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(Article begins on next page)



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Potential phosphorus and arsenic mobilization from
Bangladesh soils by particle dispersion

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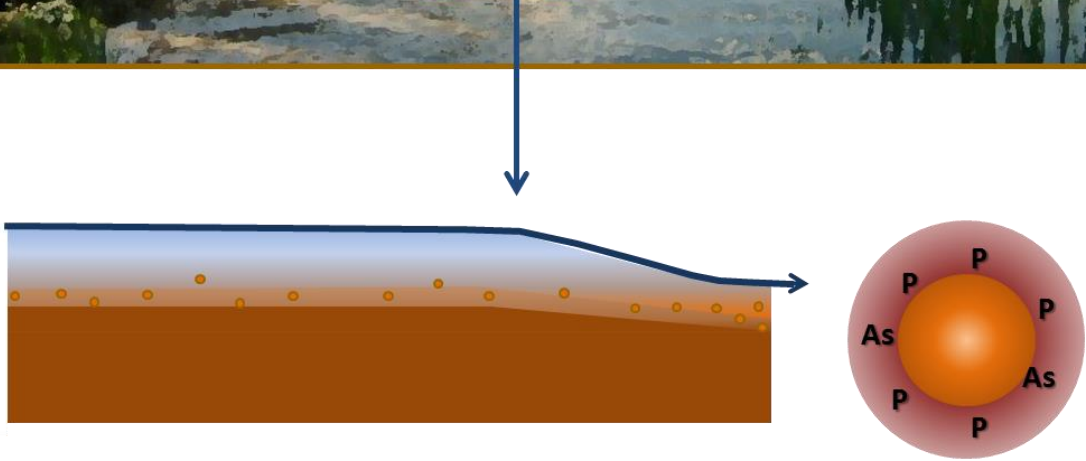
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KEYWORDS: Soil; Particle dispersion; Phosphorus; Arsenic; Bangladesh

Graphical Abstract



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ABSTRACT

Besides dissolution, particle dispersion and mobilization can substantially contribute to element transfer from soils to waters. The dispersibility of the fine particulate and the associated potential losses of P and As from Bangladesh soils of the Ganges and Meghna floodplains have been evaluated with a simple dispersion test. The dispersible fraction was greater for the coarse-textured soils from the Meghna floodplain and increased with particle charge density. Particulate phosphorus (PP) and As (PAs) were the dominant forms in the dispersion, dissolved P and As being scarce to negligible. The PP and PAs were related to the amount of dispersed particulate, oxalate-extractable iron and, respectively, to the water-extractable P or phosphate-extractable As. Although reductive dissolution is reported as the main mechanism of As mobilization during prolonged monsoon flooding, the transfer in particulate form could potentially represent a major pathway for P and As transfer from soils to waters in oxic environments after sudden, extreme events. Since the frequency of extreme rainfall and floods is increasing because of the climate changes, and the intensified land cultivation is enhancing soil disturbance, larger contributions of particulate runoff to element migration from soils to waters could be expected in the future.

List of abbreviations

P_{Olsen}	Olsen-extractable P
$P_{\text{H}_2\text{O}}$	Molibdate-reactive P extracted in water
A_{SP}	As exchangeable by phosphate
Fe_o	Oxalate-extractable Fe
$SS_{<20\mu\text{m}}$	<20 μm suspended solids
$SS_{<2\mu\text{m}}$	<2 μm suspended solids
$DI_{<20\mu\text{m}}$	$[SS_{<20\mu\text{m}}/(\text{Fine Silt} + \text{Clay})] \times 100$
$DI_{<2\mu\text{m}}$	$[SS_{<2\mu\text{m}}/(\text{Clay})] \times 100$
PSI	Phosphate Sorption Index
PP	Particulate P
PAs	Particulate As
SAR	Sodium adsorption ratio
PER	P enrichment ratio to the bulk soil

KEYWORDS: Particulate; Dispersion; Phosphorus; Arsenic; Bangladesh; Soil

1. INTRODUCTION

In Bangladesh agricultural land is often intensively cultivated, with increasing mechanization, intensification of groundwater irrigation, and greater fertilizers inputs (<http://www.fao.org/docrep/003/x6906e/x6906e04.htm>). These practices have not always been rational and sustainable, determining loss of fine particles from the agricultural soils, depletion of soil organic C, accumulation of xenobiotics (Ali et al., 1997a, b; Ali et al., 1998; Ali, 2004), with a general degradation of soil fertility (Rasul and Thapa, 2004). The unbalanced use of fertilizers may lead to the depletion of some nutrients and, on the other side, to a progressive buildup of strongly retained elements, such as P (Huq and Shoaib, 2013). In several Bangladesh soils the use of groundwater irrigation is increasing the concentration of arsenic (Saha and Ali, 2007; Brammer et al., 2009; Dittmar et al., 2010), the chemical behavior of which resembles that of phosphorus (Bhattacharya et al., 2007). Agricultural soils are nonpoint sources of nutrients and contaminants that may affect the quality of water (Schoumans et al., 2014). The mechanisms leading to losses of P and As from soils depend on whether the conditions are anoxic or oxidizing. When reducing conditions are established, the solubility of P and As increases after the reductive dissolution of Fe and Mn oxides (Masscheleyn et al., 1991; Scalenghe et al., 2002) and losses mainly occur in dissolved forms (Gburek et al., 2005; Roberts et al., 2010). Conversely, when soil aerobic conditions are maintained, transport of the finest particles may represent the dominant pathway from soil to waters (Barberis and Withers, 2002; Gburek et al., 2005).

In Bangladesh hilly areas soil erosion and landslides are well documented (Biswas et al., 2012; Huq and Shoaib, 2013), while in the floodplains river floods and flash floods remodel considerable land extensions with erosion and sediment deposition (Brammer, 1990); rainwater floods, having a lower runoff potential, can however be enriched with fine suspended particles depending on soil dispersibility. Actually, Bangladesh floodplains are not uniformly flat, but there are relevant

microscale undulations (Brammer, 1990; Ahammed et al., 2014); the water of rain floods normally is not stagnant, at least during the rain events, but flows over the land to tributary rivers (Brammer, 1990 and 1995) and may carry the suspended particles from agricultural soils to surface water bodies. The mineralogical and chemical composition of suspended solids in the Ganges-Brahmaputra river system reveals that the fine particles suspended in the shallow parts of river water profiles partly consist of clays and soil aggregates with weathering indices documenting major contributions from the intensely cultivated floodplains (Garzanti et al., 2011). Topsoil fine particles losses have been observed as a general issue in Bangladesh agricultural soils (Ali et al., 1998); the measured losses from rice fields have been found to be up to $6 \text{ t ha}^{-1}\text{y}^{-1}$, with the greater amounts lost in the rainy season (Ali, 2004). Soil fine particles transferred from floodplain agricultural soils to surface waters can contribute to the transfer of strongly adsorbed anions. Chronic mobilization of dispersed particles from intensively cultivated soils may be even more relevant for the migration of nutrients or contaminants than episodic catastrophic events in natural ecosystems (Gburek et al., 2005; Withers et al., 2009). Phosphorus transfer is the most common concern regarding the transport of elements in solid phase from agricultural soils to waters (Sharpley, 1980; Gburek et al., 2005; Schoumans et al., 2014); moreover, soil particles in this area of the world are also potentially enriched with As (Huq et al., 2003; Saha and Ali, 2007; Dittmar et al., 2010). Arsenic dissolution from soils under reducing condition has been widely studied and represents the main mechanism for As release from soils under the reducing conditions following the accumulation of monsoon water (Roberts et al., 2010); however, some situations, such as rapid floods discharging water from fields to channels and rivers before reducing condition are established, could imply the transfer of relevant amounts of particle-bound elements (Li et al., 2005). Future increases of extreme rainfall events induced by climate change (Webster and Jian, 2011) might further enhance this phenomenon. There is, nevertheless, almost no information on the potential for the transfer of nutrients and contaminants from Bangladesh agricultural soils to surface waters of rivers and ponds in particulate form.

To know the degree of particle dispersibility is essential for assessing the amount of particles transferred with the flood water. Comparative tools enabling to determine the relative vulnerability of soils to particle dispersibility, such as dispersion tests, provide the basis for estimating the amounts of dispersed particles (and bound elements) during rainfall events and for comparing differences between sites. With proper integration, this information may further be used for the estimate of potentials for erosion and runoff.

The aim of this work was to assess the potential dispersibility of Ganges and Meghna floodplain soils using a dispersion test, to investigate the potential transfer from soils to waters of soil particles, particle-bound P and As, and to estimate it through regressions from easily measurable soil properties.

2. MATERIALS AND METHODS

2.1. Study areas

The sampled soils develop on recent alluvial and deltaic sediments in the Ganges (GF) and Meghna (MF) Floodplains in the districts of Meherpur, Gopalgaj, Jessore and Sathkhira in GF, and in the districts of Brahmanbaria, Comilla and Chandpur in MF (Figure 1). The sampling area and the main physical and chemical characteristics of the 59 sampled soils are described in Martin et al. (2014a) and Table S1 of the Supporting Material.

2.2. Soil analyses

The adsorption capacity for chemisorbed anionic species was estimated through a single-point phosphate sorption index (PSI) (Bache and Willims, 1971; Borda et al., 2011). Briefly, 2 g of air-dried soil (< 2 mm) were equilibrated with 50 mmol P kg⁻¹ soil in 20 ml 0.01 M CaCl₂ on a reciprocating shaker at 20° C for 24 h. After centrifugation and filtration at 0.45 μm, the equilibrium P concentration in the solution (C_e) was determined colorimetrically (Murphy and Riley, 1962). The amount of P sorbed (X) was calculated as the difference between P added and P dissolved at the equilibrium (C_e). The PSI index was calculated as X/log C_e. The ratio of a loosely bound P form

(Olsen P or water-extractable P) to PSI may provide an index of the degree of P saturation (Borling et al., 2004).

The As exchangeable by P was assessed by measuring As in the solution after P adsorption for the determination of PSI. Arsenic was detected by HG-AAS (Perkin-Elmer 4100 equipped with a FIAS 400 hydride generator; Perkin-Elmer Inc., Waltham, Massachusetts).

The potential for dispersion of soil particules was estimated with a gentle water dispersion test (Withers et al., 2007; Borda et al., 2010), hereafter defined as DESPRAL test (Figure S1): shaking in deionized water 20 g l⁻¹ of soil (<2 mm) and collecting, after the appropriate sedimentation times, 25 mL of soil suspensions containing particles <20 μm (SS_{<20μm}) and <2 μm (SS_{<2μm}).

The amount of suspended solids was determined by gravimetric method, weighting the oven-dried aliquot of the suspension collected after the different sedimentation times. The suspensions of the DESPRAL test were analyzed for those parameters that could affect particle dispersibility (pH, particle chemical composition and surface charge, anions and cations in solution). The SS_{<20μm} were characterized for *aqua-regia* extractable As, P, Fe, Mn. The water-dispersible clays (SS_{<2μm}) were characterized for zeta potential (ζ) and average particle size (d_z) (LDV-PCS, Coulter DELSA 440, Beckman, Coulter Inc., Brea, CA). The amounts of molybdate reactive P (P_{H2O}) and soluble cations (Ca, Mg, Na) were determined in the dispersant water after filtration through 0.45 μm. The As concentration was below the detection limit. The characterization of the dispersed particles is given in Table 3, and that of the dispersant solution in the Supporting Material, Table S2. The ratio between the total soil content of <20 μm particles (i.e., fine silt + clay) to the dispersible amount was considered as a dispersion index (DI_{<20μm}).

2.3 Statistical Analysis

Statistical differences at 0.01 and 0.05 level in soil properties were tested among floodplains and districts using one-way analysis of variance (ANOVA). Correlations among relevant soil variables, potentially related with As and P mobilization and transport, were evaluated using the Pearson coefficient (two-tailed), after visual inspection of the data to verify that the dependence relationship

was linear. Stepwise multiple regression, using relevant soil properties as independent variables, was used to estimate the amount of particulate and particle-bound elements which may be dispersed. As a general rule (Stanchi et al., 2009) input variables were chosen among the ones displaying better correlations with the dependent variables. Samples were stratified according to the location (MF, GF). R^2 and corrected R^2 , VIF (variance inflation factor), and SEE (standard error of the estimate) were considered for the evaluation of the model performance.

All statistical analysis was carried out with SPSS software version 20.0.

3. RESULTS AND DISCUSSION

3.1. Soil characteristics

The studied soils represent the most common agricultural lands in GF and MF, differing in several physicochemical properties, including texture, pH, OM, Fe and Al (hydr)oxides, and P and As contents (Martin et al., 2014a; Table S1).

Briefly, GF soils were mostly slightly calcareous, silt-loamy to clay-loamy, while MF soils were non-calcareous, moderately to slightly acid, and prevalent silty loam. Organic C and N contents ranged from low to medium and were slightly higher in the GF. The two floodplains differed in all As and Fe forms, the GF soils having generally greater contents, except for poorly ordered Fe oxides, more abundant in the MF soils. Regarding P forms, the two floodplains differed only in Olsen extractable P that, differently from As, was higher in MF, particularly in Comilla district. All these differences can thus imply different potentials for As and P dissolution (Martin et al., 2014b), but also for their potential release and transport in particulate runoff.

3.2. Potential for particle dispersion

The total potential losses of anions associated with fine particles are a function of the amount of dispersed solids, and of the anion enrichment of the dispersed particles. Soil dispersion tests have been proposed to provide soil and P loss quantification at field scale (Udeigwe et al., 2007; Withers et al., 2007). These tests assess the relative risk of initial mobilization of sediments and P in the flood

water and provide a basis for comparing the vulnerability to fine particles and bound elements losses between soils (Withers et al., 2007; Borda et al., 2011), which may be subsequently integrated with further parameters assessing the risk of mobilized particles to reach the watercourses. The DESPRAL test was used to identify the $SS_{<20\mu m}$ dispersible fraction. It has been shown that although the clay fraction is the most enriched with adsorbed elements (Scalenghe et al., 2007), it is the $SS_{<20\mu m}$ fraction (fine silt plus clay) which is preferentially mobilized and that is important for particle transfer (Withers et al., 2007).

The amounts of $SS_{<20\mu m}$ dispersed by the DESPRAL test (Table 1 and Table S2) ($SS_{<20\mu m}$ in GF, range: 46-233, mean: 129 g kg⁻¹ of soil; in MF, range: 56-255, mean: 166 g kg⁻¹ of soil), were greater than those measured with European soils (range: 14-170 g kg⁻¹ of soil) (Withers et al., 2007; Borda et al., 2010). The dispersed amounts varied widely at local and district level, but the differences among the two floodplains were still significant, with greater amounts dispersed by MF soils, in spite of the much lower total content of fine silt and clay (Table S1).

Within each floodplain, a rough North to South trend with increasing dispersibility could be noticed (Figure 2). In our study area the dispersibility was enhanced in samples coming from the recent/active part of the floodplains and closer to the rivers compared to those coming from older parts of the floodplain. Active alluvial plains are in fact highly dynamic and characterized mostly by poorly developed soils (Bullinger-Weber, et al., 2007), where the particles of the topsoil horizon may be easily mobilized and transported. The most recent alluvial soils, particularly those in active floodplains, contain recently deposited, less stabilized particles, as well as greater degree of sodicity when closer to the sea or to rivers affected by tidal surge (Table S3). The $DI_{<20\mu m}$ was much greater in coarse-textured soils and exponentially decreased at increasing contents of fine silt plus clay in soil (Figure S2) with a clear distinction between the two floodplains (Table 1, Figure S2). A similar trend, although with poorer correlation, was observed for the dispersibility index of the $SS_{<2\mu m}$ (Figure S3).

The dispersion of colloidal particles depends on their surface charge, kind and concentration of counter-ions, amount of organic and inorganic promoters of particle aggregation. The soil characteristics reflecting these parameters were tested for correlation with the total amount of $SS_{<20\mu m}$ (Table S3) in order to identify the relevant dependent variables to be inserted in multiple regression models. We are aware that regression relationships do not indicate strong cause-effect relationship, but they can be useful to estimate soil variables, that would require time-consuming analyses, from easier parameters. In our dataset, regression models were not able to predict the total amount of dispersed fine particles, differently from what was obtained for European soils (Borda et al., 2010). Conversely the dispersion index of the $<20\ \mu m$ fraction ($DI_{<20\mu m}$) could be predicted from other soil properties using multiple regression. $DI_{<20\mu m}$ was negatively correlated (Table S3) with those factors promoting aggregation (pH, organic C, Fe and Al contents, and PSI which is an estimate of the sites available for P adsorption), while the dispersibility of the fine fraction was promoted by the negative charge of the particles, exchangeable Na (or SAR, Sodium adsorption ratio), P saturation degree, (as inferred by P_{Olsen} or P_{H_2O} , or their ratio to $PSI - 29$). Similar relationships were found in European soils (Withers et al., 2007; Borda et al., 2010). All these parameters were thus considered in multiple regressions.

More than 70% of the variability of the $DI_{<20\mu m}$ fraction (Table 2) was explained by clay content, zeta potential, and an index of P saturation (P_{H_2O}/PSI). The clay content displayed a negative sign, evidencing greater dispersibility of those soils containing a lesser amount of clay (Kjaergaard et al., 2004), since clays enhance aggregate stability (Kemper et al., 1987). On the other hand, the particle dispersion was increased at increasing surface net negative charge which, in turn, is enhanced by the coverage with specifically adsorbed anions (Celi et al., 1999; Udeigwe et al., 2007; Withers et al., 2007; Ilg et al., 2008). Although the soils of the two floodplains significantly differ both for total content (Table S1) and surface charge (Table 3) of their clay fraction, the prediction obtained from the regression did not improve by considering the data of the two floodplains separately.

The zeta potential and P_{H_2O}/PSI are difficult to obtain, requiring specific equipment or being time consuming, hence the use of these parameters, although explanative of the dispersion mechanisms, would be unsuitable for practical purposes. The regression was thus simplified, utilizing only easily obtainable parameters: the clay content and P_{H_2O} still accounted for 65% of the variability (Table 2).

3.3. Potential element losses in particulate form

The dispersed particles chemically differed from the bulk soil mainly for their contents in P and As (Table 3). The P enrichment ratio to the bulk soil (PER) was 1.5 in MF and 1.2 in GF on an average; the As enrichment ratio (AsER) was even more marked, 2.1 in MF and 1.9 in GF on an average. This could be attributed to the larger specific surface area of the finest components and to the concentration in this fraction of the most active P and As adsorbing minerals, such as Fe oxy(hydr)oxides (Scalenghe et al., 2007; Martin et al., 2014b).

The enrichment of the fine fraction with phosphate and other anions (PER and AsER in Table 3) is generally more remarkable in coarse-textured soils where the fine fraction is scarce (Barberis and Withers, 2002), enhancing the electrostatic dispersion of the particles (Celi et al., 1999; Celi et al., 2001; Ilg et al., 2008). This contributes to explain the greater percentage of fine particles that can be dispersed in MF soils, where the measured negative charge was indeed greater, and counteracted by a smaller concentration of Ca^{2+} in the solution (Table S2, supporting information).

The total amount of an element that can be lost from soil through the dispersion of the fine particulate is function of the particle concentration in the dispersion, and of the element concentration in the dispersed particulate. The accumulation of strongly adsorbed elements, such as phosphorus, in the finest fractions is commonly found in many soils (Williams and Saunders, 1956; Barberis and Withers, 2002; Scalenghe et al., 2007). The concentration of As and P in the fine particulate of MF and GF soils suggests that their fate could be partially linked to that of this soil solid fraction. Hence, the combination of an easy, rapid dispersion test with data yielded by simple extraction methods could provide a useful tool to estimate the potential losses of elements like P and As in particulate form.

For the studied Bangladesh soils, over 70% of the variability of the particulate phosphorus (PP) could be estimated through the $SS_{<20\mu m}$, P_{Olsen} , and Fe_o .

$$PP = 0.472 SS_{<20\mu m} + 2.17 P_{Olsen} + 4.84 Fe_o - 25.439; \text{adj. } R^2 = 0.703 \text{ } p < 0.001 \text{ (Eq. 1).}$$

The performance of the predictive model only slightly improved when the data for GF and MF ($R^2 = 0.751$ and 0.762 respectively) were split (not shown).

Similar parameters ($SS_{<20}$, Fe_o and As_P) allowed to estimate nearly 65% of the variability of PAs:

$$PAs = 8.10 \cdot 10^{-3} SS_{<20\mu m} + 1.27 As_P + 0.30 Fe_o - 1.308; \text{adj. } R^2 = 0.648; \text{ } p < 0.001 \text{ (Eq. 2).}$$

In this case, when considering the data set of the two floodplains separately (Table S4), a substantial improvement of the predictive model was obtained ($R^2 = 0.757$ for GF and 0.806 for MF), possibly reflecting the differences in the total content and forms of As between the two floodplains (Martin et al., 2014a).

3.4. Environmental implications

The amount of fine particulate that can be dispersed in agricultural soils, based on DESPRAL test, can vary from nearly 20% of the total $<20\mu m$ fraction in GF, to more than 40% in MF, with significant differences among districts, from 48% in Chandpur to less than 15% in Meherpur and Jessore (Figure 2).

Data on soil erosion in Bangladesh outside the Chittagong Hill Tract are scanty available. Ali (2004) reports soil loss by water transport varying from 4.6 to 6.8 (average, 5.8) $t \text{ ha}^{-1}$ in experimental rice fields in Satkhira district in the year 2000.

In terms of anion losses in particulate form, if the maximum amount of soil runoff measured by Ali (2004) is considered to calculate the P potential losses from Satkhira soils, an average loss of $7 \text{ kg P ha}^{-1} \text{ y}^{-1}$ with soil particles could be predicted, while As potential losses would be $0.13 \text{ kg ha}^{-1} \text{ y}^{-1}$. In view of estimating the actual runoff for each District, the DESPRAL test provides a useful tool to compare the dispersibility of the fine fractions and the potential for losses of elements strongly bound to the solid particles between different soils, to be further integrated with local data for risk assessment of the particle to reach the water body.

The P concentration in solution in the dispersing water (P_{H_2O}) was always less than 1 mg l^{-1} (and As was almost always below the detection limit of $2 \text{ } \mu\text{g l}^{-1}$), the particulate form thus represented the largest proportion (from 75 to 100%) of the P and almost all the As that may be lost with the flood water. This would suggest a major contribution of the solid phase to element transfer within aerobic systems, such as during extreme rainfall events or river floods exceeding or disrupting the bounds before anoxia and reducing conditions can develop in the water column above soil. Actually, heavy storms events have been proven to increase the concentration of P and other soil-derived elements in river water, especially in particulate form (Li et al., 2005). Conversely, when slow, gradual submersion occurs during the accumulation of monsoon water, less soil particles are likely to remain in suspension over long time periods, the splash effect of rain drops on soil aggregates will be minimized by the inundation water, while reductive dissolution processes would favor the transfer of dissolved forms, as found for As by Roberts et al (2010).

If, as predicted by climate models, extreme rainfalls and rapid flooding would become more frequent (Shahid, 2011; Webster and Jian, 2011; Ahammed et al., 2014), the relative importance of solid-phase mobilization vs dissolution of P and As could increase and the effect could be different in the two examined floodplains. In MF, with mostly coarser textured soils, the total amount of dispersed fine particles is similar to that of GF soils, but the fraction of the fine particles that tend to be dispersed is much higher as well as the P and As enrichment ratios. Thus, losses by dispersion of the fine particles could contribute more significantly to the total release of adsorbed anions from MF paddy soils compared to GF soils. Despite the limited average slope, the intense rainfall regime may determine intense soil erosion as widely reported by literature data (Ali et al., 1998; Udeigwe et al., 2007; Stanchi et al., 2009; Prassannakumar et al., 2012); this process might be enhanced by climate change, and the PP (and AsP) could substantially contribute to enrich the bioavailable pools after reaching the waterbodies (Uusitalo et al., 2003).

4. CONCLUSION

The important dispersibility of the fine particles of agricultural soils in the main recent floodplains in Bangladesh, together with the enrichment of the dispersible materials with toxic and eutrophicant elements indicates the mobilization in particulate form as a potential major pathway for migration of these elements from soils to waters. The importance of this pathway which, to date, has been overlooked, could further increase in future, as the number and intensity of extreme storm events would be enhanced by the climate change.

The estimation of the potential dispersibility and transfer of P and As from easily obtainable soil variables (e.g SS_{<20µm}, Fe_o, P_{Olsen}, A_{SP}) might help the soil management and mitigation of potential pollution processes. Since soil dispersibility is considerable and can be increased, with years, by tillage and management practices affecting soil structure, SOM content and permeability, a further considerable step could be promoting field investigations to assess the amount of dispersed particulate that actually migrates to the waterbodies being eroded from the agricultural soils and then to evaluate potential mitigation strategies.

ASSOCIATED CONTENT

Supporting Material.

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Table 1. Descriptives of DESPRAL test results for the two floodplains. Letters indicate significant differences among districts ($p < 0.05$)

Property	n	mean	min	max	st.dev	bc	st							
							n	mean	min	max	dev.			
GF							MF							
SS _{<20μm} (g kg ⁻¹)	M	9	102.3	60.5	157.9	29.49	bc	B	10	118.0	56.0	171.9	42.98	c
	J	8	91.6	46.5	130.1	33.01	c	CM	10	166.7	76.0	205.0	37.26	b
	G	6	149.3	62.0	189.2	46.38	ab	C	10	214.1	181.1	255.4	21.68	a
	S	6	197.6	169	232.4	22.95	a							
	GF	29	128.8	46.5	232.4	52.20		MF	30	166.3	56.0	255.4	52.37	**
SS _{<2μm} (g kg ⁻¹)	M	9	46.4	18.5	84.0	20.18	b	B	10	33.7	5.84	59.3	19.61	b
	J	8	20.0	10.5	38.5	8.28	c	CM	10	62.6	30.0	80.2	17.77	a
	G	6	58.8	26.0	74.5	19.61	ab	C	10	28.2	12.5	52.5	12.87	b
	S	6	82.6	67.5	105.0	14.20	a							
	GF	29	49.2	10.5	105.0	27.24	ns	MF	30	41.5	5.84	80.2	22.51	ns
DI _{<20μm}	M	9	14.1	9.2	21.0	4.51	b	B	10	35.0	14.4	52.9	11.62	b
	J	8	14.9	5.9	30.0	8.11	b	CM	10	39.8	21.2	61.8	11.64	ab
	G	6	24.9	10.7	32.5	8.58	ab	C	10	48.6	39.0	58.7	5.49	a
	S	6	32.5	20.3	46.6	9.91	a							
	GF	29	20.4	5.9	46.6	10.50		MF	30	41.1	14.4	61.8	11.22	**
DI _{<2}	M	9	11.9	5.6	19.0	4.07	bc	B	10	42.1	13.4	72.0	24.00	
	J	8	8.4	3.9	26.4	7.51	c	CM	10	50.9	26.6	69.3	21.48	
	G	6	20.7	8.6	34.3	9.33	ab	C	10	43.2	18.2	100	14.72	
	S	6	31.0	20.9	39.2	7.21	a							
	GF	29	16.7	3.9	39.2	10.87		MF	30	45.4	13.4	100	20.13	**

SS_{<20 μ m} <20 μ m suspended solids
SS_{<2 μ m} <2 μ m suspended solids
DI_{<20 μ m} [SS_{<20 μ m}/(Fine Silt + Clay)] $\times 100$
DI_{<2 μ m} [SS_{<2 μ m}/(Clay)] $\times 100$

Table 2. Multiple regressions for the estimation of $DI_{<20}$ (%). SEE: Standard Error of the Estimate

The two models have the same target variable; the second has been simplified using more easily determined independent variables.

Target variable	Adj. R^2	SEE	Independent variables	Unstand. coefficients	Stand. coefficients
$DI_{<20}$ μm (%)	0.717	7.99	constant	32.585	-
			Clay	-0.578	-0.565
			ζ	-0.700	-0.247
			$P_{(H_2O)}/PSI$	6.872	0.238
$DI_{<20}$ μm (%)	0.652	8.86	constant	42.747	-
			Clay	-0.696	-0.679
			$P_{(H_2O)}$	0.295	0.239

$DI_{<20}$ μm $[SS_{<20} \mu\text{m}/(\text{Fine Silt} + \text{Clay})] \times 100$
 $DI_{<2}$ μm $[SS_{<2} \mu\text{m}/(\text{Clay})] \times 100$

Table 3. Physical and chemical properties of the dispersed particles. Letters indicate significant differences among districts at the 0.05 level

		n	mean	min	max	st.dev		n	mean	min	max	st dev.		
ζ clays (mV)	M	9	-7.2	-10.3	-2.4	2.70		B	10	-11.4	-18.5	-3.0	4.76	
	J	8	-7.9	-11.0	-5.6	2.00		CM	10	-15.9	-21.8	-9.6	4.45	
	G	6	-10.8	-14.5	-5.2	3.30		C	10	-15.6	-26.0	-6.9	6.49	
	S	6	-11.1	-17.7	-7.7	4.00								
	GF	29	-8.9	-17.7	-2.4	3.30		MF	30	-14.31	-26	-3	5.55	**
d _z (μm)	M	9	1.09	0.078	0.97	1.17	b	B	10	0.86	0.75	0.98	0.067	b
	J	8	1.26	0.238	0.99	1.58	a	CM	10	0.99	0.75	1.21	0.144	a
	G	6	1.09	0.145	0.93	1.28	b	C	10	0.97	0.83	1.17	0.117	a
	S	6	0.94	0.038	0.90	1.00	b							
	GF	29	1.11	0.182	0.90	1.58		MF	30	0.94	0.75	1.21	0.125	**
Fe<20μm (g kg ⁻¹ particulate)	M	9	52.1	42.3	67.4	7.0	a	B	10	39.5	27.8	52.2	7.0	a
	J	8	42.1	31.9	51.3	6.4	ab	CM	10	34.5	24.6	46.5	6.7	a
	G	6	36.8	30.2	43.1	5.1	b	C	10	22.6	17.2	30.5	4.3	b
	S	6	40.1	33.3	48.3	6.7	b							
	GF	29	43.7	30.2	67.4	8.5		MF	30	32.2	17.2	52.2	9.3	**
P<20μm (mg kg ⁻¹ particulate)	M	9	834	586	1319	28	ab	B	10	953	559	2008	396	b
	J	8	658	568	775	75	ab	CM	10	1560	828	2676	531	a
	G	6	426	378	556	68	b	C	10	519	158	938	261	b
	S	6	1017	455	1617	501	a							
	GF	29	739	378	1617	33		MF	30	1011	158	2676	588	*
PER	M	9	1.3	0.96	1.8	0.24		B	10	1.9	1.2	2.7	0.52	a
	J	8	1.3	1.2	1.5	0.09		CM	10	1.6	0.75	2.7	0.60	ab
	G	6	1.1	0.96	1.3	0.14		C	10	1.1	0.12	1.7	0.49	b
	S	6	1.1	0.87	1.3	0.15								
	GF	29	1.2	0.87	1.8	0.18		MF	30	1.5	0.12	2.7	0.64	**
PAs (mg kg ⁻¹ particulate)	M	9	16.7	12.5	25.6	3.9		B	10	12.9	6.1	22.9	6.3	ab
	J	8	31.6	9.7	59.3	16.8		CM	10	18.8	5.3	42.3	12.8	a
	G	6	14.2	7.9	25.0	7.11		C	10	3.5	2	7.2	1.6	b
	S	6	18.6	8.7	31.4	9.0								
	GF	29	20.7	7.9	59.3	12.1		MF	30	11.7	2	42.3	10.2	**
AsER	M	9	2.1	1.1	2.8	0.61		B	10	2.19	1.68	2.89	0.41	
	J	8	1.8	1.2	2.3	0.41		CM	10	2.36	1.05	5.18	1.25	
	G	6	2	1.4	2.8	0.64		C	10	1.62	1.28	2.24	0.31	
	S	6	1.7	0.6	2.4	0.74								
	GF	29	1.9	0.6	2.8	0.53		MF	30	2.05	1.05	5.18	0.82	

ζ clays (mV) zeta potential of clays

d_z (μm)

average particle size

Fe<20µm(g kg⁻¹ particulate) Fe in the <20µm fraction
 P<20µm (mg kg⁻¹ particulate) P in the <20µm fraction
 PAs Particulate As
 AsER As enrichment ratio

Table 4. Multiple regressions for the estimation of PP_{20µm} and PAs_{20µm} for the whole data set. SEE: Standard Error of the Estimate

Target variable	Adj. R ²	SEE	Independent variables	Unstandardised coefficients	Standardised coefficients
PP	0.703	46.38	Const	-25.439	-
			Fe _o	4.844	0.086
			SS_{20µm}	0.472	0.306
			P _{Olsen}	2.167	0.702
PAs	0.648	0.959	Const	-1.308	-
			Fe _o	0.301	0.282
			SS_{20µm}	0.0081	0.276
			As P	1.272	0.743

PP Particulate P
 PAs Particulate As

FIGURES

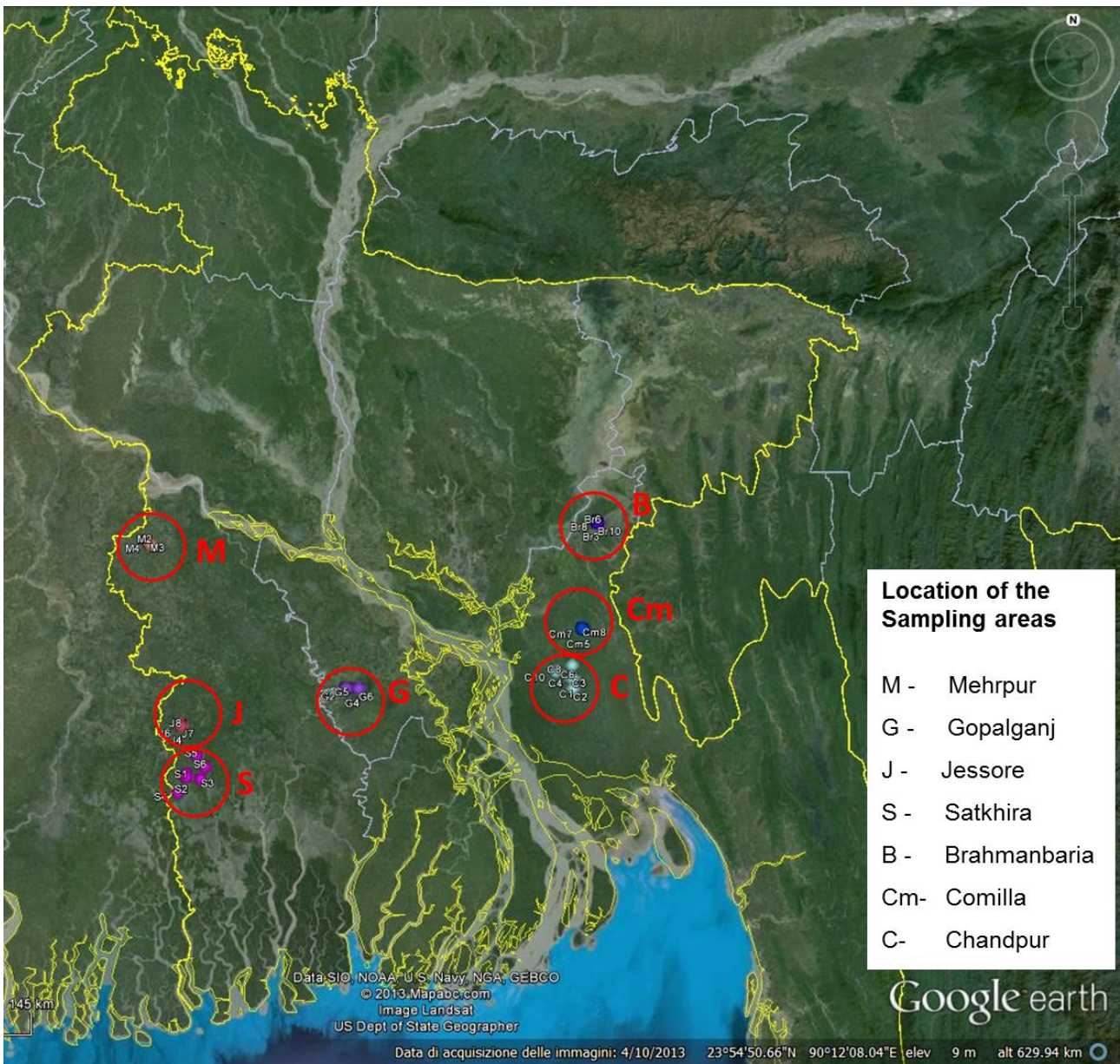


Figure 1. Location of the sampled areas. Map source: Google earth

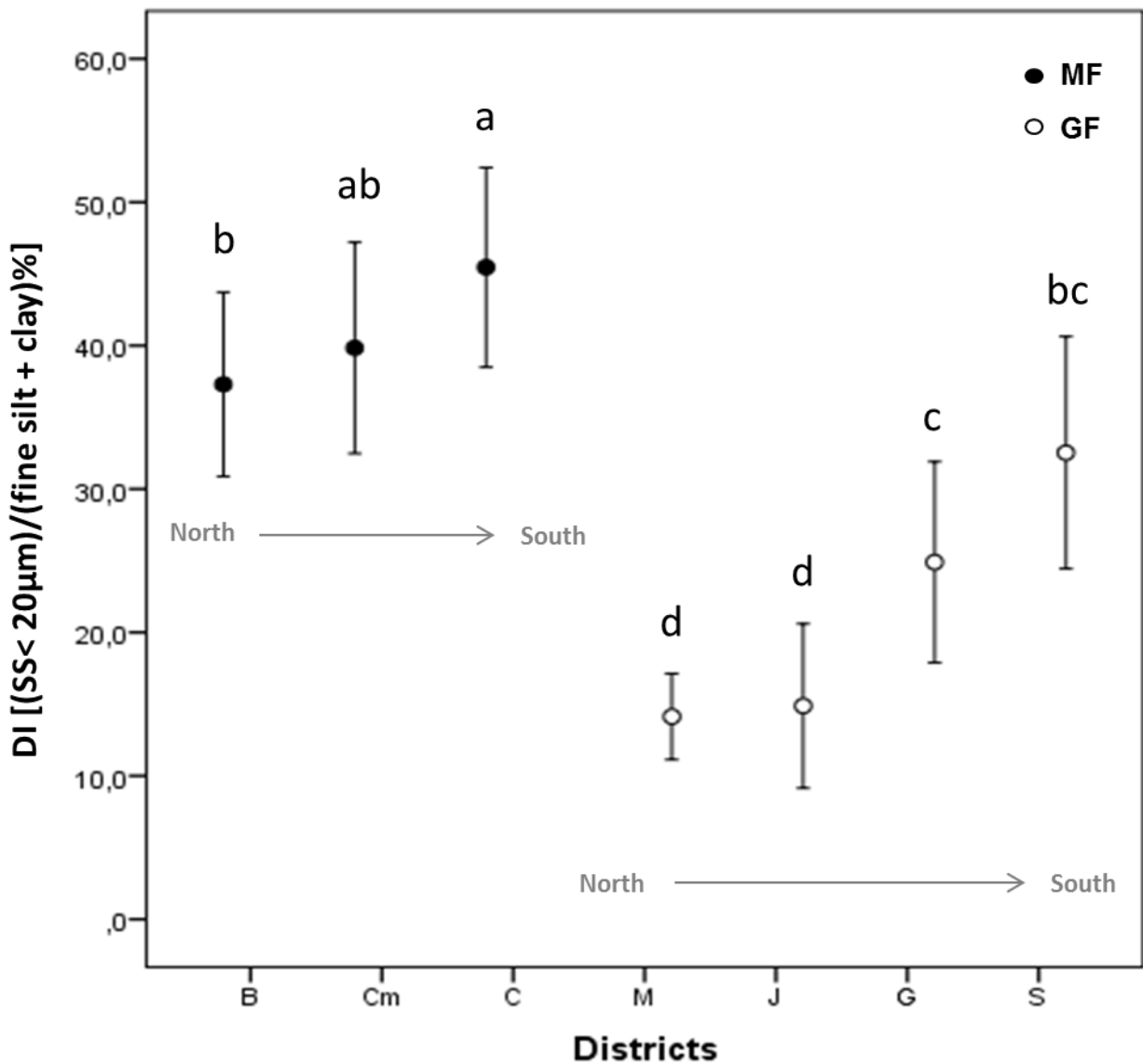


Figure 2. Average dispersible <20 μm fraction by district. Error bars are 2xSE. Differences are significant for α = 0.05. B: Brahmanbaria; Cm: Comilla; C: Chandpur; M: Mehrpur; J: Jessore; G: Gopalganj; S: Satkhira.

