Soil organic carbon dynamics in the agricultural soils of Bangladesh following more than 20 years of land use intensification

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ABSTRACT

Soil organic carbon (SOC) is a key soil quality indicator, as it is a source and storage of plant nutrients and plays a vital role in soil fertility and productivity maintenance. Intensification of agriculture is known to cause SOC decline; however, much of the evidence stems from field-scale experimental trials. The primary aim of this study is to investigate how more than 20 years of agricultural land use intensification in Bangladesh has influenced SOC levels at landscape levels. This was achieved by revisiting in 2012 four sub-sites from the Brahmaputra and Ganges alluviums which were previously sampled (1989-92) by the Soil Resource Development Institute and collecting 190 new samples. These were located at different elevations and subjected to differing amounts of inundation. The SOC was determined using the same method, potassium dichromate wet oxidation, used in the 1989-92 campaign. A comparison of the SOC in the 2012 samples with their historic levels (1989-92) revealed that overall SOC declined significantly across both alluviums as well at their four sub-sites. Further analysis, however, showed that SOC has declined more at higher sites. The higher sites are inundated to a limited level, which makes them suitable for growing multiple crops. Among the land types considered here, the low land sites (because of their topographical position) remain inundated for a greater part of the year, allowing a maximum of only one crop of submerged rice. As a result of reduced biomass decomposition due to anaerobic conditions when inundated, and lower land use/cropping intensity, SOC accretion has occurred in the lower land sites.

The SOC levels in South Asian countries are inherently low and agricultural land use intensification fuelled by growing food production demand is causing further SOC loss, which has the potential to jeopardise food security and increase the environmental impact of agriculture.

Key words: Cropping intensity, land types, soil management practices, food security

1. INTRODUCTION

Soil organic carbon (SOC) is the largest terrestrial carbon pool and plays an important role in the global carbon cycle (Grace, 2004; Lal, 2004; Scharlemann *et al.,* 2014). Land use change is a critical component with respect to global carbon dynamics and at the same time has become a key concern due to its adverse effect on climate through the emission of greenhouse gases (Post and Kwon, 2000; Gal *et al*., 2007). Changes in land use from native vegetation to agricultural crops are known to deplete SOC (Lewis *et al.* 2016) and increase atmospheric CO_2 concentration (Cruz *et al*., 2010; Wiesmeier, 2014). However, land-use driven change in SOC at a given site depends on several factors, such as crop type, cropping intensity and land management practices, including the management of crop residues (Ogle et al., 2005; Deng et al., 2016; Ramesh et al., 2019; Uddin et al., 2019). Assessing the impact of land-use change and management practices, particularly on landscape levels, is therefore critical to better understanding the spatial and temporal dynamics of SOC, as well as their drivers (Canadell, 2002; Guo and Gifford, 2002; Grunzweig et al., 2004). Such studies are particularly relevant in countries where population expansion is fuelling intensive land use in agriculture (e.g., Bangladesh, China, India) in order to develop policies that attain a balance between food production needs and environmental provisions (Zhang et al., 2006; Qiu et al., 2016). SOC is an important indicator of sustainable land management and productivity (Nandwa, 2001), as it is a source and storage of plant nutrients and plays a vital role in soil fertility maintenance (Bationo et al., 2007; Gal et al., 2007). Decline in SOC due to unsustainable land management practices (e.g., intensive tilling, complete crop residue removal or burning of crop residue, insufficient nutrient inputs and little or no manure application) can therefore result in reduction in food production, jeopardising food security (FAO, 2001; Blum, 2008).

Increasing SOC has been proposed to mitigate climate change with an additional benefit of improving soil structure and productivity (Zhao et al., 2015; Lal, 2016), as soil carbon (1550 Pg organic carbon) pool is >2 times larger than that of the atmosphere (750 Pg) (Eswaran et al., 1993; Lal et al., 1995). A relatively small increase in SOC stocks therefore could exert a significant role in mitigating greenhouse gas emissions. Recognising this, in 2015 the French Minister of Agriculture (Stéphane Le Foll) set up an ambitious international programme, the '4 per mille Soils for Food Security and Climate' as part of the Lima-Paris Action Agenda. This programme aims to increase global soil organic matter stocks by 0.4%

per year to compensate for the global emissions of greenhouse gases by anthropogenic sources (Minasny et al., 2017). It was launched at the annual Conference of Parties (COP21) in December 2015 and supported by almost 150 signatories. Stakeholders commit, in a voluntary action plan, to implement farming practices that maintain or enhance soil carbon stocks in agricultural soils and to preserve carbon-rich soils (Chambers et al., 2016; Lal, 2016).

A significant portion of SOC stock has been lost from agricultural soils since the beginning of intensive agriculture. The loss of SOC stock has been estimated to approximately 60% and 75% of SOC in temperate and tropical ecosystems, respectively (Lal et al., 2007; Ghimire et al., 2015). In South Asia, SOC in cultivated lands range from 8 to 10 g kg^{-1} - a low level resulting from nutrient depletion, intensive tillage, erosion, unbalanced fertilization, and crop residue removal (Lal 2004; Srinivasarao et al., 2019). Bangladesh is a highly populated and land scarce country. Its net cultivated area (NCA) is 8.50 million ha and per capita NCA is only about 0.060 ha (BBS, 2017) - less than one quarter of the estimated contemporary world per capita NCA of about 0.26 ha. Increasing population is putting considerable pressure on land for food production. Consequently, the cropping intensity has gradually increased over the last twenty years (BBS, 2017; Uddin et al., 2019), which may have further decreased SOC in the agricultural soils of Bangladesh. This is underscored by Kopittke et al. (2019) who state that the intensification of agricultural practices globally is causing unsustainable degradation of soils, including loss of soil organic carbon, jeopardising the long-term ability of soils to provide food and ecosystem services.

Soil organic carbon levels are directly influenced by primary production, the amount of external organic inputs (e.g., manure) and decomposition (Ontl and Schulte, 2012). The intensification of agriculture in Bangladesh has led to a situation where generally no manure is used (Uddin et al., 2019; Nandi and Nusrat, 2020; Shaibur *et al*., 2021), and the only productivity additions are through crop root biomass. The characteristic hot and humid climatic conditions prevailing in Bangladesh are conducive to rapid mineralization and thus loss of SOC (Ontl and Schulte, 2012). This is supported by Uddin et al. (2019) where 268 samples were collected from soils developed on the two major alluvial deposits of the Brahmaputra and Ganges Rivers in Bangladesh. The results showed that high land use intensity sites had lower SOC than relatively low land use intensity sites.

Given the intensification of agriculture in Bangladesh (increased cropping intensity and little to no use of manure), we hypothesise that SOC in cultivated lands has decreased, particularly those developed on the Brahmaputra and Ganges alluvial deposits – these are some of the most intensively used agricultural soils in the country. To test this hypothesis, we analysed SOC in 190 soil samples in 2012, collected from locations which were previously sampled and analysed by SRDI (1989-92) for SOC more than 20 years earlier. A comparison of SOC between the two datasets (Supplementary Information, Tables S1 and S2) allows us to examine how SOC has been influenced by land use intensity and management practices during this period.

2. MATERIALS AND METHODS

2.1 Study sites

Four sub-sites: Delduar, Melandah, Fultala, and Mirpur were selected within the two major alluvial deposits of Bangladesh – the Brahmaputra and the Ganges (Fig. 1). Sediments on the Brahmaputra and the Ganges floodplains are derived from the Himalayas and are rich in easily weatherable minerals, such as feldspars and biotite (Brammer, 2016). The Ganges alluvial deposits contain lime, and their sand fraction contains more garnet than epidote and they have smectite type clay minerals which give them strong swelling and cracking properties (Brammer, 2016). The Brahmaputra alluvial deposits, on the other hand, do not contain lime; their sand fraction contains more epidote than garnet, and they have a mixture of illite and kaolinite clays (Brammer, 2016).

The climate of the study sites is hot and humid in summer and cold and dry in winter. Due to location of the Himalayas to the north and the Bay of Bengal to the south, Bangladesh is characterized by a monsoon climate. The distribution of rainfall is highly skewed both spatially and seasonally (Islam, 2017) with mean annual rainfall increasing towards the north-east and decreasing towards the west. Seasonal variation shows that about 80% of the rainfall occurs during the five-month monsoonal period which usually starts from June. The dry season, which extends over seven months, has a high deficit in water and soil moisture (Islam, 2017).

The sampling information about the study sites and their geographic locations are presented in Table 1. A total of 190 composite soil samples were collected from the four sub-sites (Fig. 1), which were previously sampled by the Soil Resource Development Institute between 1989 and 1992 (SDRI, 1989-1992). The Delduar and Melandah sub-sites fall under the Brahmaputra River alluvial deposits (Fig. 1), which were previously sampled during 1990-91 and were re-sampled in this study in March 2012. The sub-sites at Fultala and Mirpur fall under the Ganges River alluvial deposits which were previously sampled during 1989-1992 and were re-sampled in April 2012. The Land and Soil Resource Utilization Guide (LSRUG) maps of the SRDI were used in the field for locating the previous sampling sites. These maps gave the sampling location by geo-coordinates (latitude and longitude) in the respective land types. A global positioning system (GPS) receiver was used in the field to locate the sampling sites.

Information on land types, land use and cropping intensity were recorded during field work, by interviewing local farmers and following the land and soil resource utilization guides of the Soil Resource Development Institute (SDRI, Bangladesh). This included interviewing farmers around each soil sampling location as was done during the 1989-92 soil sampling by the SDRI (SDRI, 1989-1992)

The study sites cover a range of agro-ecological zones that are favourable for multiple cropping. In Bangladesh, land is categorized into five inundation land types depending on the nature of frequent flooding and inundation – high land (HL): where the land is above normal flood level; medium high land (MHL): where the land is flooded up to about 90 cm deep during the flooding season; medium low land (MLL): where the land is flooded up to between 90 to 180 cm; low land (LL): where the land is normally flooded up to between 180 to 300 cm deep, and very lowland (VLL): where land is normally flooded deeper than 300 cm (FAO-UNDP, 1988). HL and MHL are the most suitable land types for a wide range of agricultural uses due to their limited inundation. These land types are intensively cultivated around the year with irrigation water used.

2.2 Soil sampling and analysis

Soil samples from each of the four sub-sites were collected from the top 30 cm (0-30 cm) depth using an auger. It should be stressed that the sampling locations exclude settlements, industry, woodlands, waterbodies, and infrastructure, as the focus of this work is on land that is used for farming purposes. A composite soil sampling strategy was followed to obtain representative samples from the sampling locations. This involved randomly collecting 10 soil samples around the geo-coordinates (10x10m) of each sampling location. These 10 samples were spread on a polythene sheet, discarding non-soil materials. The samples were thoroughly mixed, quartering was achieved by splitting the thoroughly mixed sample into four equal parts, two opposite quarters were discarded, and the remaining quarters were remixed, and the process repeated until the desired composite sample size (about 500 g) was obtained. In this way, 190 composite samples were collected in polythene bags which were then sealed to preclude moisture loss before being transferred to the laboratory for analysis. The samples were prepared by spreading them on polythene sheets, with larger aggregates disaggregated and allowed to air dry under shade. The soil samples were then gently ground using a pestle and mortar and passed through a 2 mm sieve and mixed thoroughly before being stored in plastic bags ready for laboratory analysis. Within 2 weeks following sampling, soil organic carbon was determined by the Walkley and Black wet oxidation method, as outlined in Nelson and Sommers (1982); this is the same SOC determination method as used during the previous (1989-1992) soil sampling campaign. In each soil sample, SOC was determined using 3 replicates, with variation between the replicates ranging from <5% to <10%.

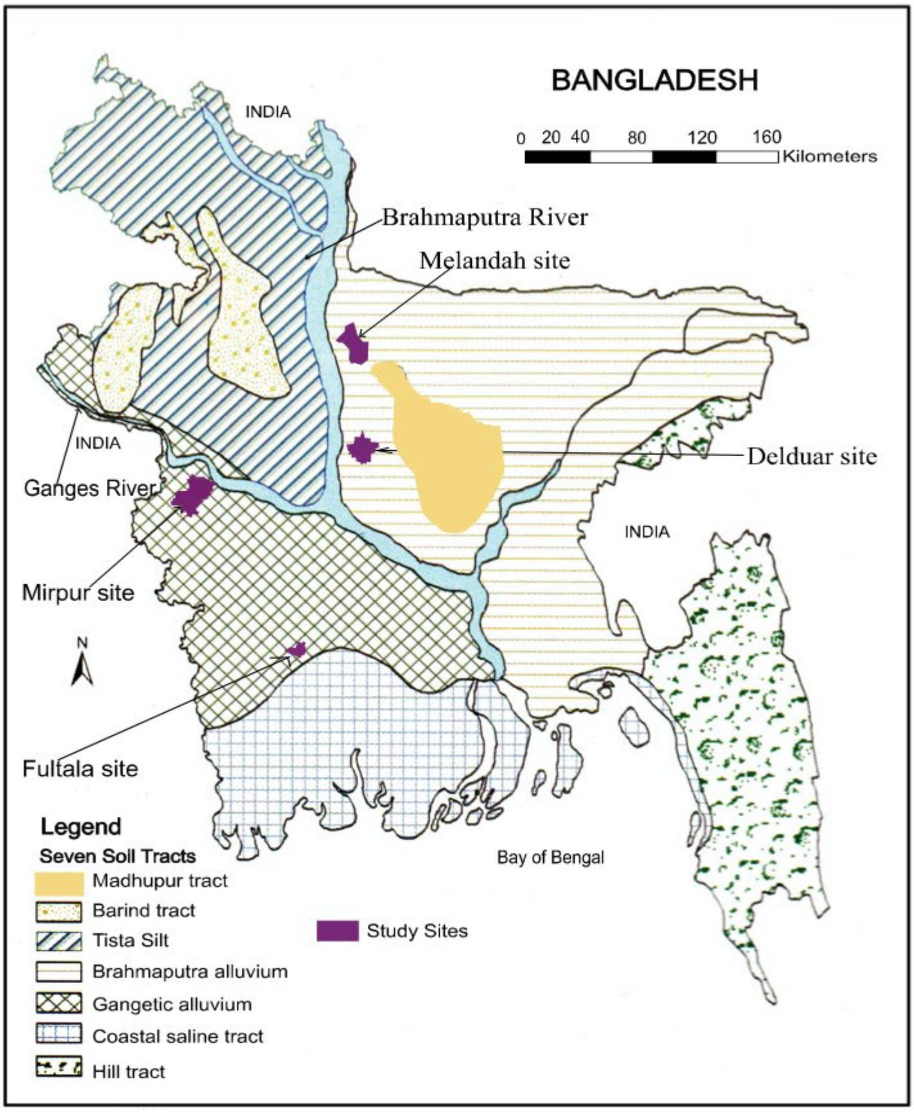

Figure 1. Location map of the four sub sites across the Brahmaputra and the Ganges alluvial deposits of Bangladesh (Adapted from Hussain et al., 2003)

2.3 Data analysis

Prior to data analysis, the nature of SOC distribution of both sets of data (1989-92 and 2012) was assessed initially by examining Q-Q plots, histograms and skewness and kurtosis (Supplementary Information, Figures S1 and S2). Further analysis by the Shapiro-Wilk test (Supplementary Information, Table S3) confirmed that the SOC datasets were not normally distributed ($p<0.001$). As a result, the 1989-92 and 2012 SOC datasets and their sub-sets (individual sites, sub-sites, and land types) were evaluated using the Wilcoxon singed-rank test (nonparametric equivalent of the paired student's t-test), using SPSS, 2012 version 20.0. The SOC dynamics were assessed by comparing the 2012 SOC measurements with those measured previously (1989-92) across the individual sites, sub-sites, and land types. The SOC variability was further assessed by boxplot analysis using R (R Core Team, 2013).

Table 1: Geographic locations, total area, sampled area, soil types, sampling year and number of soil samples (n) across the four study sites

Sites	Sub-sites	Total area (ha)	Sampled area (ha)*	Geographic locations	**Soil types	Sampling year		Number of samples
						This work	Previous study	
Brahmaputra Alluvium	Delduar	18,097	14,399	23˚ 14' to 24˚ 03' N latitude, 89˚ 50' to 90˚ 02' E longitude	Inceptisols and Entisols	2012	1990	36
	Melandah	23,992	20,861	24˚ 51' to 25˚ 04' N latitude, 89˚ 43' to 89˚ 54' E longitude	Inceptisols and Entisols	2012	1991	60
Ganges Alluvium	Fultala	7,438	5143	22˚ 54' to 23˚ 01' N latitude, 89˚ 23' to 89˚ 31' E longitude	Inceptisol, Entisols and Histosols	2012	1989	28
	Mirpur	30,454	26,683	23˚ 47' to 24˚ 01' N latitude, 88˚ 51' to 89˚ 07' E longitude	Inceptisols and Entisols	2012	1992	66
Total number of soil samples								190

Source: SRDI (1989-1992)
*Excludes non-agricultural land, settlements, and waterbodies
**Rahman (2005)

3. RESULTS

Table 2: Statistics of the Wilcoxon signed-rank test analysis comparing SOC (%) change in the study sites between the two sampling periods (1989-92 and 2012)

Parameters of SOC statistics	Sampling Year	N	Median	Mean	SD*	SEM**	P***
Whole study site (Brahmaputra and Ganges combined)	1989-92	190	0.870	0.978	0.559	0.040	
	2012		0.675	0.842	0.469	0.034	<0.001
Brahmaputra alluvium	1989-92	96	0.870	1.099	0.622	0.063	
	2012		0.790	0.921	0.521	0.053	<0.001
Ganges alluvium	1989-92	94	0.750	0.855	0.458	0.047	
	2012		0.630	0.762	0.397	0.040	<0.001
Delduar sub-site	1989-92	36	1.240	1.502	0.811	0.135	
	2012		0.980	1.228	0.684	0.114	<0.001
Melandah sub-site	1989-92	60	0.860	0.860	0.276	0.035	
	2012		0.665	0.739	0.260	0.033	<0.001
Fultala sub-site	1989-92	28	1.425	1.311	0.518	0.097	
	2012		1.120	1.135	0.511	0.096	<0.010
Mirpur sub-site	1989-92	66	0.690	0.661	0.248	0.030	
	2012		0.560	0.603	0.178	0.021	<0.010
Highland (HL)	1989-92		0.580	0.641	0.274	0.038	
	2012	51	0.500	0.553	0.174	0.024	<0.001
Medium highlands (MHL)	1989-92	98	0.870	1.066	0.589	0.059	
	2012		0.660	0.823	0.422	0.042	<0.001
Medium lowlands (MLL)	1989-92	34	1.125	1.258	0.601	0.103	
	2012		1.135	1.301	0.593	0.101	0.067
Lowlands (LL)	1989-92	07	0.870	0.854	0.258	0.097	
	2012		1.000	1.041	0.255	0.096	0.022

*SD = Standard deviation

**SEM = Standard Error of the Mean

***p (Wilcoxon signed-rank test, nonparametric equivalent of the paired t-test)

3.1 SOC dynamics over the alluvial deposits, sub-sites and land types

SOC dynamics in the study sites were assessed by comparing the 2012 and previous (1989-92) SOC datasets over the two alluvial deposits, four sub-sites and land types of the study sites. SOC in the Brahmaputra alluvial deposits in the 2012 samples varies from 0.40 to 2.60% (Fig. 2), with an overall mean of 0.92±0.52% (n = 96, Table 2) whereas in the 1989-92 samples varied from 0.46 to 2.78% (Fig. 2) with a mean of 1.09±0.62% (n = 96, Table 2). On the other hand, SOC in the Ganges alluvial deposits sampled during the 2012 sampling campaign varies from 0.31 to 2.30% (Fig. 2), with an overall mean of 0.76±0.397% (n = 94, Table 2) while in the 1989-92 sampling varied from 0.23 to 2.03% (Fig. 2) with a mean SOC of 0.85±0.458% (n = 94, Table 2). It should be noted that the higher SOC values observed in both datasets (1989-92 and 2012) are outliers outside the upper range – these SOC values differ significantly from the other observations (Fig. 2)

SOC in the soil samples collected in the 2012 campaign across all four sub-sites varies from 0.31 to 2.60% (Fig. 3), with an overall mean of 0.84±0.469% (n = 190, Table 2). SOC in the soil samples collected during the previous sampling period (1989-92) from the same locations across all 4 subsites over the two alluvial deposits ranged from 0.23 to 2.78% (Fig. 3) and the overall mean SOC was 0.97± 0.559% (n= 190; Table 2). A comparison of the 2012 SOC levels with those from the previous sampling (1989-92), using the Wilcoxon signed-rank test, showed that SOC has declined significantly ($p<0.001$) in the two alluvial deposits over the two sampling periods (Table 2). It provides clear evidence of considerable SOC decline in the Brahmaputra and the Ganges alluvial deposits between the 1989-92 and 2012 sampling periods i.e., over a period of 20-23 years. Similarly, SOC has declined during this period significantly ($p<.001$) at all four sub sites i.e., Delduar, Melandah, Fultala and Mirpur (Table 2). A similar analysis (the Wilcoxon signed-rank test) was used to compare the SOC measured in 2012 with the previously (1989-92) measured SOC levels across the land types, based on data pooled over the two alluvial deposits. It is interesting to note that SOC levels have declined significantly in the HL and MHL sites but SOC levels over the same period (1989/92-2012) show no statistically significant change in the MLL and SOC has increased significantly in the LL sites (Table 2).

3.2 Temporal and spatial variability in SOC distribution

The SOC temporal and spatial variability was assessed using boxplot analysis. SOC variability was compared across the alluviums, the individual sub-sites and land types to examine the site and land type associated trends between the two sampling periods i.e., 1989-92 and 2012.

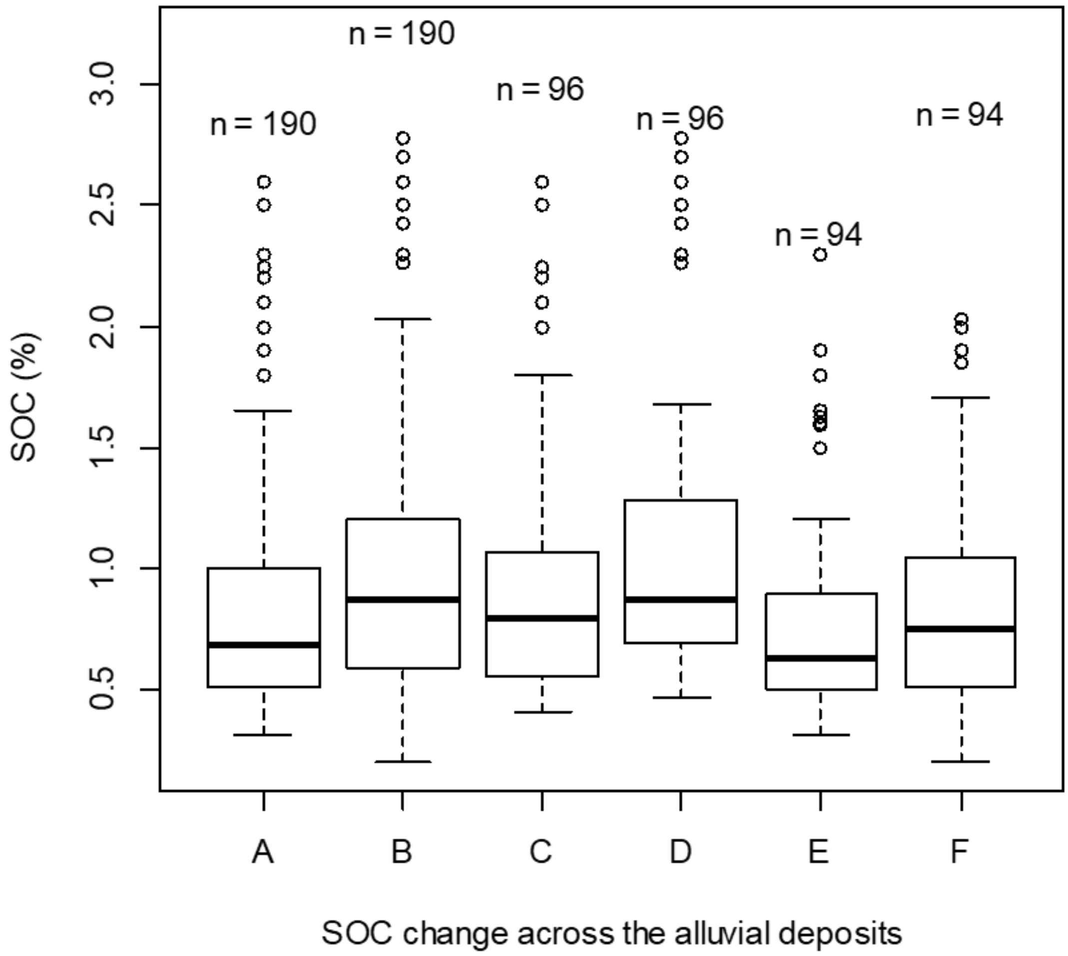

Figure 2: Boxplots showing change in SOC distribution, measured in 1989-92 and 2012 across the alluvial deposits (A and B: SOC in 2012 and 1989-92 in both alluviums combined, respectively; C and D: SOC in 2012 and 1989-92 in the Brahmaputra alluvium, respectively; E and F: SOC in 2012 and 1989-92 in the Ganges alluvium, respectively).

3.2.1 SOC distribution and variability over the two alluvial deposits

SOC variability between the two soil sampling periods (1989-92 and 2012) was compared across the two alluvial deposits. The results show that across both the alluviums SOC variation is lower in the 2012 SOC dataset compared to its variation in the previous (1989-92) dataset (Fig. 2). That is, not only has the SOC decreased (Table 2) in the two alluvial deposits, but its variability has also decreased between the two sampling periods (Fig. 2). Boxplot analysis of the combined data from both the alluviums shows that SOC distribution changed from approximately symmetric to positively skewed when the two SOC datasets (1989-92 vs. 2012) are compared (Fig. 2). The decline in the combined (Brahmaputra and Ganges alluviums) SOC levels is further supported by its decreases in both the upper and lower quartile ranges and reduction in the interquartile range, with a lower median SOC in the samples collected in 2012 compared to those during 1989-1992 (Fig. 2).

Likewise, the distribution of SOC in the Ganges alluvial deposits also considerably changed, becoming less variable in the 2012 samples compared to the 1989-92 dataset, with clear decreases in its upper/lower quartiles and interquartile range (Fig. 2). The SOC distribution changed from nearly symmetric to positively skewed and the median SOC decreased from 0.75% to 0.63% (Table 2). The SOC distribution also changed in the Brahmaputra alluvial deposits from positively skewed to nearly symmetric, and its median value also declined though to a relatively lower extent (0.87 to 0.79%; Table 2) compared to the Ganges alluvial deposits (Fig 2). However, unlike the Ganges alluvial deposits, the upper quartile SOC range of the Brahmaputra increased compared to its 1989-92 dataset, indicating SOC sequestration in its upper range concentrations.

The boxplot analysis clearly showed that the SOC distribution and variability across the whole study site (i.e., the Ganges and Brahmaputra combined data) and individual alluvial deposits have changed in terms of its reduced spread and median values. Although the SOC decreases have occurred in the upper and lower quartiles as well as in the interquartile ranges, generally much greater SOC losses are evident in the upper quartiles (Fig. 2), suggesting larger declines where SOC was relatively higher in the 1989-92 samples, except for the Brahmaputra alluvial deposits.

3.2.2 SOC distribution and variability over the sub-sites

The changes in SOC distribution and variability across the 4 sub-sites over the two sampling periods (1989-92 and 2012) show similar trends (Fig. 3), as seen for the two alluviums (Fig. 2). The median SOC levels across the sub-sites decreased compared to their 1989-92 median values (Fig. 3), supporting the trend observed for the two alluviums (Fig.2). However, the extent of SOC decrease and change in its general distribution across the four sub-sites vary. In Delduar sub-site, while SOC distribution remained asymmetric, there are considerable reductions in the upper quartile and the interquartile range, indicating clear decreases in the top 25% and the middle 50% of the SOC values (Fig. 3).

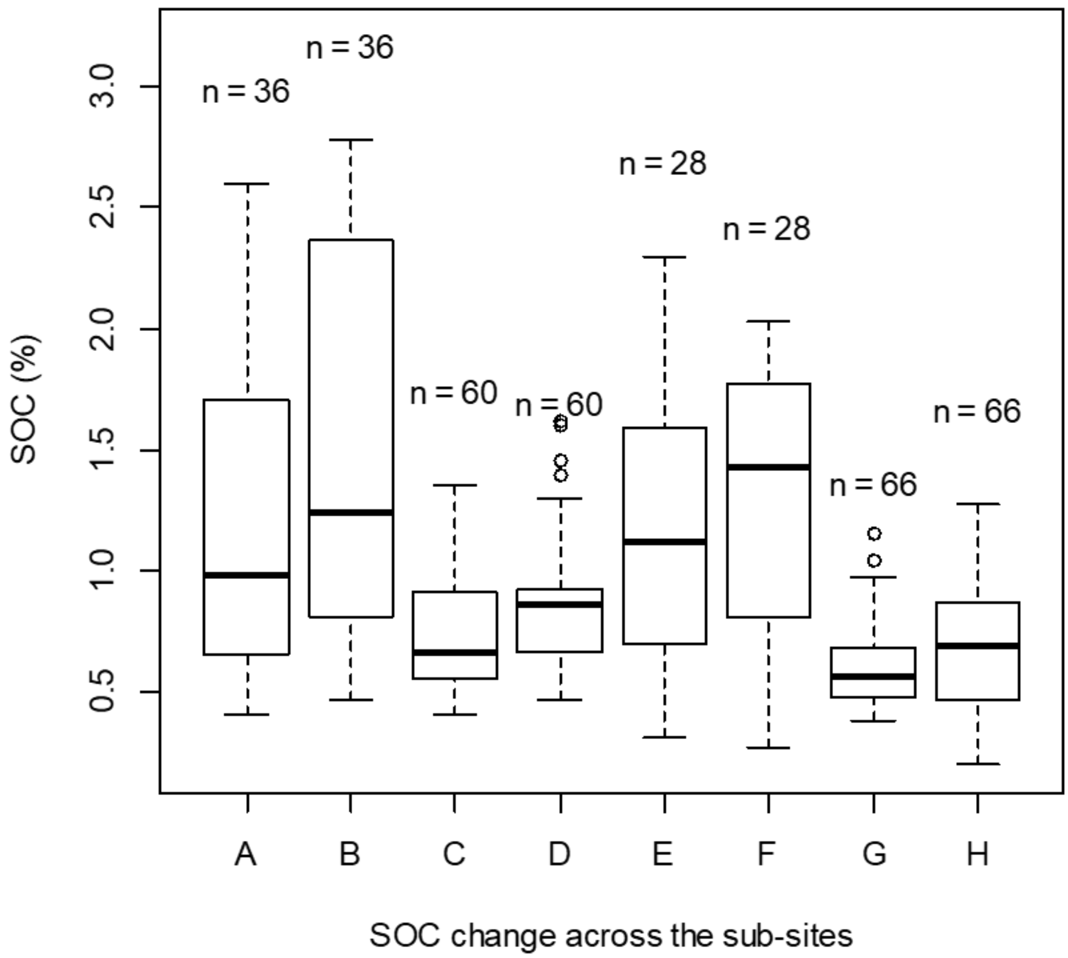

Figure 3: Boxplots showing change in SOC distribution during 1989-92 and 2012 across the sub-sites. (A and B: SOC at Delduar in 2012 and 1989-92, respectively; C and D: SOC at Melandah in 2012 and 1989-92, respectively; E and F: SOC at Fultala in 2012 and 1989-92 respectively; G and H: SOC at Mirpur in 2012 and1989-92, respectively.

In Melandah sub-site, on the other hand, SOC distribution in the 2012 samples changed from negatively (1989-92) to positively skewed, and its interquartile range increased, primarily due to its increase in the lower 50% of the SOC values in the 2012 dataset (Fig. 3). The SOC distribution in Fultala site in the 2012 samples changed from positively skewed asymmetric (1989-92) to symmetric, with a clear downward shift in its interquartile range, indicating decreases in the lower 50% of the SOC values (Fig. 3). At the same time, increases in the top 25% SOC values are also evident, suggesting increases in the top 25% and the lower 50% of SOC, i.e., a decline in the lower SOC values. In Mirpur sub-site, the SOC distribution changed from approximately symmetric to positively skewed in the 2012 samples compared to those collected during 1989-92, with clear decreases in its upper and lower quartiles as well in the interquartile range. These changes provide unambiguous evidence of SOC changes/decreases over its entire range (Fig. 3).

The boxplot analysis of SOC at the 4 sub-sites, when comparing the two datasets (1989-92 and 2012), shows median values have decreased and so have the interquartile ranges and the lower 50% and upper 25% (except for Delduar and Fultala sub-sites) of the SOC values, supporting evidence of clear decline in SOC in the two alluviums, as seen previously (Fig. 2).

3.2.3 SOC distribution and variability across the land types

Since cropping intensity or agricultural land use intensity in Bangladesh is strongly influenced by land type i.e., depending on the nature and extent of flooding (Brammer, 2016; Uddin et al. 2019), it is possible that SOC distribution and variability over the two sampling periods (1989-92 and 2012) may have been influenced by land types. We examined this by box plotting the SOC data for each land type from the two alluviums together for the individual sampling periods (Fig. 4). As compared to 1989-92, the SOC variability in the high land and medium high land sites has decreased considerably in the 2012 dataset, as indicated by clear decreases in the upper and lower quartiles as well the interquartile ranges (Fig. 4). This decrease in SOC is further supported by lowering of the median SOC values during the two sampling periods. On the other hand, the pattern of change in SOC distribution and variability in the medium low land sites is different. Here the SOC upper quartile and the interquartile range measured in 2012 are higher than their previous estimates (1989-92), though the median values are similar as is the distribution i.e., asymmetric positively skewed (Fig. 4). Nonetheless, it indicates some increases in the top 50% SOC values.

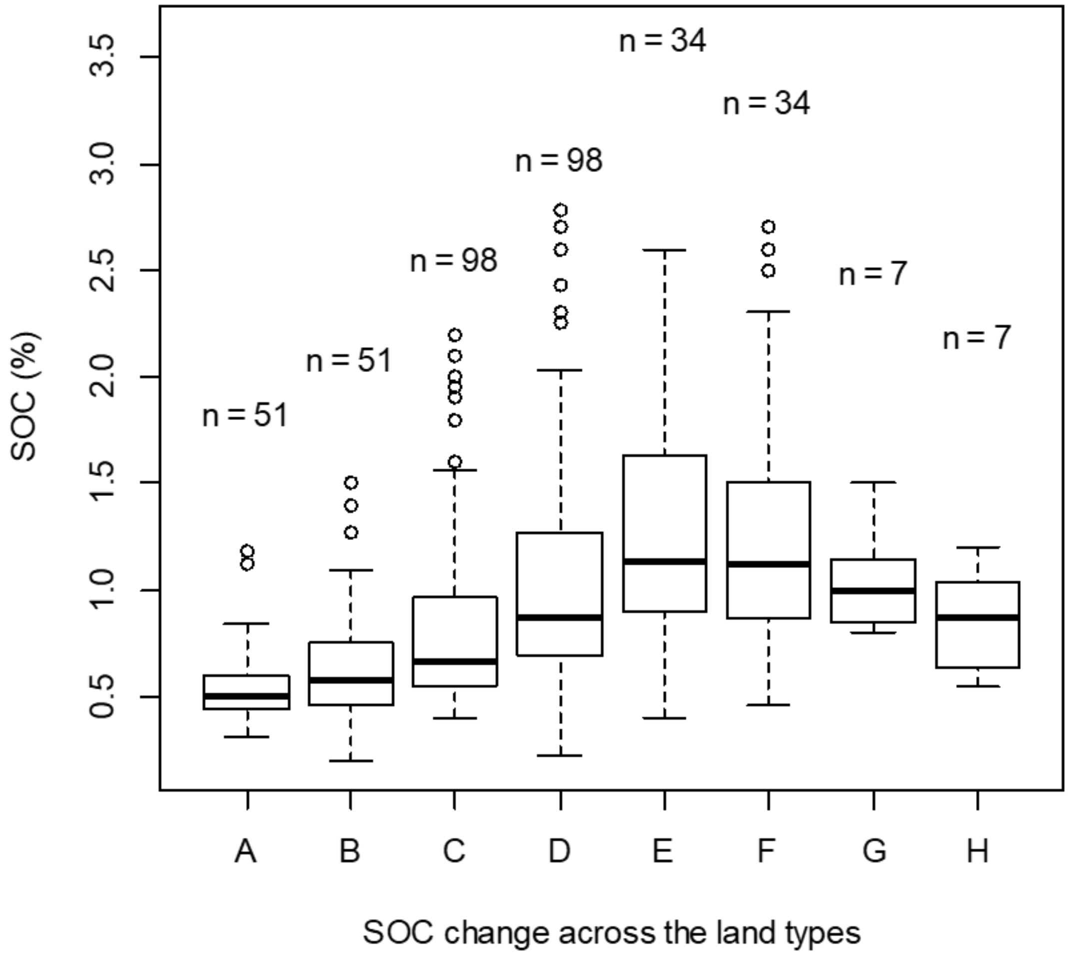

Figure 4: Boxplots showing change in SOC distribution during 1989-92 and 2012 across the land types (A and B: SOC in 2012 and 1989-92 in the highland sites respectively; C and D: SOC in 2012 and 1989-92 in the medium highland sites respectively; E and F: SOC at 2012 and 1989-92 in the medium lowland sites respectively; G and H: SOC in 2012 and 1989-92 in the lowland sites respectively), based on combined data from the Ganges and Brahmaputra alluvial deposits.

In the low land sites, the upper SOC quartile increased but the interquartile range and the lower quartile decreased considerably in 2012 compared to their 1989-92 estimates, with a clear increase in the median SOC (Fig. 4, Table 2). This indicates increase in the upper 50% SOC values and decrease in the lower 50% SOC values, indicating its sequestration during the two sampling periods.

3.2.4 Changes in Land Use Intensity

Changes in land use and cropping patterns in Bangladesh started in the early 1970s; however, the pace of change from the 1980s – and during the study period (1989/92-2012) is particularly noticeable. These changes in land use, cropping intensity, and cropping patterns started with breakthroughs in rice production technologies (Rahman, 2010; Uddin *et al*., 2019). At the same time the introduction of canal water for irrigation, high yielding cultivars, and (in some areas) flood protection allowed farmers to grow 2-3 crops annually instead of a single crop (Tables 3 and 4).

Traditional crop cultivars were replaced by new high yielding varieties and growing 2-3 crops a year on the same land became a common phenomenon, increasing the cropping intensity across all 4 subsites (Supplementary Information, Figure S3), particularly in the HL (high land) and MHL (medium high land) sites (Tables 3 and 4). In contrast, the level of inundation restricts the MLL (medium low land) sites to 1-2 crops and LL (low land) sites to one crop a year i.e., a relatively lower cropping intensity (Tables 3 and 4; Supplementary Information, Figure S3) in the lower lands. While the cropping patterns have changed, the cropping intensities changes are limited in the MLL and LL sites (Tables 3-4, and Supplementary Information, Figure S3); the principal difference being that local or traditional rice varieties have been replaced by high yielding rice cultivars in these sites, specifically those grown under submerged rice conditions. The major changes that occurred between the two sampling periods (1989-92 and 2012) include intensification of vegetable crops, high-yielding rice cultivars, and other crops now commonly grown in the HL and MHL sites (Tables 3 and 4). Winter crops and vegetables are specifically grown under intensive management at these sites where as the MLL and LL sites are being used for high yielding rice cultivars under submerged conditions as well as aquaculture, particularly at the LL sites. Thus, the number of crops has enhanced cropping intensity (CI) in the HL and MHL sites compared to the MLL and LL sites.

Table 3: Changes in land use/cover in the studied sites under the Brahmaputra alluvial deposits

Land type	Land use (1989-92)*	Land use (2012)**
High land (HL)	1. Sugarcane	1. Sugarcane/Pineapple/Banana-Wheat-Potato
	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/Tobacco/Jute-Transplanted *Aman* rice
		3.3 Mustard/Potato/Cowpea -Mixed *Aus* and *Aman* rice
		3.4 Mustard/Cowpea/Pulses -Transplanted *Aman* rice
		3.5 Wheat/Pepper/Mustard-Transplanted *Aman* rice
	4. Broadcast *Aman* Rice-Fallow	*4.1 Boro* rice -Transplanted *Aman* Rice
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* rice- Transplanted *Aman* rice
		1.4 Mustard/Cowpea/Pulses -Transplanted *Aman* rice
	2. *Aman* Rice-Mustard- ***HYV *Boro* rice	2.1 Mustard/Potato - HYV *Boro* rice -Transplanted *Aman* rice
		2.2 Wheat/Jute/Pepper/Mustard -Transplanted *Aman* rice
		2.3 Potato/Jute -Transplanted *Aman* rice
		2.4 Potato/HYV *Boro* rice -Transplanted Aman rice
	3 Transplanted *Aman* Rice-Fallow	3.1 Potato/Pulses- Boro rice -Transplanted Aman rice
	4 Broadcast *Aman* Rice-Fallow	4.1 Pepper/HYV *Boro* rice-Transplanted *Aman* rice
		4.2 Potato/Tobacco-Transplanted *Aman* rice
Medium lowland (MLL)	1. Mixed *Aus* and Broadcast *Aman* rice/*Aus* rice	1.1 Mustard/Cowpea/Pulses-HYV *Boro* rice
		1.2 HYV *Boro* rice- Deep transplanted *Aman* rice
	2. HYV *Boro* rice-Fallow	2.1 HYV *Boro* rice-Fallow
		2.2 HYV *Boro* rice-Deep Transplanted *Aman* rice
Low land (LL)	1. Grazing land/Fallow	1.1 HYV *Boro* Rice-Fallow
		1.2 Fallow/Aquaculture

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

** Numbers under land use indicate crop rotations/sequences, reflective of changes in cropping patterns /intensity. ***HYV= High Yielding Varieties or cultivars Boro is the dry season irrigated, grown in winter planted from December to early February and harvested between April and June. Aman rice is shown in rainy season (July/August) in harvested in November/December. Broadcast Aman is sown in March/April and transplanted Aman is planted during July August

Table 4: Changes in land use/cover in the studied sites under the Ganges alluvial deposits

Land use (1989-92)*		Land use (2012)**
	1. *Aus* rice/Jute -Vegetables	1.1 Wheat/Mustard/Maize/Rabi vegetables - Fallow
		1.2 Date palm plantation/Coconut/Betel nut
High land (HL)		1.3 Homestead gardens/Banana/Rabi vegetables
	2. *Aus* rice/Jute-Transplanted *Aman* rice	2. Rabi crops/vegetables -Transplanted *Aman* rice
	3. *Aus* rice /Jute/Vegetable-Rabi crops	3.1 Jute/ Rabi vegetables -Transplanted *Aman* rice
		3.2 Transplanted *Aman* rice/Rabi vegetables -Fallow
	4. Sugarcane	4.Tobacco/Wheat/Maize/Rabi Vegetables-Transplanted *Aman* rice
Medium high land (MHL)	1. *Aus* rice/Jute-Transplanted Aman rice/Rabi crops	1. HYV *Boro* rice/Rabi vegetables –Transplanted *Aman* rice
	2. *Aus* rice/Jute-Transplanted *Aman* Rice-Fallow	2. HYV *Boro* rice-Transplanted *Aman* rice
		2.1 Tobacco/Pulses/Wheat/Jute/Rabi Vegetables-Transplanted *Aman* rice
	3. Transplanted *Aman* Rice-Fallow	3.1 HYV *Boro* rice-Transplanted *Aman* rice
		3.2 Rabi vegetables- Transplanted *Aman* rice
	4. Transplanted *Aman* rice-HYV*** *Boro* rice	4. Mustard/Cowpea/Rabi vegetables-HYV *Boro* rice-Transplanted *Aman* rice
Medium lowland (MLL)	1. Mixed *Aus* rice and Broadcast *Aman* Rice-Fallow/Rabi vegetable crops	1. HYV B*oro* rice-Transplanted *Aman* rice
	2. Mixed broadcast *Aus* rice and Transplanted *Aman* rice-Rabi vegetables- Fallow	2.1 Shrimp/Hogla/Bamboo
		2.2 HYV *Boro* rice-Fallow
Lowland (LL)	1. Broadcast *Aman* Rice-Fallow	1.1 HYV *Boro* rice-Fallow
		2.2 Shrimp aquaculture

* According to previous database of SRDI 1989-1992; Note: Italics indicates the local name of the crops
Aus rice is sown during the month of March-April and harvested in June-July.
Rabi crops are sown in winter and harvested in spring
** Numbers under land use indicate crop rotations/sequences, reflective of changes in cropping patterns /intensity. *** HYV= High Yielding Varieties or cultivars

4. DISCUSSION

Intensification of agriculture, cropping intensity and soil organic carbon. The results provide clear evidence of SOC decline in the Brahmaputra and Ganges alluvial deposits as well as their individual sub-sites (Table 2) between the two sampling periods (1989-92 and 2012). The decline in SOC, it would appear, is mediated by several contributory factors that occurred during this period such as an increase in land use intensity i.e., cropping intensity (Supplementary Information, Figure S3 and Tables 3 and 4) and changes in agricultural land management practices. Land tilling intensity inevitably increases with cropping intensity, which has become a common phenomenon in Bangladesh, as in many South Asian and other countries. Long-term experimental studies show that intensive tillage enhances organic matter mineralization, particularly in situations where little or no organic amendments are applied and crop residues are poorly managed, resulting in loss of SOC (Cui *et al.,* 2003; Congreves et al., 2015; Carr, 2017 Grahmann *et al*., 2020). The rate of organic matter mineralisation is intensified by tillage through increased soil aeration, weakening of soil aggregate stability and hence decreased physical protection to decomposition of organic matters by micro-organisms i.e., enhanced tillage driven SOC loss (Post and Kwon, 2000). The characteristic hot and humid climatic conditions in Bangladesh further promote mineralisation of organic matter due to alternate drying and wetting conditions, and because organic substrate decomposition accelerates with increasing temperature (Davidson and Janssens, 2006), making maintenance of soil organic matter in tropical and sub-tropical agricultural soils relatively difficult (Anda *et al.,* 2010).

Agriculture in most countries has gone through intensification though to a variable degree, which without doubt has increased global food production; however, the process has caused a range of land degradation problems, including increased soil erosion and SOC loss (Bronson *et al.,* 1998; Lal, 2006; Lal *et al*., 2007; Ghimire *et al.,* 2015). In Bangladesh intensification of agriculture is at least partly driven by increasing food demand to feed over 162 million people from only 8.75 million hectares of agricultural land, which is shrinking due to its conversion for housing, road construction, industry, and other infrastructure developments, resulting in an annual loss of about 0.73% of agricultural land (BBS, 2017). To meet the increasing demand for food from limited land resources, cropping intensity has gradually increased (Supplementary Information Figure S3, and Tables 3. And 4). As a result, considerable changes in land use and cropping patterns have occurred in Bangladesh since the early 1970s. These changes in land use, cropping intensity, and cropping patterns started with breakthroughs in rice production technologies (Rahman, 2010). At the same time, the introduction of canal water for irrigation, construction of flood protection dams particularly in the Ganges and Brahmaputra alluviums and availability of high yielding cultivars and chemical fertilizers were also major factors responsible for changes in cropping patterns and cropping intensity (Mondal *et al*., 2015), as seen at the study sites (Tables 3 and 4; Supplementary Information Figure S3) and consequential decline in SOC.

Land use management practices and SOC. The observed decline in SOC however is also likely to be caused, in-part, by changes in land management practices during the sampling interval of 20-23 years. The intensification of agriculture in Bangladesh was not only limited to growing multiple crops in a year but also involved a shift from traditional manure-based cop-rotational agriculture to farming systems that rely largely on the use of chemical fertilizers (Uddin *et al*., 2019). Crop residues in agricultural soils are important biomass inputs and returning crop residues to the soil can help maintain or increase SOC depending on the extent of their input (Dolan *et al*., 2006). Crop residue removal in Bangladesh is common practice for use as fuel and/or livestock fodder e.g., wheat, barley, oat, and rice straw (FAO, 2015; Uddin *et al.,* 2019; Nandi and Nusrat, 2020, Islam *et al*., 2020). Similarly, much of the livestock waste in Bangladesh is used for household cooking as fuel in the form of dried-manure cakes, particularly in rural areas (Nandi and Nusrat, 2020; Shaibur *et al*., 2021), leaving little or no manure for use as soil amendment in agriculture. Such practices of crop residue removal and little or no manure use, when combined with intensive tilling, ultimately results in SOC decline (Anderson-Teixeira *et al*., 2009; Fujisaki *et al*., 2015; Deng *et al*., 2016), as found in this study. The importance of manure use in maintaining SOC has long been established in field trials. For example, a number of 20-years long field trials involving two (rice-wheat) or three (rice-wheat-cowpea/jute) crops provided clear evidence of SOC decline even when the soils received appropriate amounts of chemical fertilisers (N, P and K), whereas in treatments that included both NPK and FYM (farmyard manure) the SOC was either maintained at its initial levels or increased after the 20-year experimental period (Nambiar, 1995; Swarup, 1998; Ladha *et al*., 2003; Majumder et al., 2008; Ladha *et al*., 2009).

The findings of SOC decline over a period of more than 20 years in the agricultural soils of Bangladesh are consistent with many field trials designed to assess the influence of land use intensification on SOC dynamics. These trials, though limited to the field scale, clearly show that loss of SOC is mediated by a combination of factors associated with intensification of agriculture i.e., intensive tilling, removal or burning of crop residues, reduced/seasonal vegetation cover, enhanced mineralisation, weak soil aggregates and soil erosion (Bronson *et al.,* 1998; Balesdent *et* *al*., 2000; Stoate *et al*., 2001; Hamza and Anderson, 2005; Lal *et al.* 2007; Ghimire *et al.,* 2015). Our findings are further supported by the SOC loss estimates in Bangladesh, which between 1967 and 1995 ranged from 3.8 to 30.5 t C/ha, with an average loss of 16.2 t C/ha (Lal, 2006). These estimated losses in SOC were attributed to removal of crop residue, changes in cropping systems and other non-conservation practices. On the other hand, conservation practices, such as reduced- or no-tillage farming are interlinked with crop residue and nutrient management (fertilizers, manure, and green manures), which help sequester SOC in cropping systems (Ladha *et al.,* 2011; Bhattacharyya *et al.,* 2012; Ghimire *et al.,* 2012).

Land types and SOC. In this study a clear SOC depletion has taken place in the high land and medium high land sites, whereas the SOC levels in medium low land (MLL) sites remained unchanged during the two-sampling periods (Table 2), and SOC in low land sites (LL) show clear evidence of SOC accretion (Figure 4). This is not surprising as at these sites (MLL and LL), whilst the crops have changed, the cropping intensity has remained largely in the similar range over the 20–23-year interval (Tables 3 and 4; Supplementary Information, Figure S3). This is due to the sites' low-lying topographic position in the landscape which means they remain inundated for long periods of time (Uddin *et al*., 2019); at the LL sites it is only possible to grow a crop of submerged rice. Here the lower cropping intensity and the associated decreased tillage compared to higher land means relatively slower rates of organic matter mineralisation (Post and Kwon, 2000; Cui *et al*., 2003). Furthermore, slower mineralisation of organic material (including crop residues e.g., root biomass) due to inundation may also be responsible for preventing SOC loss in the MLL and LL sites (Ritchie *et al.* 2007; Chaplot *et al.,* 2010).

In the lower lands (MLL and LL) there are additional contributory factors, which are likely to have mitigated SOC decline. For example, soils receive runoff from higher land i.e., HL and MHL, (potentially including sediment-bound organic matter), possibly contributing some SOC. Similar observations were made by Xie *et al.* (2007) who found higher SOC in lowland paddy soils than in upland soils. Furthermore, as floodwater recedes at the time of rice crop maturity, farmers harvest rice panicles, leaving the stubble to rot in the standing water. These are not removed and subsequently tilled into the land when preparing for the next rice planting. Higher SOC in the lower lands and no SOC decline in the medium lowlands thus may have been contributed by the low tillage and cropping intensity, slower organic matter decomposition, SOC accretion due to runoff from higher land, and the incorporation of rice crop residues, particularly in the low land sites. Incorporation of crop residues in long-term continuous rice cultivation trials is known to promote carbon sequestration (Zhang and He, 2004; Pampolino *et al*., 2008; Minasny *et al*., 2012). This is at least partly due to the slower organic matter decomposition under submerged rice cultivation conditions and the formation of recalcitrant complexes with organic carbon in the soils, which makes SOC less prone to microbial attack, and thus sequestering or maintaining SOC (Sahrawat, 2004; Nath *et al.*, 2018), as found in the MLL and LL sites in this study.

SOC loss, land degradation and food security implications. Soil organic carbon is a key indicator of soil quality/fertility and is the largest store of terrestrial carbon (Jobbagy and Jackson, 2000; Lal 2010) - more than atmospheric and biosphere C storage. However, land degradation due to intensification of agriculture (intensive tilling, poor crop residue management and little or no manure inputs) has resulted in significant losses of SOC, contributing to increased global CO_2 emissions (Lal, 2010; FAO, 2017). While the loss of organic carbon due to land conversion to agriculture and intensification of agriculture is a global phenomenon, it is particularly common in developing countries where declining SOC threatens food security (Lal, 2010; FAO, 2017). For example, in South Asia, agricultural soils have low levels of SOC, often <1%, mainly due to nutrient depletion, intensive tillage, erosion, unbalanced fertilization and removal of crop residues (Lal, 2004). The low level of SOC has been suggested as the main cause of crop productivity stagnation, seen widely in the region and in the wider world with similar land use and management practices (e.g., Duxbury *et al*., 2000; Ladha *et al*., 2003; Manna *et al*., 2007; Singh *et al.,* 2007; Chauhan *et al*., 2012). This is further supported by a review of long-term rice and wheat cultivation studies in South Asia where crop productivity stagnation was observed in 72% (of rice) and 85% (of wheat) studies (Ladha *et al*., 2009), largely due to exploitation of the soil inherent nutrient supply as nutrient removal often exceeds replenishment through fertilizers (Panaullah *et al.,* 2006; Dwivedi *et al.,* 2014).

Food crop productivity stagnation is a serious challenge for Bangladesh with its population of 162 million and an annual growth rate of 1.6% (Unnayan Onneshan, 2014). If the present trend of population growth (two million people per year) continues, Bangladesh will potentially face severe food shortage. From a climate change perspective, this has been formally recognized through the 'soil carbon 4 per mille' initiative, the aim of which is to increase global soil organic stocks by 4 per 1000 (0.4%) per year as compensation for global emissions of greenhouse gases (ADEME, 2015; Minasny *et al*., 2017). The aim of increasing soil organic carbon by 0.4% per year is encouraging for the restoration of soil quality and offsetting global CO_2 emissions. However, it is a challenging aim, given soil organic carbon accretion is a slow process and agricultural soils in the tropics and sub-tropics are inherently low in SOC – in many situations it would mean doubling the SOC in a year. The current situation of declining SOC is not sustainable as existing agricultural land management practices are causing considerable CO_2 emissions and also threaten food security, particularly in developing countries. However, it should be possible to at least maintain or sequester SOC even for two crops per year (200% cropping intensity) systems where crop residues more than the mineralization capacity are returned to the soil, and a third short-term cover crop could be grown, preferably leguminous, for the purpose of green manuring (Lal, 2003). Replacing intensive tillage with conservation tillage (reduced or no tillage) should help conserve and accrue SOC. Equally important is the use of appropriate amounts of chemical fertilizer use so that maximum crop biomass (and hence residues, including root biomass) can be produced. Although a slow process, SOC sequestration should help increase farm productivity.

5. CONCLUSION

This study aimed to investigate long-term change in soil organic carbon (SOC) in the agricultural soils of Bangladesh by comparing the previously measured (1989-92) SOC dataset with that obtained by resampling the same locations in 2012. During this period of 20-23 years (1989-92 and 2012), agriculture in Bangladesh underwent major changes, including increased land use and cropping intensities, a shift from traditional manure and rotation-based one crop farming to multiple cropping systems (2-3 crops per year) with little or no manure inputs or crop residue return.

The levels of SOC during the 20-23 years period have significantly decreased across the two alluvial deposits as well as their sub-sites. However, the overall SOC decline is due to its loss from the higher land sites (high and medium high lands), as among the land types in Bangladesh these lands are most intensively used (multiple crops and hence high intensity tilling; Supplementary Information, Figure S3), mainly due to their limited inundation because of their topographically higher position. In the medium lowland sites, which remain inundated to a greater extent and period, SOC did not show any reduction because of relatively low cropping intensity. SOC in the low land sites (lowest topographical position among the land types considered) during the same period show SOC accretion. This, however, is not surprising as these lowlands remain inundated for a greater part of the year, allowing only one crop of submerged rice where the crop residues are not removed (unlike other land types) and allowed to rot in the field. No reduction or accretion of SOC in the medium lowlands and lowlands sites further confirms the influence of land use and cropping intensity on SOC though reduced rates of biomass decomposition in these low-lying lands (longer periods of anaerobiotic conditions due to inundation) may also have helped maintain or increase SOC. It is possible though that the lower lands (medium lowlands and lowlands) may have had some SOC accretion due to runoff/erosion from the higher lands.

Overall, the levels of SOC in the agricultural soils of Bangladesh, particularly those developed on the Ganges and Brahmaputra alluvial deposits are low and it may be difficult to sustain increasing food production demand to feed an increasing population. Declining SOC, however, is not uncommon in Southeast Asian and other countries where intensification of agriculture and associated changes in land management practices have caused SOC loss. This also has major environmental consequences in terms of general land degradation and increased CO_2 emissions. Whilst farming for multiple crops is inevitable to meet the increasing food production demand, without adopting sustainable agricultural land use and management practices e.g., conservation tillage (or no till farming), maximum crop residue return, crop-rotations instead of monoculture, with short-term cover crops for the purpose of green manuring, it will not be possible to maintain sustainable agriculture for food production and lessen the environmental impact of food production.

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REFERENCES

ADEME, 2015. Organic Carbon in Soils- Meeting Climate Change and Food Security Challenges. French Environment and Energy Management Agency (ADEME), France.

Anda, M., Shamshuddin, J., Fauziah, C. I., and Omar, S.R.S. 2010. Increasing the organic matter content of an Oxisol using rice husk compost: changes in decomposition and its chemistry. *Soil Science Society of America Journal* **74**, 1167–1180.

Anderson-Teixeira, K.J., Davis, S.C., Masters, M.D., and Delucia, E.H. 2009. Changes in soil organic carbon under biofuel crops. *GCB Bioenergy* **1**, 75-96; https://doi.org/10.1111/j.1757-1707.2008.01001.x

Balesdent, J., Chenu, C., and Balabane, M. 2000. Relationship of soil organic matter dynamics to physical protection and tillage. *Soil and Tillage Research* **53**, 215-220.

Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., and Kimetu, J. 2007. Soil organic carbon dynamics, functions and management in West African Agro-ecosystems. *Agricultural Systems* **94**, 13-25.

BBS (Bangladesh Bureau of Statistics), 2017. Ministry of Planning, Govt. of Bangladesh, Dhaka.

Bhattacharyya. P., Roy. K.S., Neogi, S., Adhya, T.K., Rao, K.S., and Manna, M.C. 2012. Effects of rice straw and nitrogen fertilization on greenhouse gas emissions and carbon storage in tropical flooded soil planted with rice. *Soil and Tillage Research* **124**, 119–130.

Brammer, H. 2016. Bangladesh: Landscapes, Soil Fertility and Climate Change. The University Press Limited, Dhaka. 7p.

Bronson, K.F., Cassman, K.G., Wassmann, R., Olk, D.C., Noordwijk, M. V., and Garrity, D.P. 1998. Soil carbon dynamics in different cropping systems in principal eco-regions of Asia. In: Lal, R., Kimble, J. M., Follett, R. F., and Stewart, B. A. (Eds.), *Management of Carbon Sequestration in Soil*. Advances in Soil Science, pp. 35-57. CRC Press, New York.

Blum, W.E.H. 2008. Characterization of soil degradation risk: an overview. In: Toth, G., Montanarella, L., and Rusco, E. (Eds). *Threats to Soil Quality in Europe*. JRC Scientific and Technical Reports EUR 23438 EN. Ispra, Italy. pp. 5-10.

Chambers, A., Lal, R., and Paustian, K., 2016. Soil carbon sequestration potential of US croplands and grasslands: implementing the 4 per thousand initiatives. *Journal of Soil and Water Conservation* **71**, 68A-74A; https://doi.org/10.2489/jswc.71.3.68A

Chaplot, V., Bouahom, B., and Valentin C. 2010. Soil organic carbon stocks in Laos: Spatial variations and controlling factors. *Global Change Biology.* **16**, 1380-1393.

Chauhan, B.S., Mahajan. G., Sardana, V., Timsina, J., and Jat, M.L. 2012. Productivity and sustainability of the rice–wheat cropping system in the Indo-Gangetic Plains of the Indian subcontinent: problems, opportunities, and strategies. *Advances in Agronomy* **117**, 315–369.

Canadell, J.G. 2002. Land use effects on terrestrial carbon sources and sinks. *Science in China* **45**, 1-9.

Carr, P.M. 2017. Guest Editorial: Conservation Tillage for Organic Farming. *Agriculture* **7**, 19; https://doi.org/10.3390/agriculture7030019

Congreves, K.A., Hayes, A., Verhallen, E.A., and Van Eerd, L.L. 2015. Long-term impact of tillage and crop rotation on soil health at four temperate agroecosystems. *Soil and Tillage Research* **152**, 17-28.

Cruz, F.T., Pitman, A.J., and McGregor, J.L. 2010. Probabilistic simulations of the impact of increasing leaf-level atmospheric carbon dioxide on the global land surface. *Climate Dynamics* **34**, 361-379.

Cui, H.S., Zhang, B., Yu, L., Zhu, J.H., and He, Y.F. 2003. Pattern and change of black soil resources in China. *Resources Science* **25**, 64-68.

Davidson, E.A., and Janssen, I.A. 2006. Temperature sensitivity of soil carbon decomposition and feed backs to climate change. *Nature* **41**, 12-15.

Deng, L., Zhu, G., Tang, Z., Shangguan, Z. 2016. Global patterns of the effects of land-use changes on soil carbon stocks. *Global Ecology and Conservation* **5**, 127-138.

Dolan, M.S., Clapp, C.E., Allmaras, R.R., Baker, J.M., and Molina, J.A.E. 2006. Soil organic carbon and nitrogen in a Minnesota soil as related to tillage, residue and nitrogen management. *Soil and Tillage Research* **89**, 221–231.

Duxbury, J.M., Abrol, I.P., Gupta, R.K., and Bronson, K. 2000. Analysis of long-term soil fertility experiments with rice-wheat rotation in South Asia. In: Abrol, I.P., Bronson, K., Duxbury, J.M., Gupta, R.K. (Eds). Long-term Soil Fertility Experiments in Rice-wheat Cropping Systems. RWC Research Series #6. New Delhi, India. p vii-xxii.

Dwivedi, B.S., Singh, V.K., and Dwivedi, V. 2014. Application of phosphate rock, with or without Aspergillus awamori inoculation, to meet P demands of rice-wheat systems in the Indo-Gangetic plains of India. *Australian Journal of Experimental Agriculture* **44**, 1041–1050.

Eswaran, H., Berg, E. V. D., and Reich, P. 1993. Organic Carbon in soils of the World. *Soil Science Society of America Journal* **57**, 192-194

FAO-UNDP. 1988. Land resources appraisal of Bangladesh. Technical Report 2. Agroecological regions of Bangladesh. Food and Agriculture Organization (FAO), Rome. 570 p.

FAO. 2001. Soil carbon sequestration for improved land management. World soil resources report 96. FAO of the UN, Rome. 47p.

FAO. 2015. Status of the World's Soil Resources - Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils. Rome, Italy.

FAO, 2017. Soil organic carbon: the hidden potential. In: Clara, L., Fatma, R., Viridiana, A., and Liesel W. (Eds). Food and Agriculture Organization of the United Nations, Rome, Italy. 90p.

Fujisaki, K., Perrin, A.S., Desjardins, T., Bernoux, M., Balbino, L.C., and Brossard, M. 2015. From forest to cropland and pasture systems: a critical review of soil organic carbon stocks changes in Amazonia. *Global Change Biology* **21**, 2773-2786.

Gal, A., Vyn, T.J., Micheli, E., Kladivko, E.J., and McFee, W.W. 2007. Soil carbon and nitrogen accumulation with long-term no-till versus mouldboard plowing overestimated with tilled zone Sampling depths. *Soil and Tillage Research* **96**, 42-51.

Ghimire, R., Adhikari, K.R., Chen, Z.S., Shah, S.C., and Dahal, K.R. 2012. Soil organic carbon sequestration as affected by tillage, crop residue, and nitrogen application in rice-wheat rotation system. *Paddy Water Environment* **10**, 95–102.

Ghimire, R., Machado, S., and Rhinhart K. 2015. Long-term crop residue and nitrogen management effects on soil profile carbon and nitrogen in wheat-fallow systems. *Agronomy Journal* **107**, 2230–2240.

Grace, J. 2004. Understanding and managing the global carbon cycle. *Journal of Ecology* **92**, 189-202.

Grahmann, K., Dellepiane, V.R., Terra, J.A., and Quincke, J.A. 2020. Long-term observations in contrasting crop-pasture rotations over half a century: statistical analysis of chemical soil properties and implications for soil sampling frequency. *Agriculture, Ecosystems and Environment* **287**, https://doi.org/10.1016/j.agee.2019.106710

Grunzweig, J.M., Sparrow, S.D., and Yakir, D. 2004. Impact of agricultural land use change on carbon storage in boreal Alaska. *Global Change Biology* **10**, 452-472.

Guo, L.B., and Gifford, R.M. 2002. Soil carbon stocks and land use change: A meta-analysis. *Global Change Biology* **8**, 345-360.

Hamza, M.A., and Anderson, W.K. 2005. Soil compaction in cropping systems: a review of the nature, causes and possible solutions. *Soil and Tillage Research* **82**, 121-145.

Hussain, M.S., Elahi, S.F., Eswaran, H., Uddin, M.J., and Islam, S. 2003. Bangladesh: In Quest of Resource Management Domain. GIS laboratory Publication No. 2. Department of Soil, Water and Environment. University of Dhaka, Bangladesh.

Islam, N. 2017. *National Atlas of Bangladesh.* Asiatic Society of Bangladesh, Dhaka. 25p.

Jobbagy, E.G., and Jackson, R.B. 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications* **10**, 423-436.

Kopittke, P.M., Menzies, N.W., Wang, P., McKenna, B.A., Lombi, E. 2019. Soil and the intensification of agriculture for global food security. *Environment International*, **132**, https://doi.org/10.1016/j.envint.2019.105078

Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y., Singh, P., Kundu, A.L., Sakal, R., Ram, N., Regmi, A.P., Gami, S.K., Bhandari, A.L., Amin, R., Yadav, C.R., Bhattarai, E.M., Das, S., Aggarwal, H.P., Gupta, R.K., and Hobbs, P.R. 2003. How extensive are yield declines in long-term rice-wheat experiments in Asia? *Field Crops Research* **81**, 159-180.

Ladha, J.K., Singh, Y., Erenstein, O., and Hardy, B. (eds). 2009. "Integrated Crop and Resource Management in the Rice-Wheat System of South Asia," International Rice Research Institute (IRRI), 395 p. Los Banos, Philippines.

Ladha, J.K., Reddy, C.K., Padre, A.T., and van Kessel, C. 2011. Role of nitrogen fertilization in sustaining organic matter in cultivated soils. *Journal of Environmental Quality* **40**, 1756–1766.

Lal, R. 2003. Soil erosion and the global carbon budget. *Environment International* **29**, 437-450.

Lal, 2004. Soil carbon sequestration to mitigate climate change. *Geoderma* **123**, 1-22.

Lal, R. 2006. Enhancing crop yields in developing countries through restoration of soil organic carbon pool in agricultural lands. *Land Degradation and Development* **17**, 197-206.

Lal, R. 2010. Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. *BioScience* **60**,708-721.

Lal, R. 2016. Beyond COP 21: potential and challenges of the "4 per Thousand" initiative. *Journal of Soil and Water Conservation* **71**, 20A–25A DOI: https://doi.org/10.2489/jswc.71.1.20A

Lal, R., Follett, F., Stewart, B.A., and Kimble, J.M. 2007. Soil carbon sequestration to mitigate climate change and advance food security. *Soil Science* **172**, 943–956.

Lal, R., Kimble, J., Levine, E., and Whitman, C. 1995. World soils and greenhouse effect: An overview. In: Lal, R., Kimble, J., Levine, E. and Stewart, B.A. (eds.), Soils and Global Change. *Advances in Soil Science,* CRC Lewis Publishers.

Lewis, T., Smith, T. E., Hogg, B., Swift, S., Verstraten, L., Bryant, P., Wehr, B.J., Tindale, N., Menzies, N.W., and Dalal, R.C. 2016. Conversion of sub-tropical native vegetation to introduced conifer forest: impacts on below-ground and above-ground carbon pools. *Forest Ecology and Management* **370**, 65-75.

Majumder, B., Mandal, B., Bandyopadhyay, P.K., Gangopadhyay, A., Mani, P.K., Kundu, A.L., and Majumder, D. 2008. Organic amendments influence soil organic carbon pools and crop productivity in 19-year old rice-wheat agroecosystems. *Soil Science Society of America Journal* **72**, 775-785.

Manna M.C., Swarup A., Wanjari R.H., Mishra B., and Shahi D.K. 2007. Long-term fertilization, manure and liming effects on soil organic matter and crop yields, *Soil and Tillage Research* **94**, 397–409.

Minasny, B., McBratney, A.B, Hong, S.Y., Sulaeman, Y., Kim, M.S., Zhang, Y.S., Kim, Y.H., and Han, K.H. 2012. Continuous rice cropping has been sequestering carbon in soils in Java and South Korea for the past 30 years. *Global Biogeochemcal Cycles* **26**, GB3027, https://do.org/10.1029/2012GB004406

Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.S., Cheng, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C.B., Hong, S.Y., Mandal, B., Marchant, B.P., Martin, M., McConkey, B.G., Mulder, V. L., O'Rourke, S., Richer-de-Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I ., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C.C., Vågen, T.G., Wesemael, B.V., and Winowiecki, L. 2017. Soil carbon 4 per mille. *Geoderma* **292**, 59-86.

Mondal, R.I., Begum, F., Aziz, A., and Sharif, S.H. 2015. Crop sequences for increasing cropping intensity and productivity. *SAARC Journal of Agriculture* **13**, 135-147.

Nambiar, K.K.M. 1995. Major cropping systems in India. P. 135-142. In: Barnett, V., Payne, R. and Steiner, R. (eds.), *Agricultural Sustainability: Economic, Environmental and Statistical Considerations.* John Wiley and Sons Ltd, Chichester.

Nandwa, S.M. 2001. Soil organic carbon management for sustainable productivity of cropping and agro-forestry systems in Eastern and Southern Africa. *Nutrient Cycling in Agroecosystems* **61**, 143-158.

Nandi, R., and Nusrat M. 2020. Household biomass fuel consumption pattern in rural areas of Bangladesh. *Journal of Energy Research and Reviews* **4**, 1-9.

Nath, A.J., Brahma, B., Sileshi, G.W., and Das, A.K. 2018. Impact of land use changes on the storage of soil organic carbon in active and recalcitrant pools in a humid tropical region of India. *Science of the Total Environment* **624**, 908–917.

Nelson, D.W., and Sommers, L.W. 1982. Total carbon, organic carbon and organic matter. pp. 539-577. In: Page, A.L., Miller, R.H., Keeney, D.R. (eds.), *Methods of Soil Analysis*. Part 2. Agronomy monograph, 2nd edition, ASA and SSSA. Inc. Madison, Wisconsin, USA.

Ogle, S.M., Breidt, F.J., and Paustian, K. 2005. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. *Biogeochemistry* **72**, 87–121.

Ontl, T. A., and Schulte, L. A. 2012. Soil Carbon Storage. *Nature Education Knowledge* **3**, 35.

Pampolino, M.F., Laureles, E.V., Gines, H.C., and Buresh, R.J. 2008. Soil carbon and nitrogen changes in long-term continuous lowland rice cropping. *Soil Science Society of America Journal* **72**, 798-807.

Panaullah, G.M., Timsina, J., Saleque, M.A., Ishaque, M., Pathan, A.B.M.B.U., Connor, D.J., Saha, P.K., Quayyum, M.A., Humphreys, E., and Meisner, C.A. 2006. Nutrient Uptake and Apparent Balances for Rice-Wheat Sequences. III. Potassium. *Journal of Plant Nutrition* **29**, 173–187.

Post, W.M., and Kwon. K.C. 2000. Soil carbon sequestration and land use change: processes and potential. *Global Change Biology* **6**, 317-327.

Qiu, L., Zhu, J., Wang, K., and Hu, W. 2016. Land use changes induced county-scale carbon consequences in Southeast China 1979-2020, Evidence from Fuyang, Zhejiang Province. *Sustainability* **8**, 38, doi.org/10.3390/su8010038

R Core Team. 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Rahman, M.R. 2005. *Soils of Bangladesh*. Darpan publications, Dhaka Bangladesh.

Rahman, S. 2010. Six decades of agricultural land use changes in Bangladesh: effects on crop diversity, productivity, food availability and the environment, 1958-2006. *Singapore Journal of Tropical Geography* **31**, 254-269.

Ramesh, T., Bolan, N.S., Kirkham, M.B., Wijesekara, H., Kanchikerimath, M., Srinivasa, R.C., Sandeep, S., Rinklebe, J., Ok, Y.S., Choudhury, B.U., Wang, H., Tang, C., Wang, X., Song, Z., and Freeman, O.W. 2019. Soil organic carbon dynamics: Impact of land use changes and management practices: A review. In Sparks, D.L. (Ed.), *Advances in Agronomy* ***156,*** 1-107; https://doi.org/10.1016/bs.agron.2019.02.001

Ritchie, J.C., McCarty, G.W., Venteris, E.R., and Kaspar, T.C. 2007. Soil and soil organic carbon redistribution on the landscape. *Geomorphology* **89**, 163-171.

Sahrawat, K.L. 2004. Organic matter accumulation in submerged soils. *Advances in Agronomy* **81**, 169-201.

Scharlemann, J.P.W., Tanner, E.V.J., Hiederer, R., and Kapos, V. 2014. Global Soil Carbon: Understanding and managing the largest terrestrial carbon pool. *Carbon Management* **5**, 81-91.

Shaibur, M.R., Husain, H., and Arpan, S.H. 2021. Utilization of cowdung residues of biogas plant for sustainable development of a rural community. *Current Research in Environmental Sustainability* **3**; https://doi.org/10.1016/j.crsust.2021.100026

Singh, M., Reddy, K.S., Singh, V.P., and Rupa, T.R. 2007. Phosphorus availability to rice (Oryza sativa L.)–wheat (Triticum aestivum L.) in a vertical soil after eight years of inorganic and organic fertilizer addition. *Bioresource Technology* **98**, 1474–1481.

SPSS, 2012. SPSS base version 20.0 user's guide. SPSS Inc. Chicago, USA. 537p.

SRDI, 1989. *Land and soil resource utilization guide of Fultala Upazila of Khulna district.* Upazila guide series 10. Ministry of Agriculture, Bangladesh. 85p.

SRDI, 1990. *Land and soil resource utilization guide of Delduar Upazila of Tangail district.* Upazila guide series 49. Ministry of Agriculture, Bangladesh. 71p.

SRDI, 1991. *Land and soil resource utilization guide of Melandah Upazila of Jamalpur district*. Upazila guide series 53. Ministry of Agriculture, Bangladesh. 77p.

SRDI, 1992. *Land and soil resource utilization guide of Mirpur Upazila of Kushtia district.* Upazila guide series 8. Ministry of Agriculture, Bangladesh. 95p.

Srinivasarao, C.H., Kundu, S., Lakshmi, C.S., Rani, Y.S., Nataraj, K.C., Gangaiah, B., Laxmi, M.J., Basu, M.V.S., Rani, U., Nagalakshmi, S., and Manasa, R. 2019. Soil Health Issues for Sustainability of South Asian Agriculture. *EC Agriculture* **5.6**, 310-326.

Stoate, C., Boatman, N.D., Borralho, R.J., Carvalho, C.R., de Snoo, G.R., and Eden, P. 2001. Ecological impacts of arable intensification in Europe. *Journal of Environmental Management* **63**, 337-365.

Swarup, A. 1998. Emerging soil fertility management issues for sustainable crop productivity in irrigated systems. In: Swarup, A., Reddy, D., Prasad, R.N. (Ed)., Long term Soil Fertility Management through Integrated Plant Nutrient Supply. pp 54-67. Indian Institute of Soil Science, Bhopal, India.

Uddin, M.J., Hooda, P.S., Mohiuddin, A.S.M., Smith, M. and Waller, M. 2019. Land inundation and cropping intensity influences on organic carbon in the agricultural soils of Bangladesh. *Catena* **178**, 11-19.

Unnayan Onneshan. 2014. Recent trends of growth in agriculture, industry and power. Bangladesh Economic. Update March 2014. Vol. 5, No 3.

Xie, Z., Zhu, J., Liu, G., Cadisch, G., Hasegawa, T., Chen, C., Sun. H., Tang, H., and Zeng, Q. 2007. Soil organic carbon stocks in China and changes from 1980s to 2000s. *Global Change Biology* **13**, 1989-2007.

Wiesmeier, M., Hubner, R., Sporlein, P., Geuß, U., Hangen, E., Reischl, A., Schilling, B., Lutzow, M., and Kogel-Knabner, I. 2014. Carbon sequestration potential of soils in southeast Germany derived from stable soil organic carbon saturation. *Global Change Biology* **20**, 653-665.

Zhang, F., Li, C., Wang, Z., and Wu, H. 2006. Modeling impacts of management alternatives on soil carbon storage of farmland in Northwest China. *Biogeosciences* **3**, 451-466.

Zhang, M., and Z, He. 2004. Long-term changes in organic carbon in Southeast China. *Geoderma* **118**, 167-179.

Zhao, M.S., Zhang, G.L., Wu, Y.J., Li, D.C., and Zhao, Y.G. 2015. Driving forces of soil organic matter change in Jiangu Province of China. *Soil Use and Management* **31**, 440-449.

Supplementary Information

Soil organic carbon dynamics in the agricultural soils of Bangladesh following more than 20 years of land use intensification

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Table S1

Soil organic carbon (SOC, %)* measured in the Brahmaputra alluvium samples collected during 1989-92 and 2012. The 2012 soil samples were collected by revisiting the same sampling locations which were sampled in the previous sampling period (1989-92). The % SOC levels are presented according to the land types: HL (high land), MHL (medium high land), MLL (medium low land) and LL (low land). Note that not all sub-sites have all land type sampling locations. The SOC values are average of 3 replications.

	Brahmaputra Alluvium											
Sub site	**Geo-coordinates**	**1989-92**	**2012**	**Geo-coordinates**	**1989-92**	**2012**	**Geo-coordinates**	**1989-92**	**2012**	**Geo-coordinates**	**1989-92**	**2012**
	LAND TYPES											
	HL			**MHL**			**MLL**			**LL**		
Delduar Upazila	-	No HL data	-	89°56′50″ 24° 13′ 00″	2.70	2.00	89°56′12″ 24°11′ 26″	1.39	1.32	89°54′ 52″ 24° 07′ 55″	1.20	1.50
				89° 55′ 10″ 24° 12′ 38 ″	0.87	0.53	89°57′ 50″ 24° 11′ 23″	1.21	1.28			
				89° 56′ 10″ 24° 11′ 51″	1.20	0.84	90° 00′ 30″ 24° 09′ 43″	1.21	1.25			
				89° 58′ 57″ 24° 09′ 52″	1.33	1.21	89° 57′ 56″ 24° 09′ 05″	2.50	2.60			
				89° 59′ 53″ 24° 07′ 52″	1.62	0.86	89° 58′ 40″ 24° 07′ 51″	2.60	2.50			
				89° 57′ 02″ 24° 07′ 53″	1.68	0.98	89° 57′ 50″ 24° 07′ 06″	2.30	2.25			
				89° 57′ 12″ 24° 06′ 05″	0.87	0.70	89° 53′ 54″ 24° 11′ 35″	0.69	0.86			
				89° 57′ 25″ 24° 05′ 20″	0.58	0.40	89° 55′ 30″ 24° 05′ 10″	0.98	0.92			
				89° 54′ 24″ 24° 11′ 39″	2.30	1.50	89° 55′ 22″ 24° 04′ 40″	0.55	0.60			
				89° 55′ 25″ 24° 10′ 51″	0.75	0.56	89° 56′ 12″ 24° 04′ 00″	0.46	0.56			
				89° 55′ 36″ 24° 09′ 48″	2.26	1.56	89° 53′ 55″ 24° 08′ 35″	2.70	2.60			
				89° 54′ 14″ 24° 09′ 08″	2.43	2.00	-	-	-			
				89° 55′ 40″	0.58	0.50						

				24˚ 08′ 52″								
				89˚ 56′ 24″ 24˚ 09′ 10″	0.52	0.41						
				89˚ 55′ 45″ 24˚ 08′ 21″	2.78	2.20						
				89˚ 54′ 41″ 24˚ 06′ 37″	0.92	0.76						
				89˚ 5453″ 24˚ 0716″	0.55	0.44						
				89˚ 55′ 39″ 24˚ 07′ 44″	2.70	2.10						
				89˚ 52′ 28″ 24˚ 09′ 20″	1.04	0.74						
				89˚ 51′ 45″ 24˚ 08′ 50″	1.56	0.98						
				89˚ 52′ 13″ 24˚ 08′ 09″	0.58	0.50						
				89˚ 57′ 12″ 24˚ 10′ 09″	1.27	0.82						
				90˚ 00′ 18″ 24˚ 09′ 10″	2.60	1.80						
				89˚ 53′ 51″ 24˚ 09′ 47″	2.60	1.60						
Melandah Upazila	89˚ 50′54″ 24˚ 56′07″	0.46	0.40	89˚ 51′42 ″ 24˚ 55′ 49 ″	0.69	0.65	89˚ 53′56″ 24˚ 57′06″	0.87	0.99	89˚49 ′ 50 ″ 24˚ 53′ 11 ″	0.64	0.81
	89˚ 52′16″ 24˚ 55′47″	0.55	0.43	89˚ 53′ 45″ 24˚ 55′10 ″	0.52	0.41	89˚ 52′57″ 24˚ 56′54″	0.75	0.77	89˚ 50′ 18″ 24˚ 52′ 53″	0.64	0.80
	89˚ 53′57″ 24˚ 52′55″	0.69	0.56	89˚ 52′13″ 24˚ 53′30″	0.92	0.65	89˚ 52′56″ 24˚ 56′43″	0.69	0.75	89˚ 48′ 07 ″ 24˚ 57′ 09″	0.92	1.00
	89˚ 52′37″ 24˚ 53′48″	0.92	0.60	89˚ 52′ 24 ″ 24˚ 52′ 21″	0.87	0.74	89˚ 51′14″ 24˚ 57′09″	0.55	0.40	89˚ 47′ 56″ 25˚ 02′ 30 ″	1.16	1.25
	89˚ 51′48″ 24˚54′ 30″	0.58	0.40	89˚ 52′ 35 ″ 24˚ 51′ 55″	1.62	1.02	89˚ 51′10″ 24˚ 56′31″	0.92	0.90			
	89˚49′46 ″ 24˚ 53′28″	0.58	0.50	89˚ 53′ 30″ 24˚ 52′ 08″	1.60	1.16	89˚52′ 25″ 24˚54′ 44″	0.87	0.93			
	89˚ 48′38″ 24˚52′41 ″	0.75	0.55	89˚ 51′ 00″ 24˚ 54′ 37″	0.98	0.84	89˚ 52′35″ 24˚52′30 ″	1.39	1.08			
	89˚ 48′53″	0.85	0.55	89˚ 50′ 21″	0.92	0.79	89˚ 48′15″	1.27	1.35			

	24° 56′00″			24° 54′ 47″			24° 57′19″					
	89° 51′23″ 24° 58′22″	0.55	0.41	89° 49′ 23″ 24° 55′ 10″	1.45	1.05	89°47′ 00″ 24° 57′42″	0.87	1.00			
	89° 50′15″ 24° 58′43″	0.81	0.79	89° 49′ 27″ 24° 53′ 02″	0.87	0.61	89° 44′33″ 24° 59′50″	1.04	0.99			
	89° 49′44″ 24° 58′29″	0.55	0.50	89° 49′ 42″ 24° 56′ 13″	0.87	0.65	89° 43′51″ 24°59′ 08″	0.81	0.86			
	89° 44′51″ 24° 59′39″	0.75	0.55	89° 49′ 08″ 24° 58′ 51″	0.63	0.44	89° 43′44″ 24° 59′32″	0.87	0.90			
	89° 49′32″ 25° 00′39″	0.58	0.50	89° 48′ 12″ 24° 54′ 55″	0.81	0.60	89° 43′30″ 24° 59′10″	0.80	0.90			
	89° 48′40″ 25° 04′10″	0.87	0.80	89° 48′ 51″ 24° 55′ 10″	0.81	0.67	89° 46′21″ 24° 59′17″	1.39	1.30			
	89° 49′06″ 25° 03′13″	0.75	0.43	89° 44′ 17″ 24° 59′ 53″	0.92	0.61	89° 48′14″ 24° 59′53″	0.90	1.12			
				89° 43′ 56″ 24° 59′ 36″	0.81	0.55	89° 48′11″ 25° 02′32″	1.30	1.25			
				89° 46′ 16″ 24° 59′ 45″	1.39	1.00						
				89° 49′ 42″ 24° 59′ 47″	0.52	0.50						
				89° 50′ 25″ 25° 00′ 38″	0.87	0.70						
				89° 50′ 09″ 25° 00′ 58″	0.46	0.40						
				89° 49′ 30″ 25° 01′ 17″	0.69	0.61						
				89° 49′ 23″ 25° 01′ 45″	0.58	0.44						
				89° 48′ 17″ 25° 01′ 08″	0.92	0.66						
				89° 48′ 32″ 25° 02′ 37″	0.98	0.60						
				89° 48′ 16″ 25° 03′ 29″	0.92	0.55						

*SOC values are average of 3 replications, with variation between the replicates ranging from <5% to <10%.

Table S2

Soil organic carbon (SOC, %)* measured in the Ganges alluvium samples collected during 1989-92 and 2012. The 2012 soil samples were collected by revisiting the same sampling locations which were sampled in the previous sampling period (1989-92). The % SOC levels are presented according to the land types: HL, MHL, MLL and LL. Note that not all sub-sites have all land type sampling locations. The SOC values are average of 3 replications.

	Ganges Alluvium											
Sub site	**Geo-coordinates**	**1989-92**	**2012**	**Geo-coordinates**	**1989-92**	**2012**	**Geo-coordinates**	**1989-92**	**2012**	**Geo-coordinates**	**1989-92**	**2012**
	LAND TYPES											
	HL			**MHL**			**MLL**			**LL**		
Fultala Upazila	89˚26′ 08″ 23˚ 01′05″	1.09	0.80	89˚26′38″ 22˚58′12″	1.60	1.10	89˚ 24′ 35″ 22˚ 57′ 15″	2.00	2.30	No data		
	89˚ 27′36″ 22˚ 59′10″	1.40	0.80	89˚26′10″ 22˚ 57′34″	1.85	1.12	89˚ 25′ 10″ 22˚ 55′ 27″	1.27	1.59			
	89˚ 26′46″ 22˚ 58′40″	1.50	1.12	89˚ 25′40″ 22˚ 56′47″	1.90	1.60	89˚ 26′ 08″ 22˚ 56′ 16″	1.70	1.90			
	89˚ 30′55″ 22˚ 55′07″	1.27	1.18	89˚ 27′01″ 22˚ 57′19″	2.03	1.80	89˚ 26′ 57″ 22˚ 56′ 10″	1.85	1.80			
	89˚ 29′53″ 22˚ 55′30″	0.75	0.70	89˚ 28′00″ 22˚ 57′18″	1.90	1.20	89˚ 27′ 36″ 22˚ 55′ 48″	1.68	1.65			
	89˚28′ 55″ 22˚ 56′10″	0.92	0.70	89˚ 28′26″ 22˚ 56′12″	1.85	1.20	89˚ 28′ 07″ 22˚ 55′ 20″	1.50	1.63			
	89˚ 27′12″ 23˚ 00′53″	0.27	0.31	89˚ 29′02″ 22˚ 55′40″	1.68	1.50						
	89˚ 25′27″ 22˚ 57′07″	0.69	0.40	89˚ 30′31″ 22˚ 55′25″	1.45	1.20						
	89˚ 26′15″ 22˚ 58′52″	0.69	0.56	89˚ 29′20″ 2255′56″	1.19	1.00						
				89˚ 27′30″ 22˚ 57′28″	0.58	0.50						
				89˚ 27′09″ 22˚ 58′17″	0.69	0.63						
				89˚ 27′33″ 23˚ 00′37″	0.87	0.63						
				89˚ 27′28″ 22˚ 58′18″	0.55	0.87						

	88˚57′30″ 23˚ 58′ 09″	0.92	0.41	88˚59′ 08″ 23˚58 ′42″	0.92	0.64	88˚58′43″ 23˚56′04″	0.92	1.15	88˚58′30″ 23˚56′28″	0.87	1.04
Mirpur Upazila	88˚58′57″ 23˚56′40″	0.55	0.49	88˚ 58′38″ 23˚58′ 10 ″	0.87	0.75				89˚03′42″ 23˚59′10″	0.55	0.89
	89˚04′48″ 23˚57′10″	0.40	0.40	89˚00′46″ 23˚57′33″	0.87	0.51						
	89˚00′30″ 23˚55′56″	0.50	0.45	88˚58 ′43″ 23˚57′13″	0.75	0.64						
	89˚ 02′21″ 23˚55′22″	0.43	0.38	89˚02′22″ 23˚59′05″	0.23	0.44						
	89˚00′53″ 23˚55′26″	0.52	0.45	89˚02′11″ 23˚58′ 27″	0.27	0.49						
	88˚58′42″ 23˚54′02″	0.52	0.51	89˚01′13″ 23˚57′52″	0.58	0.54						
	88˚56′ 55″ 23˚54′06″	0.27	0.45	89˚02′12″ 23˚57′25″	0.75	0.71						
	88˚54′03″ 23˚53′30″	0.46	0.47	89˚03′21″ 23˚56′53″	0.69	0.56						
	88˚54′36″ 23˚52′ 55″	0.75	0.62	89˚04′10″ 23˚56′24″	0.87	0.64						
	88˚55′40″ 23˚52′ 48″	0.75	0.70	89˚02′53″ 23˚56′ 50″	0.75	0.56						
	88˚55′26″ 23˚51′20″	0.46	0.50	89˚03′15″ 23˚55′25″	0.98	0.64						
	89˚01′ 48″ 23˚53′52″	0.40	0.49	89˚04′26″ 23˚55′ 30″	1.04	0.95						
	88˚59′30″ 23˚52′ 06″	0.40	0.51	89˚04′47″ 23˚54′41″	0.56	0.45						
	89˚01′28″ 23˚52′29″	0.50	0.42	89˚01′55″ 23˚54′ 22″	0.81	0.64						
	89˚00′51″ 23˚52′ 53″	0.23	0.48	88˚59′55″ 23˚55′36″	0.58	0.68						
	88˚53′56″ 23˚ 51′54″	0.20	0.40	89˚00′10″ 23˚54′50″	0.40	0.44						
	88˚52′40″ 23˚50′ 54″	0.30	0.45	88˚57′04″ 23˚54′49″	0.87	0.72						
	88˚53′20″	0.46	0.50	88˚57′54″	0.69	0.51						

	23˚50′00″			23˚54′08″								
	88˚55′32″ 23˚ 49′43″	0.58	0.52	88˚58′22″ 23˚ 53′30″	0.75	0.53						
	88˚58′ 21 ″ 23˚50′50″	0.50	0.56	88˚57′45″ 23˚ 52′25″	1.04	0.86						
	89˚00′ 20″ 23˚ 50′35″	0.75	0.60	88˚55′12″ 23˚53′ 38″	1.27	0.93						
	88˚57′ 27″ 23˚ 50′00″	0.40	0.40	88˚54′21″ 23˚52′15″	0.87	0.63						
	88˚59′58″ 23˚49′ 30″	0.86	0.84	88˚55′50″ 23˚52′ 07 ″	0.92	0.83						
	88˚58′56″ 23˚48′ 50″	0.51	0.50	88˚59′57″ 23˚53′50″	0.40	0.40						
	88˚57′22″ 23˚48′ 51″	0.75	0.60	88˚58′12″ 23˚ 52′50″	0.69	0.54						
	88˚59′41″ 23˚48′ 31″	0.50	0.60	89˚00′ 40″ 23˚ 52′49″	0.75	0.66						
				89˚03′10″ 23˚53′35″	0.75	0.63						
				89˚02′13″ 23˚52′30″	0.92	0.78						
				89˚01′08″ 23˚52′ 05″	0.98	0.85						
				89˚01′52″ 23˚51′ 30″	1.20	0.92						
				88˚55′04″ 23˚50′ 26″	0.46	0.45						
				88˚55′ 53″ 23˚ 48′37″	0.55	0.56						
				89˚00′ 06″ 23˚51′ 56″	1.05	0.97						
				88˚57′ 31″ 23˚50′57″	0.50	0.40						
				88˚58′03″ 23˚49′ 57″	0.89	0.62						

*SOC values are average of 3 replications, with variation between the replicates ranging from <5% to <10%.

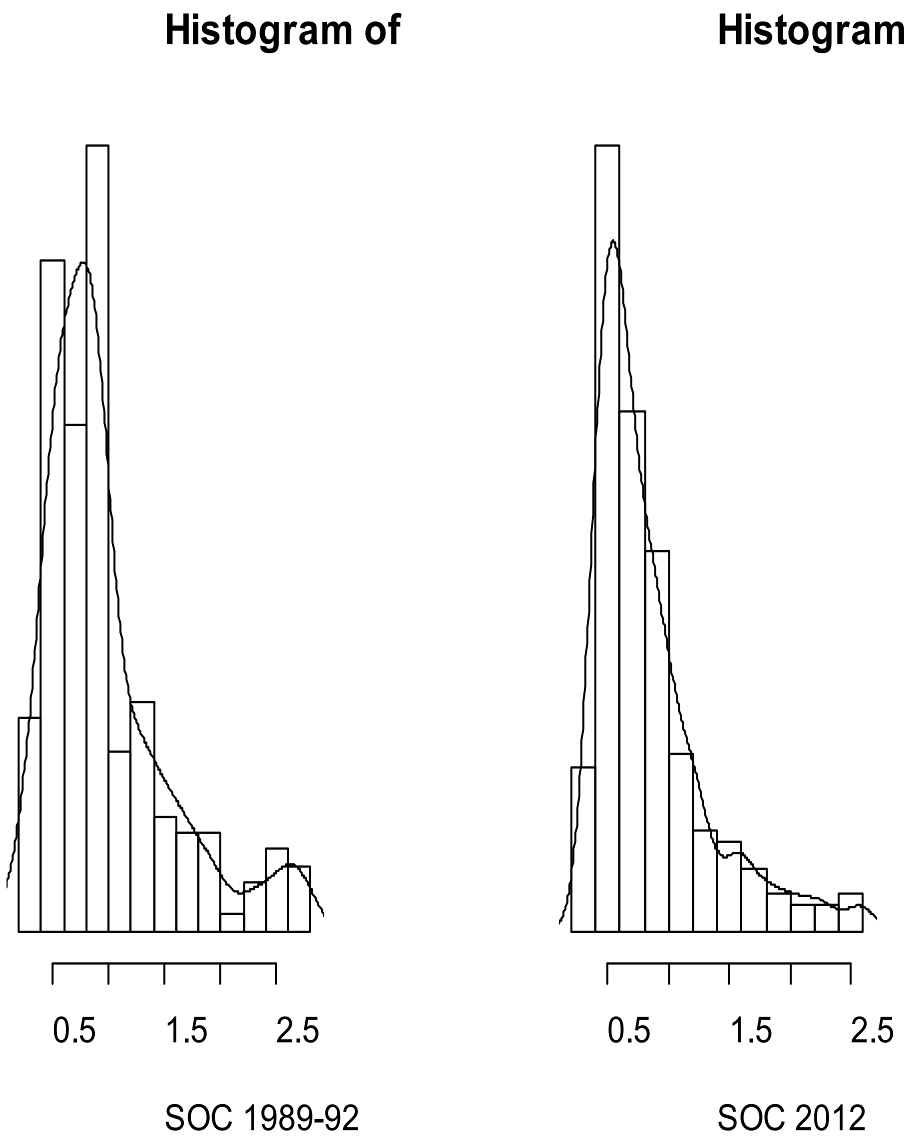


Figure S1: Nature of SOC (%) distribution analysis-based on histograms using combined SOC data from the Brahmaputra and Ganges alluvium samples

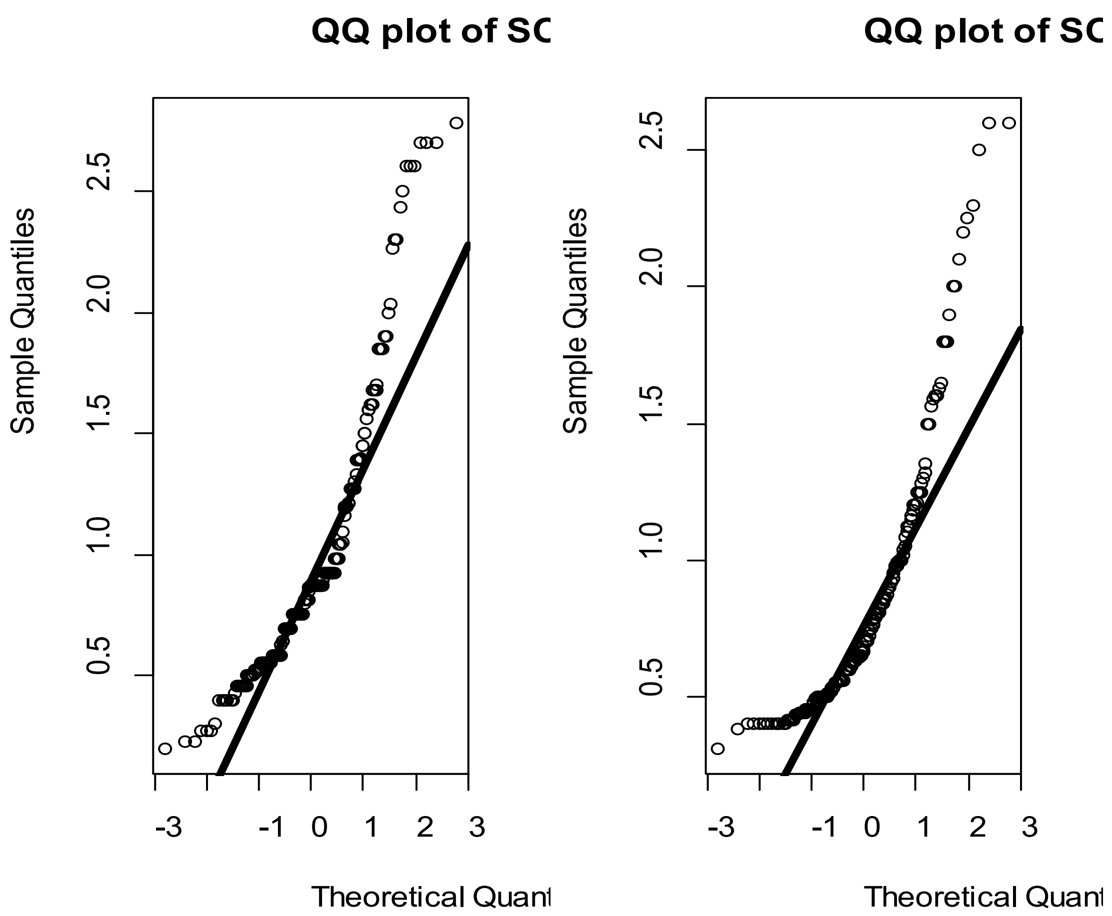


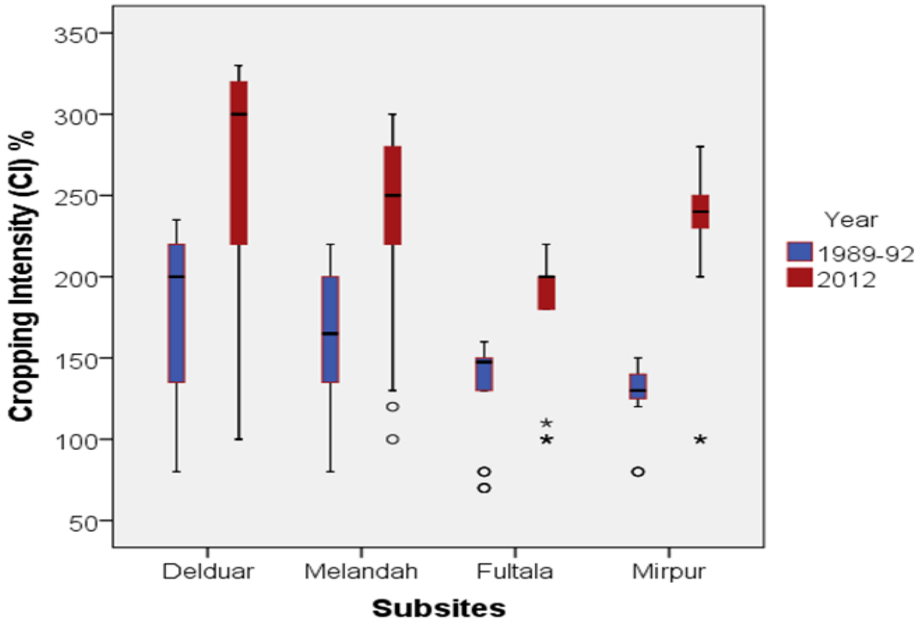
Figure S2: Nature of SOC (%) distribution analysis based on Q-Q plots using combined SOC data from the Brahmaputra and Ganges alluvium samples

Table S3: Nature of SOC (%) distribution analysis by the Shapiro-Wilk test

Shapiro-Wilk normality test

Year	Test statistic (W)	p-value
1989-92	0.8512	<0.001
2012	0.8144	<0.001

Figures S1 and S2 and Table S3 show that SOC data do not follow a normal distribution.



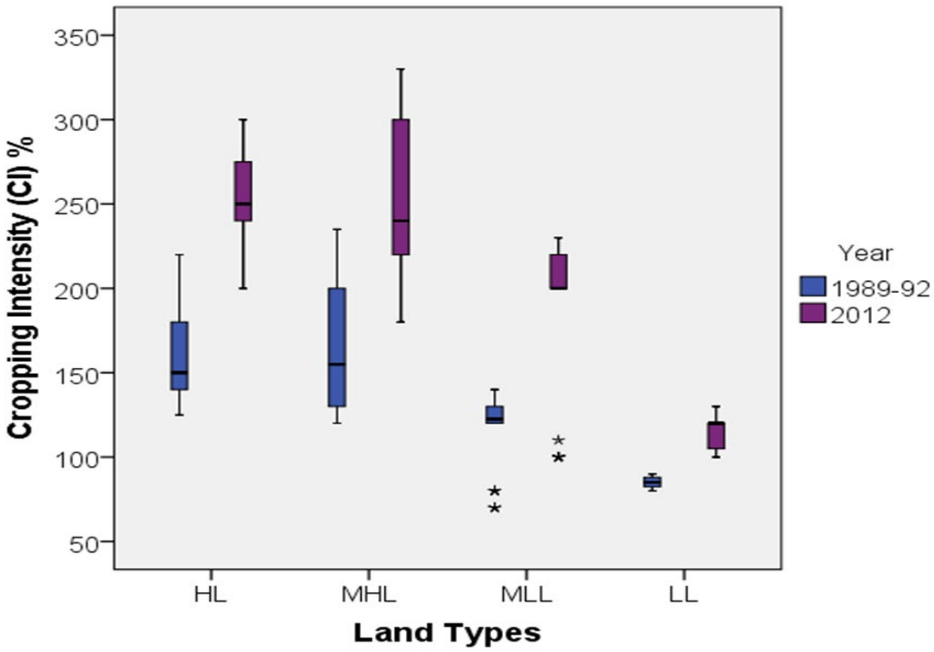


Figure S3: Changes in cropping Intensity, CI (the number of crops grown in a given agricultural year on the same field) in (a) the four sub sites and (b) land types between the two periods 91989-92 and 2012). The nature flooding inundation categorizes land types: high land (HL); medium high land (MHL); medium low land (MLL), and low land (LL).