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Land Inundation and Cropping Intensity Influences on Organic Carbon in the Agricultural Soils of Bangladesh

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ABSTRACT

Land inundation is a common occurrence in Bangladesh, mainly due to the presence of two major river systems – the Brahmaputra and the Ganges. Inundation influences land use and cropping intensity. However, there is little information on the influences of the extent of flooding and cropping intensity has on soil organic carbon (SOC), particularly at the landscape level. To investigate these influences, we collected 268 surface (0-30cm) soil samples from 4 large sites within the two alluviums deposits (the Brahmaputra river and the Ganges river), on a regular grid (1600m). The findings show that SOC levels are generally low, reflecting the intensity of agriculture and land management practices. SOC variability was higher across the medium high land (MHL) and medium low land (MLL) sites than in the high land (HL) and low land (LL) sites. The relatively low SOC levels and variability in the HL sites indicate soils here might have reached to equilibrium levels due to higher land use intensity. Topographically higher lands (HL and MHL), due to less of inundation, had higher cropping intensities and lower SOC's than lower lands (MLL and LL), which had lower cropping intensities, as they remain inundated for longer periods of time. The findings clearly demonstrate the intrinsic influence of land inundation in driving cropping intensity, land management practices and SOC levels.

Key words: Land Inundation, cropping intensity, soil management practices, soil organic carbon

Highlights

- Land inundation determines cropping intensity
- Cropping intensity is higher in less inundated land than lower lands
- SOC is dependent on inundation land types and cropping intensity
- High cropping intensity sites had considerably lower levels of SOC

1. INTRODUCTION

Soils are naturally variable over time and space (Grunwald, 2006); therefore, understanding the distribution of soil properties is important for refining land management practices (Ozcan et al., 2006) and assessing the effects of agriculture on soil quality, e.g. soil organic carbon (SOC). Soil organic carbon has a considerable influence on soil quality, including nutrient supply and plant growth, because of its vital role in soil physical, chemical and biological processes (Gomez et al., 2008; Ladoni et al., 2010). Most SOC studies have largely been limited to field scale measurements using grid sampling and various mapping techniques to assess its temporal and spatial variations (e.g., Hao et al., 2001; Pennock and Frick, 2001; Ritchie and McCarty, 2003). Spatial patterns of SOC are a function of soil redistribution, vegetation productivity, mineralization of SOC, landscape position and land management practices (West and Marland, 2003; Jacinthe et al., 2004). Within a given land management/cover regime, soil water regime, tillage and erosion can influence SOC redistribution/change across the landscape, with both soil and SOC being eroded and re-deposited within the field as well as being moved off the field (Smith et al., 2001; McCarty and Ritchie, 2002; Ritchie and McCarty, 2003). Understanding the influence of such processes on SOC redistribution or levels across agricultural landscapes is critical to comprehend its management/sequestration or to assess its loss. Factors such as topography, land use, management practices, soil texture and vegetation are known to influence the spatial variability of SOC (Tan and Lal, 2005; Liu et al., 2006; Wang et al., 2010; Chuai et al., 2011).

Land use changes have profound influences on the physical, chemical and biological properties of soils (Virto et al. 2015). Long-term experimental studies have confirmed that SOC is highly sensitive to land use changes from native ecosystems, such as forest or grassland, to crop lands, (Conant and Paustian, 2002; Jiao et al. 2010). Soil management practices, particularly those in intensive agriculture have a considerable impact on soil carbon, resulting in its decline due to reduced inputs of crop plant residues and their increased mineralization due to tillage (Ghimire et al. 2017; Hydbom, 2017). Bangladesh due to its increasing population has seen much expansion of agriculture, resulting in major land use changes. Over the years (particularly since the late 1970s), cropping patterns and 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). Here it is worth noting Bangladesh being a low-lying country, where flooding is a common occurrence. As a result, inundation is a key factor in driving cropping intensity, with higher lands being much more intensively cultivated than lower lands due to the latter types remaining inundated for longer time periods. It is thus possible that low land types because of their relatively lower cropping intensity may have higher level of SOC than higher land types.

The main aim of this study was to assess the distribution of SOC across the two major alluvial deposits in Bangladesh at a landscape level, primarily to investigate the influence of land use intensity, which in this low-lying country is dictated by the depth and extent of inundation. The investigation is limited to the top 30 cm of soil, as this is the most important soil layer in regard to soil fertility and crop productivity. The specific objectives therefore were to:

(i) determine the influence of the inundation land types on SOC distribution, and

(ii) assess how SOC might have been affected by cropping intensity.

2. MATERIALS AND METHODS

2.1 Study sites

2.1.1 Geomorphology

This work considered two major alluvial deposits which comprise much of the agricultural land in Bangladesh – the Brahmaputra and the Ganges floodplains (Fig. 1). The study sites are situated in the Bengal basin, the largest fluvio-deltaic sedimentary system on Earth. Sediment accumulates in the basin from the Ganges, Brahmaputra and Meghna (GBM) river systems and is dispersed into the Bay of Bengal, forming the largest submarine fan in the world (Mukherjee et al., 2009), with a combined area of over 60,000 km^2 of riverine channels, floodplains, and delta plains.

The floodplain areas of Bangladesh have a complex sequence of geomorphic surfaces, resulting from the combined effects of frequent shifting of the braided and meandering river channels, erratic and catastrophic floods, continuous bank erosion and deposition of fresh alluvium in and around the active channels. As a result, the sediments vary widely in age, texture and mineralogy (Saheed, 2005). This delta plain is bounded by the Pleistocene terraces to the west, the Barind and Madhupur terrace to the north, the Tippera surface to the east and the Bay of Bengal in the south (Mukherjee et al., 2009). Like many of the large alluvial systems of the world, the GBM plain is formed by the overlapping of a number of sub-deltas and alluvial flood plains (Mukherjee et al., 2009). Moreover, avulsion of the major streams in the area within a time scale of 100 years has resulted in a Holocene sediment succession of about 100 m of overbank silts and clays incised by channel sands (Goodbred and Kuehl, 2000; Allison et al., 2003).

The sedimentology and mineralogy of the Bengal basin largely depend on the types of sediments eroded and transported by the Ganges, the Brahmaputra, and their northern tributaries. Because of the differences in sediment provenance, the Brahmaputra and Ganges systems have quite distinctive mineralogizes (Heroy et al., 2003). Late Quaternary sediments of the Bengal basin contain a history of river switching and climate change as seen from sand- and clay-size mineralogy of boreholes and modern riverbed grabs (Heroy et al., 2003). Due to the flat terrain nature, the rivers (Ganges-Brahmaputra-Meghna) 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 remainder of the 2.5 billion tons of sediment annually move to the offshore areas through the Meghna estuary (Goodbred et al., 2003). These sediments compensate the natural compaction and subsidence of the delta and keep its size relatively stable. Thus, sediment replenishment has taken place to balance subsidence of the delta that consequences a net sea level rise.

2.1.2 Soil resources

Soils at the two Brahmaputra subsites (Delduar and Melandah) belong to Aeric Endoaquepts and Typic Endoaquepts taxonomic soil classes; these soils are non-calcareous floodplain sediments. The texture of these soils varies largely from loam to clay loam or clay, though some sandy loam and sandy soils are also found close to the river. In contrast, the Mirpur subsite on the Ganges alluvial deposits hosts mainly Aeric Endoaquepts, Typic Endoaquepts, Aeric Endoaquents, Typic Endoaquerts and Vertic Endoaquepts soil types. The texture of these soils varies from loam to clay loam or clay. However, some sandy and sandy loam texture soils are also found near the immediate vicinity of the Ganges. All these soils (Mirpur subsite) are calcareous floodplain sediments. The Fultala subsite (the Ganges alluvial deposits) includes Aeric Endoaquepts, Typic Endoaquepts and Typic Halaquept soil types where peat basin portion comprises of Typic Haplofibrists and Typic Haplohemists. Here the soils are calcareous floodplain sediments and tidal floodplain sediments with peat basin. The texture of these soils varies from silt loam to silty clay loam or silty clay. Based on topography or physiography, soils developed from the Ganges-Brahmaputra alluvial deposits are classed as Fluvisols (Spaargaren, 2001). About 80% of soils in Bangladesh are of fluvisols or fluviatile nature.

2.1.3 Land diversity and cropping systems

Floodplain landscapes are never entirely flat (Brammer, 2016). Typically, they comprise slightly higher parts (ridges) separated by depressions (basins), resulting in differences in soils, flooding depths, land use and cropping intensity. Different parts of the topographical relief are often affected in different ways or to differing degrees by floods of different heights or coming at different times of the year. The distance between ridge tops and adjoining depression centres is generally between 0.5 and 2 km. Local villages are generally on ridge tops, however, village boundaries include both ridges and depression land. Therefore, even a small village's land can include many land types as classified by FAO-UNDP (1988). These are the core land types as regards to physical, biological and environmental conditions as well as land use and agricultural potential of Bangladesh. Later, these units were named as the agroecological subunits of Bangladesh. These subunits are the baseline land characteristics used for land development domain or agricultural resources management domain.

The Ganges and the Brahmaputra rivers are relatively dynamic and thus the spatial pattern of these land categories changes through time. These land units change within themselves e.g. due to siltation some land types change from VLL (very low land) to LL (low land) or LL to MLL (medium low land) though the physical, biological and environmental characteristics remain largely unchanged. These diversified land types encourage farmers to grow different crops during a season or year. Thus, the cultivator has the opportunity to grow a range of different crops adapted to different soil types and flooding conditions. Thus, cropping/management techniques differ for different locations within the land types. Land levels in relation to flooding are particularly important in determining farmers' cropping choices and practices. In Highland (HL) *broadcast aus* paddy or jute, is followed by a dry land *rabi crop* (especially pulses, oilseeds, wheat); a third crop could include vegetables or spices. With irrigation, rainfed *aus* paddy or jute is followed by irrigated *rabi crops* (especially wheat, potato, and vegetables). In medium highland (MHL) transplanted *aman* paddy, or *aus* (broadcast or transplanted) is followed by *transplanted aman* rice. Some soils are suitable for cultivating *transplanted aman* rice. Soils flooded less than 30 cm deep are often used for high yielding varieties (HYVs) of *aman* rice. Dry land *rabi crops* are grown in areas with no irrigation water availability. In medium lowland (MLL) mixed *aus* and deep water *aman* paddy, followed by dry land *rabi* crops are commonly grown. Jute is substituted for *aus* and *aman*. HYV *boro* paddies are grown extensively; sometimes wheat, potatoes, and other vegetables are grown. In some areas, boro paddy is preceded by mustard early in the dry season and/or followed by transplanted deep water *aman*. In lowland (LL) deep water *aman* is followed by dry land *rabi* crops (pulses) grown early in the dry season. With irrigation, *boro* HYV paddy are grown; usually land is kept fallow in the *kharif* season. In very lowland (VLL) usually traditional, early-maturing varieties of HYV boro paddy are grown, often with or without irrigation before the onset of monsoon. The expansion of high yielding rice cultivars has been increasing at a considerable rate with the increasing availability of modern inputs (seeds, fertilisers and pesticides). Expansion of areas under high yielding cultivars with irrigation facilities is largely responsible for the agricultural expansion in Bangladesh (Rahman, 2010). Thus, over the years, cropping patterns and 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, including soil organic carbon.

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 (LSRUG) of the Soil Resource Development Institute (SRDI, Bangladesh). Cropping intensity is the ratio of the area under crops for each season during the year to the cultivable area operated by the farmer. Cropping intensity (%) thus can be expressed as: (Gross cropped area) / Net sown area) x 100. In Bangladesh, land is categorized into five inundation land types – high land (HL), medium high land (MHL), medium low land (MLL), low land (LL), and very lowland, VLL (Table 1) (FAO-UNDP, 1988). These land types are also known as resource management domains (RMDs), with each RMD being regarded as a uniform biophysical unit in the landscape (Hussain et al. 2003). Table 2 summarizes the geographic location, areas of the study sites, soil types, sample number and cropping intensity. The four sites were chosen as they are representative of the changes in land use intensity and due to the occurrence of typical inundation land types in Bangladesh. Together the sites exemplify a diverse agroecological region in the country.

Bangladesh, in general, enjoys a sub-tropical monsoon climate. The variation in the mean annual temperature throughout the country is small (25.2-25.7°C), but the seasonal variation is important for crop selection/suitability and production. The most important feature of climate is that there are highly distinct cool and dry, hot and dry and hot and wet seasonal variations that occur in a year. The mean annual rainfall in Bangladesh ranges from 1458 mm to 2275 mm. It is interesting to note that although nearly half of the country lies within the tropics, Bangladesh appears to lack isohyperthermic soil temperature regimes and typical tropical soils. Around 80% of soils in Bangladesh are alluvial soils, which are commonly flooded during the monsoon season. Here because of the prevailing favourable temperatures and soil moisture conditions two or three rice or other crops are grown in a year.

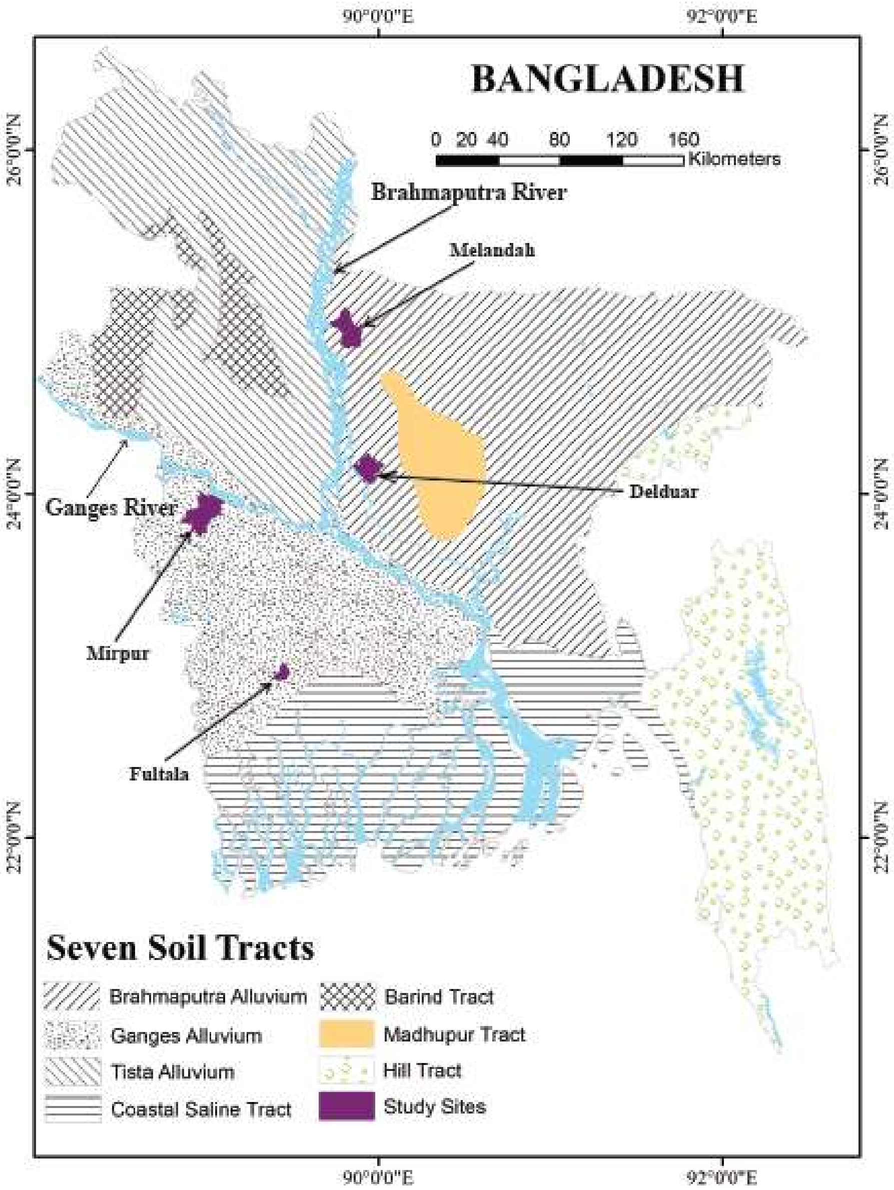

Figure 1. Location map indicating the study area and sampling sites (Delduar, Melandah, Mirpur and Fultala). Adapted from Hussain et al. (2003).

Table 1. Classification of land types in Bangladesh based on inundation

Land Types	
Highland (HL)	Land, which is above the normal flooding level
Medium highland (MHL)	Land, which is flooded up to about 90 cm deep during the flooding season
Medium lowland (MLL)	Land which is flooded, between 90 cm and 180 cm deep during flooding season
Lowland (LL)	Land which is normally flooded up to between 180 cm and 300 cm deep during the flooding season.
Very lowland (VLL)	Land which is normally flooded deeper than 300 cm during the flooding season

Table 2. Geographic location, total area, sampled area, soil types, cropping intensity (CI) and number of soil samples (n) across the four study sites

Study sites	Sub sites	Geographic Locations	Total area (ha)	Sampled area (ha)	**Soil types	Cropping Intensity (CI)* (%)	n
Brahmaputra Alluvium	Delduar	23˚ 14' to 24˚ 03' N latitude; 89˚ 50' to 90˚ 02' E longitude	18,097	14,399	Inceptisols and Entisols	250-270	66
	Melandah	24˚ 51' to 25˚ 04' N latitude; 89˚ 43' to 89˚ 54' E longitude	23,992	20,861	Inceptisols and Entisols	240-250	80
Ganges Alluvium	Fultala	22˚ 54' to 23˚ 01' N latitude; 89˚ 23' to 89˚ 31' E longitude	7,438	5,143	Inceptisols, Entisols and Histosols	160-180	26
	Mirpur	23˚ 47' to 24˚ 01' N latitude; 88˚ 51' to 89˚ 07' E longitude	30,454	26,683	Inceptisols and Entisols	220-240	96

Source: SRDI (1985)
*CI variation within and across the sites is largely due to inundation land types
** Raman (2005)

2.2. Soil sampling and analysis

Soil samples were collected on a regular grid from the four upazilas (in Bangladesh uplazila is a sub-district): Delduar, Melandah, Fultala and Mirpur (Table 2), using one-minute latitude and longitude intervals (representing a distance of 1600m between grid points) following a random grid sampling strategy. A portable GPS (Magellan, Model 320) was used to identify the sampling location in the field. Grid soil sampling can become resource-intensive when the grid size is small, relative to the size of study area. A larger grid size however may not entirely capture the spatial structure and variability, with potential uncertainty in the data. Whilst a smaller size grid would have better captured the spatial variability, resource and time constraints prevented the use of a more intensive sampling strategy, as traditional methods of SOC determination are time-consuming (Reeves et al., 2002). However, remote sensing-based approaches for the spectral (visible and near-infrared spectroscopy) determination of SOC have the potential for providing its estimation over large areas with sufficient detail (Gomez et al., 2008; Stevens et al., 2010; Wolfgang and Jarmer, 2011), though such techniques are limited only to bare top soil surfaces. We believe the grid size of 1600 m used in this study is appropriate for the purpose of capturing SOC variability at a broader/landscape scale.

The sampling sites exclude settlements, industry, woodlands, water-bodies and infrastructures, as the focus of this work was on land that is used for farming purposes. This sampling strategy ensured that all four land types (HL, MHL, MLL and LL) received fair representation, proportionate to their area within the sampling sites/landscapes. Soil samples were collected in March-April 2012 from the top 30 cm (0-30 cm) depth using an auger. In mineral soils SOC is mainly concentrated in the upper 30 cm soil layer, and this is the layer which is important for both soil quality/productivity and erosion considerations. Also, most changes in SOC, soil nutrient supply or soil physical attributes (e.g. aggregate stability, compaction) arising from land management and crop intensity are largely limited to the top soil. Limiting soil sampling to the top 30 cm layer is therefore consistent with our focus on SOC variability mediated by agricultural land use intensity.

In total, 268 samples were collected in polythene bags, which were subsequently sealed to prevent moisture loss. Prior to analysis, the samples were spread on polythene sheets and, after the larger aggregates and lumps had been disaggregated, allowed to air dry under shade. The soil samples were then gently ground using a pestle and mortar and sieved through a 2 mm sieve and mixed thoroughly. The samples were then preserved in plastic bags for laboratory analysis. Organic carbon analysis is based on <2 mm soil fraction and was determined using the Walkley and Black wet oxidation method, as described by Nelson and Sommers (1982).

The distribution of SOC across the alluvium deposits and land types was assessed by boxplots analysis. The relationships between SOC and cropping intensity (CI), and SOC and land type variability were tested by using one-way analysis of variance (ANOVA). SOC variability across the land types was also tested by Tukey's post-hoc multiple comparison tests. Prior to data analysis, SOC distribution was assessed using Q-Q plots, which followed a normal distribution.

3. RESULTS

3.1 SOC distribution over the alluvial deposits

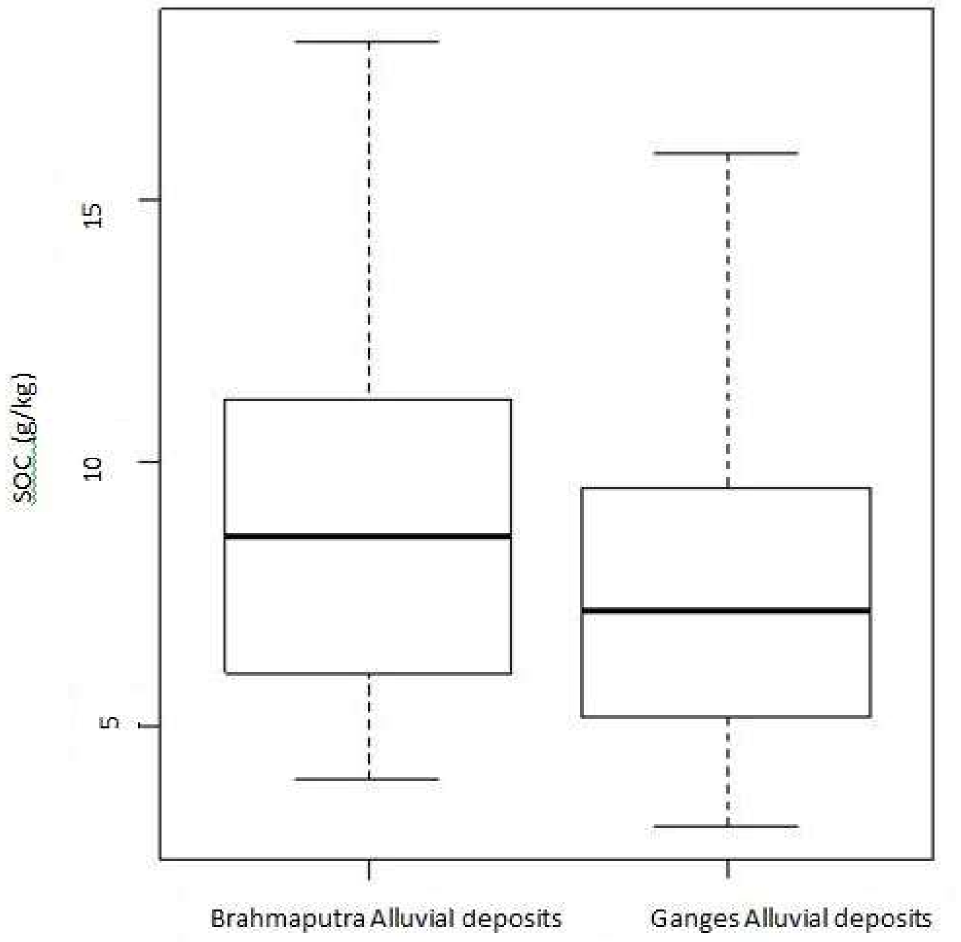

Figure 2. Boxplots showing comparison of SOC distribution across the alluvial deposits of the study sites, based on data pooled together from individual sites within each alluvium. Where the box represents roughly the middle 50% (interquartile range) of the data, and lines (whiskers) indicate the general extent of the data. The horizontal line inside the box represents the median.

Figure 2 shows the median SOC concentration in the Brahmaputra alluvial soils is higher than in the Ganges alluvial soils, and so is its interquartile range. SOC values in both the alluvial deposits are skewed to the right, i.e. a greater spread of SOC data above the medians. More importantly, while SOC is highly variable in both alluvial deposits, its median and range in the Brahmaputra alluvial are greater than the Ganges alluvial soils. These SOC variability differences might be due to the differences in land management activities and/or cropping intensity over the two alluvial deposits or due to their inherent dissimilarities.

SOC distribution across the land types was interpreted using box plots. SOC distribution ranged from approximately 2.5 to 19 g/kg across the land types when the data for each land type from the two alluvial deposits were combined together (Fig. 3). The SOC distribution within each land type is approximately symmetrical. However, a considerable variability in the median SOC values across the land types is clearly evident. The SOC variability is higher across the MHL and MLL types compared to its variability in the HL and LL sites (Fig. 3). It appears that inundation land type is an influential factor here, as median SOC across the inundation land types follows the following decreasing order: LL>MLL>MHL>HL (Fig. 3, Table 3). This is perhaps reflective of the differences in land use intensity. The land use intensity is lowest in the LL sites due to their greater extent and duration of inundation whereas the HL sites are most intensively cultivated, being above the normal flooding levels in Bangladesh.

3.2 Cropping Intensity and SOC

Cropping intensity, CI (%) across the land types varied from approximately 240 to 330% in the HL sites, approximately 200 to 240% in the MHL sites, approximately 120 to 200 % in the MLL sites and approximately 80 to 90 % in the LL sites (Fig. 4). Higher cropping intensities in the HL and MHL sites compared to the MLL and LL sites (Fig. 4), is mainly due to the length of inundation the latter land types flood for longer time periods. A one-way ANOVA test of SOC and CI shows that CI has a significant influence on SOC ($p<0.001$, $F = 43.95$).

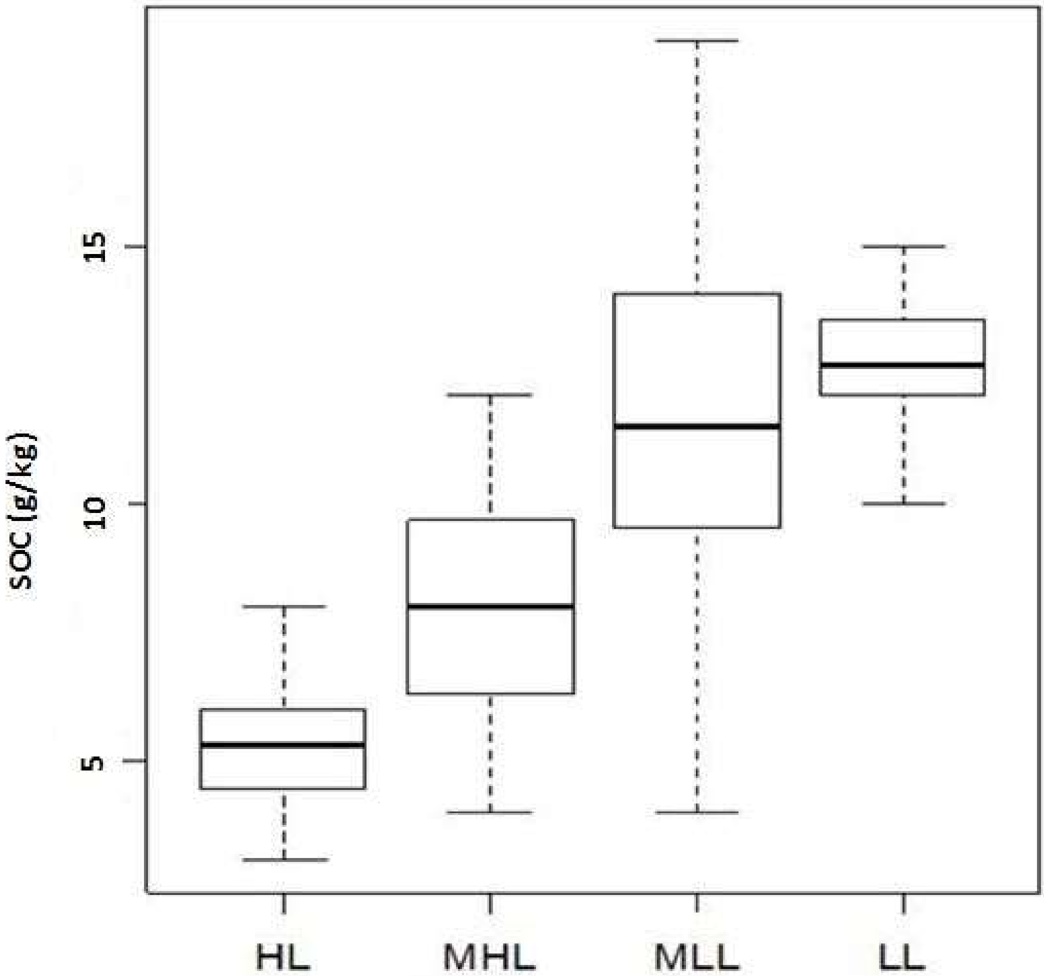

Figure 3. Boxplots showing SOC distribution across the land types of the alluvial deposits - HL (Highland), MHL (Medium Highland), MLL (Medium Lowland), LL (Lowland), based on data pooled over the two alluvial deposits. The land type classification is based on inundation (Table 1)

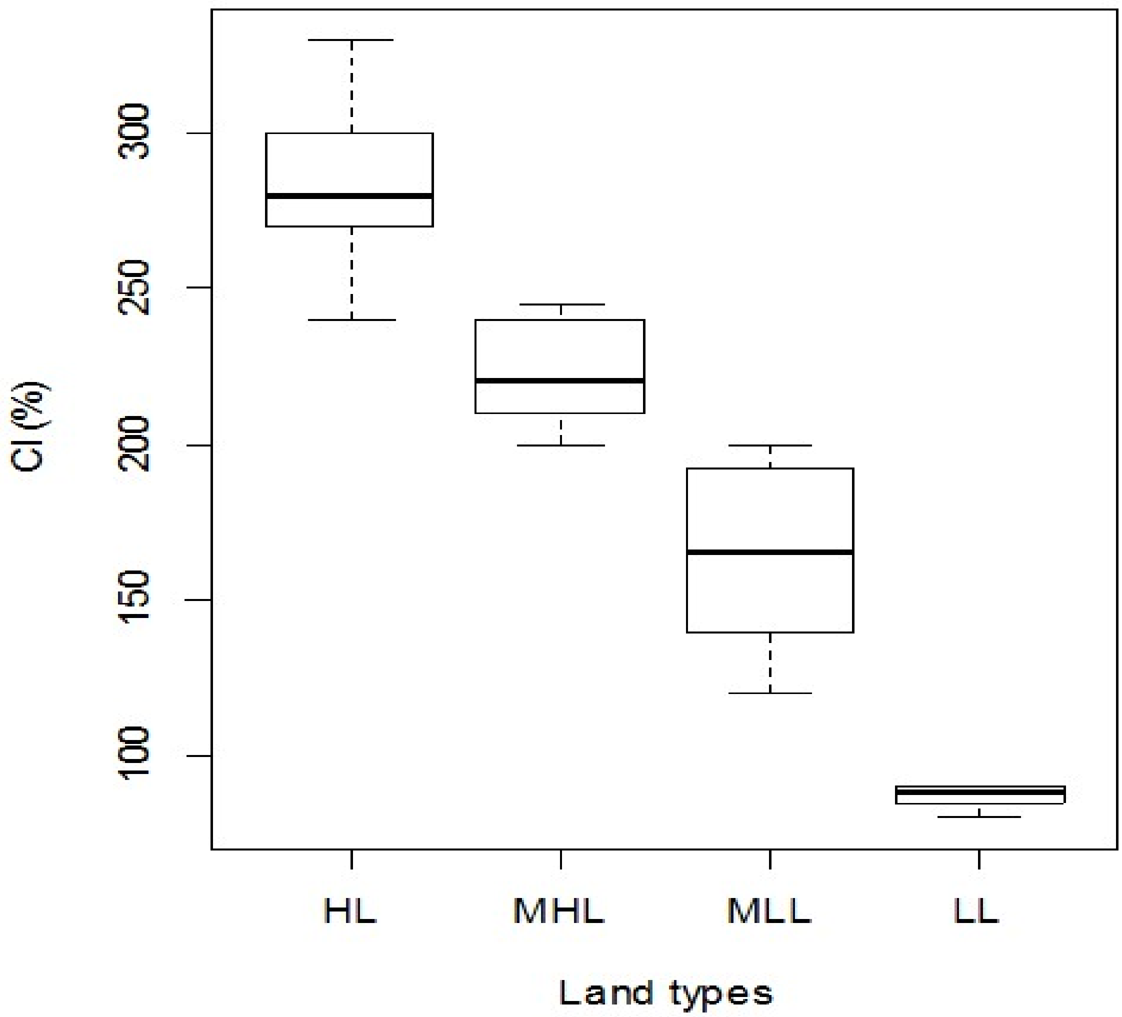

Figure 4. Boxplots showing variability pattern of cropping intensity (CI) across the land types (as in Figure 3) of the alluvial deposits. Cropping intensity is determined by inundation, with HL Highland) sites being above the normal flooding level while LL (Lowland) remain inundated up to 300cm during flooding season (Table 1).

Descriptive statistics of the SOC distribution (Table 3) show that SOC in the HL sites ranged from 3.1 to 11.8 g/kg with an average value of 5.6 g/kg while in the MHL sites it ranged from 4.0 g/kg to 22.0 g/kg with an average of 8.4 g/kg. SOC in the MLL sites averaged to 12.6 g/kg (ranged from 4.0 to 26.0 g/kg), with SOC averaging to a similar level of 13.0 g/kg in the LL sites (ranging from

10.0 to 16.0 g/kg). Clearly, as seen before the mean SOC is higher in the LL and MLL sites than the HL and MHL sites ($p<0.01$). The mean SOC in the LL and MLL sites is similar but is more variable in the MLL than LL sites (Table 3). This may be due to a more variable cropping intensity in the MLL sites than the LL sites (Fig. 4).

Table 3. Soil organic carbon (g/kg) distribution across the land types* of the alluvial deposits

	HL	MHL	MLL	LL
n	61	146	51	10
Mean	5.6	8.4	12.6	13.0
Minimum	3.1	4.0	4.0	10.0
Maximum	11.8	22.0	26.0	16.0
SD	1.5	3.4	4.9	1.6
CV (%)	26.8	40.4	38.8	12.3

SD – standard deviation; CV – coefficient of variation; n – number of samples
*Land types (HL, MHL, MLL and LL) as in Table 1.

3.3. 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 differs significantly ($p<0.001$, $F = 43.95$) for the study sites. Further Tukey's post hoc tests show that SOC differences between the HL and MHL (least significant difference, LSD = 1.03 g/kg), HL and MLL (LSD = 1.28 g/kg), HL and LL (LSD = 2.3 g/kg), MHL and MLL (LSD = 1.10 g/kg), and MHL and LL (LSD = 2.21 g/kg) types were statistically significant ($p < 0.05$). However, the SOC in the MLL and LL sites was similar (LSD = 2.34 g/kg, see Table 3 for SOC mean comparison). Tukey’s post-hoc 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 5.6 g/kg. In the MHL sites, CI varied from 200-240% and the mean SOC content is 8.4 g/kg. In the MLL sites, CI varied from 120-200% and the average SOC content is 12.6 g/kg. In the LL sites, CI varied from 80-90% whereas the average SOC content is 13.0 g/kg. Clearly there is an intrinsic link between inundation land type and CI, as SOC declines with increasing CI (Fig. 5). 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).

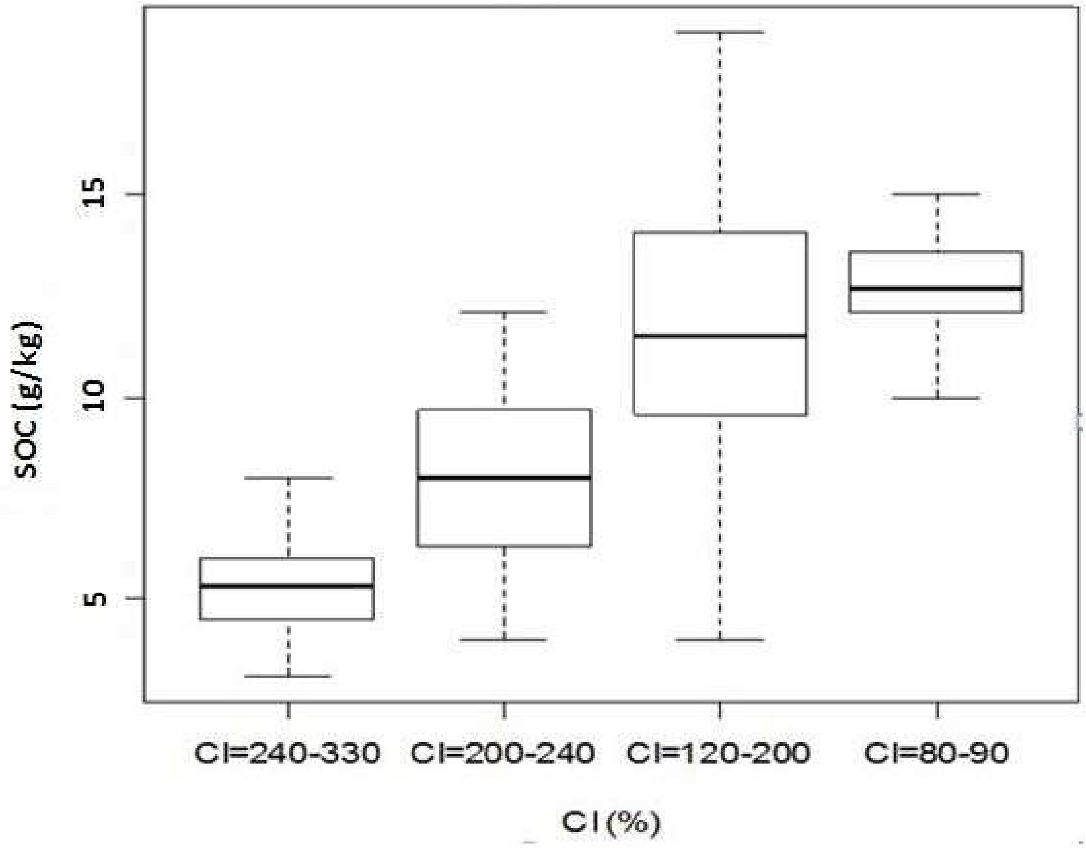

Figure 5. Boxplots showing SOC and cropping intensity (CI) variability pattern across the land types of the study sites

4. DISCUSSION

Land surface height with respect to flooding height or land type variability with respect to annual flooding level (see Table 1) is one of the major factors influencing the distribution pattern of SOC, as found in this work. It seems this influence of land type on SOC is mediated by the relationship between inundation land type and cropping intensity. SOC level is low in both of the alluvial deposits for soil quality and productivity purposes (Patrick et. al., 2013), particularly when compared to SOC threshold values for tropical agroecosystems. Soil organic carbon threshold for sustaining soil quality is widely suggested to be about 2% (20 g/kg) below which deterioration in soil quality occurs (Patrick et al., 2013). Krull et al. (2004) discussed some of the minimum and maximum thresholds of SOC, above or below which the effects of SOC on soil functions are noticeable. However, Sparling and Schipper (2002) argued that other than defining such maximum values, it is reasonable if minimum SOC levels (e.g. 2% i.e. 20 g/kg) are established to inform the farming community on levels below which there would be a loss of important soil characteristics. SOC at 2% is considered optimum for soil aggregate stability maintenance while above this level no further increase in productivity or aggregate stability is expected (Chaplot and Cooper, 2015). The quantitative basis for such a threshold, however, is limited (Loveland and Webb, 2003), with Janssen and de Willigen (2006) reporting 0.6% SOC as the minimum level to prevent soil structure collapse. Karim and Iqbal (2001) also note that good soil structure and fertility can be maintained when SOC is >2% but most soils in Bangladesh have <1% SOC and levels below 0.60% are not uncommon, as seen in this study.

In Bangladesh HL and MHL are the most intensively used lands in agriculture, often with the application of adequate quantities of chemical fertilizers, but invariably without any farmyard manures or other organic amendments. The HL and MHL sites on the two alluvial deposits investigated here are subject to intensive tillage and cropping. Their topographic position makes them more suitable for intensive agriculture due to their relatively lower inundation levels than the other land types (MLL and LL). The higher SOC levels in the MLL and LL compared to the HL and MHL sites may be attributed due to their topographic position as well as lower cropping intensity (Ritchie et al. 2007; FRG, 2012), largely due to these lands remaining inundated to much greater depths and for longer periods of time. Furthermore, slower SOC/plant residue mineralization in the MLL and LL sites due to inundation may also be responsible for their relatively higher SOC levels (Ritchie et al. 2007; Chaplot et al. 2010).

Topographic land type affects soil properties mainly through its effects on water movement. In terrain depressions, or as at the MLL and LL sites, because soils receive runoff (potentially including sediment-bound organic matter) and seepage from the surrounding land, SOC concentrations are higher than on relatively drier upland soil (Yoo et al. 2006), whilst soils on steep slopes tend to lose organic carbon because of erosion. These findings are consistent with Xie et al. (2007) who found higher SOC in paddy soils (i.e. similar to the MLL and LL in this study) than in upland soils (i.e. similar to the HL and MHL sites in this study). Ritchie et al. (2007) also noted that upland sites have significantly lower SOC than soils in depositional areas. This is not surprising as soil erosion from higher elevations is known to influence SOC dynamics through a combination of processes, including disruption of aggregates, preferential removal of C in runoff, mineralization and redistribution of mobilised SOC over the landscape, and deep burial of C-enriched sediments in depositional sites (Lal, 2003; Quinton et al., 2010). However, this is not as straightforward as it seems, because recent work suggests that erosion can increase both the loss and sequestration of SOC. The disruption of soil aggregates during erosion may lead to SOC loss due to increase in the rate of its mineralization (Quinton et al., 2010). Erosion could also result in SOC sequestration (Harden et al., 1999), because erosion results in the mixing of carbon-poor subsoil into the plough layer, and newly exposed mineral surfaces can bind SOC, increasing its inventory (Harden et al., 1999; Quinton et al., 2010). The promotion of carbon sequestration by erosion however is largely dependent on reduced rates of SOC mineralization following the burial of C-rich sediment in depositional environments (Quinton et al., 2010). Also, SOC mineralization in depositional areas often can be mitigated because of greater net primary production than in the source areas. This however is not likely to be a contributory factor in this study where the MLL and LL sites have relatively higher SOC than the HL and MHL (Fig. 3) because of lower cropping intensity at the former sites (Fig. 4). It is noteworthy here that the only net primary productivity in these land types is crop root biomass, as the above-ground biomass is harvested and little to no crop residue is left, apart from plant root biomass. It would therefore seem that reduced rate of SOC decomposition at the MLL and LL sites (due to the extent and longer period of their inundation) and erosion from the higher land types (HL and MHL) may have supressed SOC loss at these sites.

The results also show SOC being intimately related to cropping intensity. SOC is lower at the higher cropping intensity sites (i.e. the HL and MHL) than the lower cropping intensity sites (i.e. MLL and LL) because the HL sites do not normally get inundated and inundation of the MHL is limited, it is not uncommon to grow up to 4 crops a year on these sites. This means the net primary productivity is greater on these higher land types (HL and MHL) than the lower land types (MLL and LL) where because of lower cropping intensities (Figure 4) crop residue (largely limited to root biomass) inputs are limited to up to one (LL) or two crops a year. It would appear that intensive cropping promotes SOC decline, mainly due to increased tillage and reduced crop residue inputs (Song et al. 2005). In Bangladesh, the demand for growing food due to high population pressure has forced the production of 2 to 4 crops every year on the same land (e.g. HL and MHL) resulting in a very short fallow period between crops. This short period is not enough for the land to regain its natural attributes. This together with little or no manure or crop residue input have had a negative impact on the biophysical condition of the land specifically in the HL and MHL types, resulting in SOC decline (Song et al. 2005). The influence of cropping intensity on SOC is hardly surprising, although in our work CI is driven by inundation land types. Similar findings of topographic and land use influences on SOC have been observed by other workers (Jian-bing et al. 2008; Nelson et al. 2008; Wang et al. 2008). This is further supported by the observation of intensive crop cultivation accelerating SOC decline (Liu et al. 2006; Patil et al. 2011). The lower SOC in our high cropping intensity sites than lower CI sites may also be due to erosion from the higher (HL and MHL) to the lower lands (MLL and LL), as found by Wang et al. (2008). The higher SOC in the lower land sites (MLL and LL) is most likely related to their lower cropping intensity, lower decomposition rate of SOC due to the associated less-intensive tillage and high soil moisture conditions (Taggart et al. 2012), as they remain inundated to a greater extent over longer time periods.

Intensive agricultural activity (e.g. tillage) is known to enhance soil mineralization (Lal, 2002) with consequential decline in SOC, particularly in farming systems with little or no crop residue or manure inputs, as in the HL and MHL sites of this study. In such farming systems SOC declines until an equilibrium level is reached. The magnitude of this equilibrium shift depends on the climate, land use and cropping pattern, etc. In Bangladesh, organic carbon in soils may have declined to equilibrium levels and a further decline may not occur unless land use intensity changes further, particularly in the HL and MHL sites, as evidenced by a relatively low variation in SOC. Similar changes in SOC due to continuous/intensive cultivation have been reported in many soils across the world (Janzen et al. 1998; Lal, 2002; VandenBygaart et al. 2003; Campbell et al. 2005; Bernoux et al. 2006), albeit on field scale assessments. The findings of SOC decline being driven by land inundation and cropping intensity in this large landscape study are of important significance and implications for similar agroecosystems, where cropping intensity is fuelled by increasing demand for food production. Ironically this demand of increasing food production is depleting SOC, which in turn has stagnated or reduced crop yields in South Asia and other similar regions (Lal, 2009; Gomiero, 2016).

SOC depletion is one of the important processes of land degradation (Lal, 2009), about 7.5 million hectares of agricultural land in Bangladesh alone is considered as degraded due to unsustainable land use and management practices (Karim and Iqbal, 2001; Lal, 2004). Furthermore, about 0.72% of the cropland mainly from the higher land types (the HL and MHL sites) is annually lost to other land uses e.g. settlements, brickfields, other infrastructures and industries (Hasan et al., 2013). This, together with the need for increasing food production to feed the growing population is the main cause of unsustainable land use intensity, particularly on higher land types where growing 3-4 crops annually has become common practice. This, in turn, is fuelling soil degradation, and resulting in crop yield stagnation, commonly observed in Southeast Asia and other regions with similar population pressures. Decline in SOC or low SOC is intrinsically linked to land degradation, which poses a major threat to food security (Lal, 2009). FAO (2011) emphasizes that there is a strong relationship between land degradation and poverty. It is important, therefore, to act to halt soil degradation and adopt practices to improve soil health (Gomiero, 2016). Furthermore, Bangladesh will be among the most affected countries in South Asia by the expected 2°C rise in the global average temperatures, with rising sea levels, more intense cyclones threatening food production (Wold Bank, 2013). The rising sea level could submerge low-lying areas, which are currently used for food production, such as the low land types in this study.

Without doubt, such SOC depletion is a contributory factor in greenhouse gas emissions and poses a serious threat to food security (Lal, 2004; Lal, 2009; FAO, 2011), if SOC levels continue to deplete.

5. CONCLUSIONS

SOC distribution over the two alluvial deposits 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 Bangladesh, 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 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 and much of South Asia, if SOC is allowed to deplete further (Lal, 2009; FAO, 2011).

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