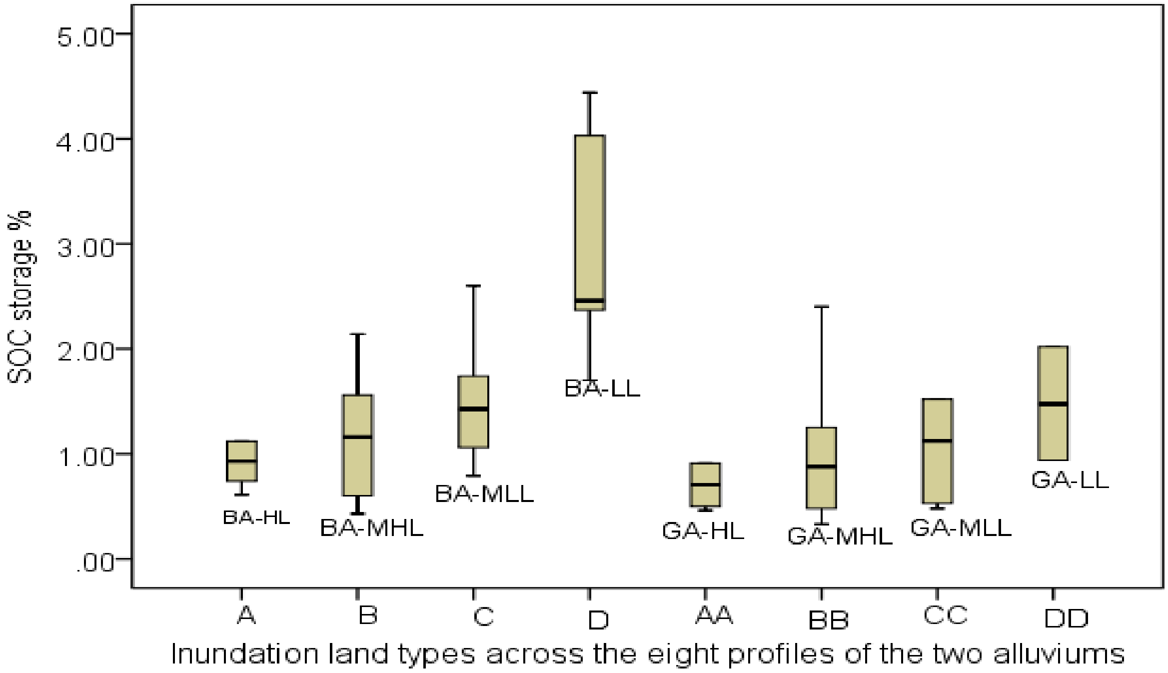

Figure 7.11: Boxplots showing SOC storage (%) across the eight profiles of the two alluviums (A, B, C, and D: SOC storage (%) at highlands, medium highlands, medium lowlands and lowlands respectively across the Brahmaputra alluvium; AA, BB, CC, and DD: SOC storage (%) at highlands, medium highlands, medium lowlands and lowlands respectively across the Ganges alluvium)

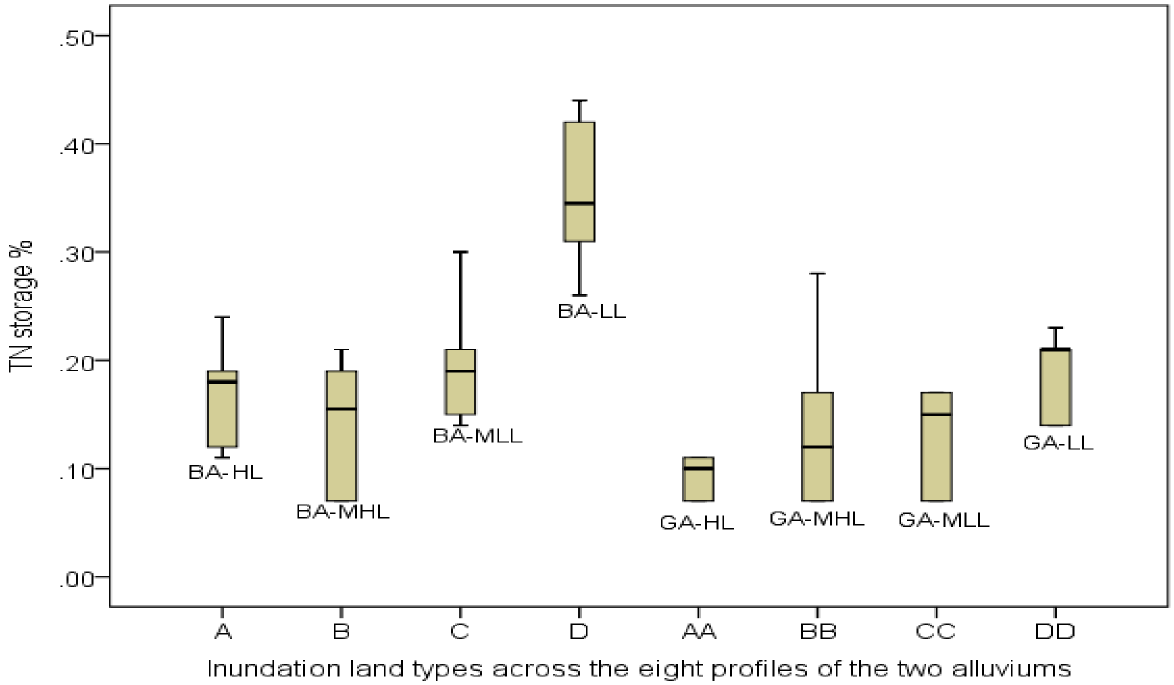

Figure 7.12: Boxplots showing total nitrogen (TN) storage (%) across the eight profiles of the two alluviums (A, B, C, and D: TN storage (%) at highlands, medium highlands, medium lowlands and lowlands respectively across the Brahmaputra alluvium; AA, BB, CC, and DD: SOC storage (%) at highlands, medium highlands, medium lowlands and lowlands respectively across the Ganges alluvium)

7.3.5 SOC Stock across the Two Alluviums

SOC stock in soil across the eight profile samples (0-120 cm depth) (Table 7.10) indicates that SOC stock is higher in the Brahmaputra alluvium (0.63 Pg) than the Ganges alluvium (0.43Pg). Hussain (2002) reported that soils of Bangladesh have a total of 2.2 Pg of organic carbon at the 120 cm depths. Lal (2004) estimated SOC pool was estimated in India at 21Pg at 30-cm depth and 63 Pg at 150-cm depth. He also reported that SOC concentration in most cultivated soils is less than 10g/kg, which is consistent with the present study. The prevalent low levels of SOC concentrations are attributed to excessive tillage, imbalanced fertilizer use, and little or no crop residue returned to the soil.

Table 7.10: Carbon stock (Pg) in soils across the land types of the alluviums at 120 cm depths

Land types	Area (ha)		SOC stock (kg/m^3)		SOC stock (Pg)	
	BA	GA	BA	GA	BA	GA
HL	2,17,097	2,49,798	6.03	5.20	0.013	0.012
MHL	2,00,610	2,11,359	7.05	6.22	0.014	0.013
MLL	2,27,016	2,39,788	9.04	8.19	0.028	0.019
LL	32,597	1,93,649	17.46	11.37	0.0025	0.022
Total	1.6 million	1.4 million	39.58	30.98	0.63	0.43

7.4 Conclusions

SOC and TN were higher in the Brahmaputra alluvium (BA) than the Ganges alluvium (GA). SOC and TN contents were higher in the surface soils than the other horizons.The SOC content is higher in LL and MLL types than the other land types of the both alluviums. A strong correlation was found between OC and TN in the soils of the two alluviums.The lower C:N ratio and lower bulk density in the surface soil is thought to be due to their intensive level of cultivation. The results showed that land types and soil depths significantly affect SOC and TN distribution, as well as their storages in soils. The SOC and TN contents in the surface layer are higher than those in the deeper layers due to the high residue inputs. The MLL and LL sites have higher SOC and TN than the HL and MHL sites across the alluviums. SOC stock calculation indicates that it is higher in the BA than the GA. Thus, the variation in SOC and TN distribution and storage is related to land condition and local management. These factors are also governed by the inundation nature across the study sites. Thus, SOC loss or gain in the soil profile is related to the nature of land types, soil depths, and their management.

CHAPTER 8

8.1 Summary and Recommendations

Bangladesh is an agrarian country where soil nutrient mining in agriculture is common. The low organic matter content is a general problem in most agricultural soils of Bangladesh. SOC depletion is mainly caused by low organic residue input and high cropping intensity. The high cropping intensity combined with limited fallow periods in cropping systems causes a rapid decline in soil biophysical conditions. In addition, the urgency of meeting the ever-increasing population's demand for agricultural produce is further declining soil quality and exacerbating SOC degradation. Strategies to address these issues involve enhancing the SOC pool to reverse the degradation processes and improve ecosystem functions. The release of this study is thus timely. This work investigated the SOC status, distribution, spatial variability, storage, stocks, flux, and factors affecting SOC change and dynamics in the sampled soils.

To estimate SOC, their spatial distribution, variability, and controlling factors, 268 soil samples were collected at 0-30 cm depths on a grid basis, covering four Upazilas/sub-sites: Delduar, Melandah, Fultala, and Mirpur across the two alluviums. Additionally, 190 soil samples were collected by revisiting the sites sampled previously (1989-92) to estimate SOC change. In addition, to estimate SOC and TN distribution, storage, and their relationships, 48 soil samples covering eight profiles at 0-120cm depths were investigated across the two alluviums. The findings are summarised as follows:

- SOC contents in the study sites were very low. SOC ranged from 0.50% to 1.45%, depending on land types across the study sites. SOC variability was higher across the MLL and LL sites than the HL and MHL sites in both alluviums. SOC across the inundation land types were found in the following order: MLL<LL<MHL<HL. Because of their suitability, mainly due to low-level inundation, the HL and MHL sites are used for multiple cropping with intensive tillage. The cropping intensity (CI) across the land types varied from 240% to 330% in the HL sites, 200% to 240% in the MHL sites, 120% to 200% in the MLL sites, and 80% to 90% in the LL sites. Findings revealed that SOC is lower (0.55%) in the HL and MHL sites (greater CI), whereas SOC is higher (1.30%) in the lower cropping intensity sites of MLL and LL. It may be concluded that the inundation land type drives CI, which in turn influences SOC. Thus, the SOC storage and distribution depend on inundation land levels and cropping intensity.

- Statistical analysis showed that SOC varied moderately across the study sites. Histogram and quantile-quantile (Q-Q) plots show that SOC distribution in the Delduar, Melandah, and Mirpur sub-site is positively skewed but in the Fultala sub-site, SOC distribution is normal. Similarly, the semivariogram model revealed that Delduar, Melandah, and Mirpur sub-site possess weak spatial dependence, whereas the Fultala sub-site had a strong spatial dependence. Intensive cultivation practices prevail in the Delduar, Melandah, and Mirpur sub-sites. On the other hand, the Fultala sub-site belongs to the coastal region where soil salinity and waterlogging are common, with relatively low cropping intensity. Kriging and Inverse Distance Weighting (IDW) interpolations of SOC in the surface soils (0-30 cm) revealed that the Fultala sub-site possesses higher SOC (0.39 to 2.03%) than the other sites. The SOC contents in the other sub-sites are low (0.40 to 1.38%) because of their higher cropping intensities. It is quite possible that the relatively large soil sampling grid (1600 m/ sample) may also be at least partly responsible for the weak SOC spatial dependence in the study sites.

- Changes in land use or land cover were intensive in the HL and MHL sites due to the extension and intensification of high yielding rice cultivars and other winter or vegetable crops. The CI in the Delduar sub-site increased from 180 to 280 %, from 165 to 245 % in the Melandah sub-site, from 130 to 180% in Fultala sub-site, and 130 to 230 % in Mirpur sub-site. CI increased significantly in all sub-sites except Fultala, where it increased only moderately. The increasing CI is possibly related to the increasing availability of modern inputs and cultivars. Traditional varieties of crops have been replaced by new cultivars increasing the number of crops as well as cropping intensity specifically in the HL and MHL sites. On the other hand, the number of crops or cropping pattern remains nearly the same in the MLL and LL sites with only difference of local or traditional rice varieties being replaced by high-yielding rice cultivars under submerged conditions. Thus, the increased cropping intensity in the HL and MHL sites under non-submerged conditions exacerbated low crop input in these sites, resulting in greater decline in SOC, whereas in the MLL and LL sites, the prevalence of submerged (rice) farming has prevented SOC decline.

- A comparison of the current (2012) and the historic (1989-92) SOC levels revealed that SOC declined across the study sites. Loss of SOC is severe in the HL and MHL sites whereas some limited SOC sequestration seemed to have taken place in the MLL and LL sites. The reason for such losses of SOC in the HL and MHL sites are at least partly due to intensive cropping with little addition of crop residues. It may also be attributed to their high land use intensity as well as their erosion susceptibility. It is possible that SOC may have reached an equilibrium state in the HL and MHL sites and that further SOC decline may not occur.

- SOC and TN distribution across the land types revealed a strong relationship between SOC and TN contents in the soils of the Brahmaputra alluvium (r = 0.95) and the Ganges alluvium (r = 0.98). The high correlation between SOC and TN indicates that the bulk of soil N is tied up in the SOC pool across the study sites. On the other hand, a strong positive correlation was also found between SOC and clay content in the Brahmaputra alluvium (r = 0.87) and the Ganges alluvium (r = 0.82) soils. MLL and LL sites contain higher SOC and TN than the HL and MHL sites across the alluviums, mainly due to the relatively lower cropping intensity in the former land types.

- SOC and TN concentrations are higher in the surface soils than the sub surface soils. The topsoil layer (0-20 cm) is tilled and receives residue inputs that are subsequently mineralized, contributing some nutrients to the soil. For this reason, this layer possesses higher SOC and TN than the lower soil layers. Relationships of SOC storage between the soil depths (0-20 cm and 0-60 cm, 0-20 cm and 0-120 cm) showed strong correlations (r = 0.92 and 0.85 respectively). Likewise, the relationship of TN storage between the same soil depths also exhibited strong correlations (r = 0.86 and 0.80 respectively). Thus, relationships between SOC and TN storage among the surface soil and deeper layers were found, which revealed that SOC and TN storage depended on soil depths.

8.2 Recommendations

Results of the soil carbon dynamics study revealed that SOC in the sites investigated has declined considerably over the last 20 years. This decline in SOC was found to be related to much increased cropping intensity and associated changes in farming practices, e.g., little or no crop residue or manure inputs. Such a significant decline in SOC poses a threat to food security. The findings of this study warrants further investigation, with the following interim recommendations:

1. There is clear nation-wide need to review the current agricultural land management practices to find out their impact on soil organic carbon and identify factors driving cropping intensity.

2. Nation-wide soil carbon assessment may not be possible, but it can be done in a targeted manner, focusing particularly on medium highlands and highlands, which are most intensively cultivated, as seen in this study. This is possible, though resource-intensive, per historical nation-wide SOC records (measured in the late 1980s and early 1990s).

3. As crop production planning in Bangladesh is dependent on inundation land types, further research should be initiated in all alluviums to assess the impacts of inundation land types and cropping intensity on SOC.

4. In addition to the top soil organic carbon and nitrogen contents, national soil research initiatives should also consider how the current land use and management practices are affecting SOC and TN storage across the land types, cropping patterns, and intensities.

5. As SOC was found to be low in all the study sites, thus there is a clear need of developing soil conservation strategies to control further loss of SOC, and where possible to sequester SOC. This could include a range of strategies, e.g., promoting the use of manure, following appropriate crop rotations for maximum crop residue inputs, and implementing conservation tillage. A fallow period between crops should be promoted. It should also be possible to grow short-term leguminous crops in between main crops for the purpose of green manuring.

6. Soil sampling resolution for SOC assessment should be relatively high, as low-resolution sampling as in this study may not capture the variability and could also fail to capture its spatial dependence. There are benefits of such grid sampling as it would allow detailed mapping of SOC. However, it is important that the validity of such interpolation based mapping techniques (Kriging) should be assessed by sampling and assessing SOC at interpolated locations.

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Appendix 1. A Brief description on the Soil Orders of the World Soils

Soil Orders	Descriptions
Aridisols	Aridsols are soils that develop in very dry environments. The main characteristic of this soil is poor and shallow soil horizon development. Aridsols also tend to be light colored because of limited humus additions from vegetation. The hot climate under which these soils develop tends to restrict vegetation growth. Because of limited rain and high temperatures soil water tends to migrate in these soils in an upward direction. This condition causes the deposition of salts carried by the water at or near the ground surface because of evaporation.
Alfisols	Alfisols form under forest vegetation where the parent material has undergone significant weathering. The most distinguishing characteristics of this soil type are the illuviation of clay in the B horizon, moderate to high concentrations of base cations, and light-colored surface horizons.
Andisols	Andisols develop from volcanic parent materials. Volcanic deposits have a unique process of weathering that causes the accumulation of allophane and oxides of iron and aluminum in developing soils.
Entisols	Entisols are immature soils that lack the vertical development of horizons. These soils are often associated with recently deposited sediments from wind, water, or ice erosion. In Bangladesh, these types of soils are more prominent and develop from deposited sediments from water.
Histosols	Histosols are organic soils that form in areas of poor drainage. Their profile consists of thick accumulations of organic matter at various stages of decomposition.
Inceptisols	Inceptisols are young soils that are more developed than Entisols. These soils are found in arctic tundra environments, glacial deposits, and relatively recent deposits of stream alluvium. Common characteristics of recognition include immature development of eluviation in the A horizon and illuviation in the B horizon, and evidence of the beginning of weathering processes on parent material sediments.
Mollisols	Mollisols are soils common to grassland environments. Mollisols have a dark colored surface horizon, tend to be base rich, and are quite fertile. The dark color of the A horizon is the result of humus enrichment from the decomposition of litter fall. Mollisols found in more arid environments often exhibit calcification.
Oxisols	Oxisols develop in tropical and subtropical latitudes that experience an environment with high precipitation and temperature. The profiles of Oxisols contain mixtures of quartz, kaolin clay, iron and aluminum oxides, and organic matter. For the most part, they have a nearly featureless soil profile without clearly marked horizons. The

	abundance of iron and aluminum oxides found in these soils results from strong chemical weathering and heavy leaching. Many Oxisols contain laterite layers because of a seasonally fluctuating water table.
Spodosols	Spodosols are soils that develop under coniferous vegetation and as a result are modified by podzolization. Parent materials of these soils tend to be rich in sand. The litter of the coniferous vegetation is low in base cations and contributes to acid accumulations in the soil. In these soils, mixtures of organic matter and aluminum, with or without iron, accumulate in the B horizon. The A horizon of these soils normally has an eluvial layer that has the color of more or less quartz sand. Most spodosols have little silicate clay and only small quantities of humus in their A horizon.
Ultisols	Ultisols are soils common in areas with high amounts of precipitation because of summer thunderstorms and the winter dominance of the mid-latitude cyclone. Warm temperatures and the abundant availability of moisture enhance the weathering process and increase the rate of leaching in these soils. Enhanced weathering causes mineral alteration and the dominance of iron and aluminum oxides. The presence of the iron oxides causes the A horizon of these soils to be stained red. Leaching causes these soils to have low quantities of base cations.
Vertisols	Vertisols are heavy clay soils that show significant expansion and contraction due to the presence or absence of moisture. The strong shrinking and swelling action is dominated by the smectite clays in these soils. Vertisols are common in areas that have shale parent material and heavy precipitation.