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Soil Properties Influence Vertical Distribution of Boron Fractions in Lateritic Soil

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ABSTRACT

The present study was conducted at Palli Siksha Bhavana (Institute of Agriculture), Visva-Bharati, West Bengal, India, during 2019-20 to evaluate the different fractions of boron (B) along depth and their relationship to some soil properties in lateritic soils of West Bengal, India. The sequential B fractionation scheme was followed to estimate B fractions in the studied soils. It was found that most of the soils fall under the sandy clay loam and clay loam soil textural categories. The soil pH was either categorized as extremely acidic or slightly acidic in nature and the range of low to medium organic carbon content was present. The studied soils' CEC varied between 5.90 to 26.64 [C mol (P^+) kg^{-1}]. In the B fractionation study, it was revealed that, for uptake of plants, the readily soluble boron (Rs-B) is the most easily accessible fraction among all other fractions, and the residual boron (Res-B) fraction accounts for the major portion of total soil boron (Tot-B). Different soil properties of the study area greatly influenced the B fractions along soil depths. The contribution of different B fractions towards total soil B (Tot-B) B followed the order: residual boron (Res-B) >> oxide-bound boron (Oxd-B) > organically bound boron (Org-B) > specifically adsorbed boron (Sad-B) > readily soluble boron (Rs-B). The current study will be helpful for adopting the fertilizer management practices of boron-deficient lateritic soils (Alfisols).

KEYWORDS: Boron fractions, soil properties, soil depths, lateritic soil

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1. INTRODUCTION

Boron (B), one of the most important inorganic micronutrients, plays a vital role in normal plant growth (Vera et al., 2019), enhanced quality of crops (Khalaj et al., 2016, Souri and Hatamian, 2019, Kanwar and Randhawa, 1974) and is also essential for human and animal health (Uluisik et al., 2018). Warington (1933) was the first to demonstrate the significance of boron as a plant nutrient. Boron (B) is known as the "unique" mineral plant nutrient because it is the only element that is normally present in soil solution as a non-ionized molecule over the pH range necessary for plant growth (Oertli and Grgurevic, 1975). Boron deficiency is more widespread than any other plant micronutrient (Tisdale et al., 1985, Reisenauer et al., 1973, Gupta, 1979, Keren and Bingham, 1985). It's the second most limiting micronutrient in the whole world (Sillanpaa, 1990, Hua et al., 2016, Tariq and Mott, 2007). If it's supply is not adequately maintained, a deficiency causes definite visual symptoms in crops (Bradford, 1965). The deficiency symptoms include reduced plant height, growth, development, fruiting, quality (Souri and Bakhtiarizade, 2019, Tohidloo and Souri, 2009, Sillanpaa, 1982), plants fail to produce panicles at the panicle formation stage (Rehman et al., 2014) and whitening and rolling of emerging leaves (Brdar-Jokanovic, 2020). Pollen germination and pollen tube growth are impacted in boron-deficient conditions (Wang et al., 2003, Lordkaew et al., 2013). Available boron status in soil usually ranges from 10 to 300 mg kg^{-1} of soil (Santos et al., 2013) but only about 5%–10% is in a form which plants can utilize (Diana 2006, Rehman et al., 2018). Boron deficiency affects approximately 33% of soils in India (Sakal and Singh, 1995, Singh, 2008, Shukla and Behera, 2012). Continuous cropping with high-yielding varieties and dependence on high-analysis fertilizers cause greater removal of boron even though soils with adequate B levels (Yousaf et al., 2017).

Similar to other minerals, the dynamics and transformations of B in soils are governed by physico-chemical properties and management practices (Ahmadi and Souri, 2018, Dhaliwal et al., 2019, Souri and Hatamian, 2019). Soil B exists in several forms like readily soluble B, specifically adsorbed B, oxide-bound B, organically bound B, and residual. Each of which is in dynamic equilibrium with the others (Xu et al., 2001). The readily soluble fraction is the most labile fraction constituting the solution, plus non-specifically adsorbed B is present on the clay edges and other variable charge surfaces by displacement through anion exchange and mass reaction. Adsorbed B is adsorbed on non-crystalline or crystalline Al and Fe oxy-hydroxides and silicates or on clay particles that are relatively unavailable for plant uptake (Rehman et al., 2018). The oxide-bound B includes tightly bounded B at non-crystalline and some crystalline Fe and Al. Organically bound B is totally associated with organic matter, and residual B exists within primary and secondary mineral structures, such as tourmaline and clay mica. The assessment of these forms in soils helps in understanding their dynamics in soils and plant availability. Physical-chemical properties and management practices always have an impact on the distribution of varying fractions of B in soil along depth. Taking these facts into account, as well as the scarcity of information on the depth-wise distribution of different fractions of boron in rice growing areas of lateritic soils (Alfisols) in Birbhum district, West Bengal, an investigation was done to find out the distribution of different fractions of B along depths and its relationship with soil physical and chemical properties to aid in developing rational B fertilization schedules for crops grown on acidic lateritic soils (Alfisols) of Birbhum, West Bengal, India.

2. MATERIALS AND METHODS

2.1. Description of the study sites

The research region is situated between 23° 32' 30" and 24° 35' 0" North latitude and 87° 5' 25" and 88° 1' 40" East longitude, covering an area of 4,545 square kilometres (km^2). Districts and rivers encircle it. Birbhum and Bardhaman districts are traversed by the Ajay River. The east and north boundaries are shared by Murshidabad and Jharkhand state, respectively.

2.2. Sampling and analyses

Soil samples were collected during 2019–20 from fifty representative locations of rice-growing areas of two different blocks (Illambazar and Bolpur) under the red and lateritic zones of West Bengal, India, representing Alfisols soil order, at three different depths: surface (0–20 cm), mid-surface (20–40 cm), and sub-surface (40–60 cm) layers. The collected soil samples were processed by air-drying, grounding, and sieving through a 2 mm sieve. Then the processed samples were analyzed using established protocols at Visva-Bharati's Soil Testing Laboratory and the Department of Soil Science and Agricultural Chemistry in West Bengal, India. The pH was determined in 1:2 soil: water suspension. Mechanical analysis, organic carbon, CEC, and were determined following standard methods (Page et al., 1982). Amorphous iron (Amr-Fe) and amorphous aluminum (Amr-Al) of the soil samples were analyzed by extracting with 0.02 M ammonium oxalate, pH 3.0, (soil:extractant :: 1:30) following the procedure of McKeague and Day (1966). The different chemical fractions of B were estimated by the modified sequential boron fractionation scheme as proposed by Datta et al. (2002) (Table 1). Boron in the extracts was determined colorimetrically by carmine (Hatcher and Wilcox 1950) or

Table 1: Modified sequential B fractionation scheme as described by Datta et al. (2002)

Step	Fraction	Extractant	Condition; Extraction procedure
1	Readily soluble (Solution+non-specifically adsorbed) (Rs-B)	0.01 M $CaCl_2$	10 g soil, 20 ml extractant, 16 hrs shaking
2	Specifically adsorbed (Sad-B)	0.05 M KH_2PO_4	Residue of step 1 shaken for 1 hr with 20 ml extractant
3	Oxide bound (Oxd-B)	0.175 M NH_4^+-oxalate, (pH 3.25)	Residue of step 2 shaken for 4 h with 40 ml extractant
4	Organically bound (Org-B)	0.5 M NaOH	Residue of step 3 shaken for 24 h with 40 ml extractant
5	Residual (Res-B)	Acid digestion	After the step-four residue was ground and dried, a 1 g dried sample was acid digested (with H_2SO_4+HF+$HClO_4$)

azomethine-H method (John et al., 1975) depending on the extraction medium. The total B (Tot-B) content of the soil was calculated by adding all fractions; from readily soluble B to residual B. Simple correlations were studied between the different fractions of boron and some soil properties. SPSS version 20.0 was used for statistical analysis.

3. RESULTS AND DISCUSSION

3.1. *Soil physico-chemical properties*

Important physico-chemical properties were used to characterize the soils, and the results are shown in Table 2. From the mechanical analysis studies, it is found that most of the soils fall into the sandy clay loam and clay loam categories. The clay content of surface soil (0–20 cm) varied from 33.54±10.42% and 33.81±11.39% in the soils of Illambazar and Bolpur blocks. The Illambazar block had low to high (0.33–0.99%) and that of Bolpur block had low to medium (0.32–0.58%) organic carbon content in top soil (0–20 cm). The CEC of studied soils varied between 5.90 to 26.64 C mol (P^+) kg^{-1} with 15.06 C mol (P^+) kg^{-1} as their mean value.Ghosh et al. (2005), Kundu (2006) and Hembram et al. (2012) confirmed similar results.

Table 2: Physico-chemical properties of lateritic soils of Birbhum district, West Bengal

Location	Clay (%) at depth (cm)			pH at depth (cm)			OC (%) at depth (cm)		
	0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60
Range	20.56-52.88	22.77-63.60	22.62-61.60	5.02-6.69	5.47-6.77	5.62-6.85	0.33-0.99	0.17-0.69	0.11-0.58
Mean	33.54	36.01	38.58	5.90	6.12	6.34	0.68	0.41	0.29
SD	10.42	11.69	11.3	0.53	0.46	0.43	0.19	0.13	0.14
Bolpur									
Range	14.16-54.13	16.88-56.34	19.60-58.88	4.33-6.26	4.48-6.77	4.68-6.91	0.32-0.58	0.20-0.47	0.10-0.29
Mean	33.81	35.34	36.89	5.34	5.79	6.15	0.46	0.32	0.18
SD	11.39	11.25	11.26	0.54	0.59	0.54	0.08	0.08	0.06

Table 2: continue...

Location	CEC [C mol (P+) kg^{-1}] at depth (cm)			Amorphous Fe (g kg^{-1}) at depth (cm)			Amorphous Al (g kg^{-1}) at depth (cm)		
	0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60
Range	5.90-26.64	6.47-27.88	5.34-29.14	4.31-8.98	3.15-7.80	2.02-5.20	2.17-6.53	1.30-4.74	1.05-3.50
Mean	14.77	16.32	15.5	6.47	5.06	3.5	4.13	2.95	1.91
SD	6.58	6.26	6.96	1.67	1.28	0.92	1.15	0.88	0.72
Bolpur									
Range	7.80-26.34	9.37-28.41	10.14-27.12	3.74-8.53	3.05-7.60	2.09-6.41	2.11-6.22	1.26-4.78	1.13-3.55
Mean	15.36	16.71	17.8	6.78	5.65	4.11	3.92	2.76	2.09
SD	5.22	5.12	5.13	1.22	1.17	1.32	1.28	0.93	0.72

The pH values of the selected soils were increased with an increasing soil depth (up to 40 cm). This is because the upper horizons receive maximum leaching by rainfall, and by dissolved carbonic acid and organic acids, which remove metal cations (e.g., Ca^{2+}, K^+, and Mg^{2+}) and replace them with H^+ ions. Lower horizons are not so strongly leached and, in fact, in dryer areas, they may accumulate calcium and other materials removed from the upper soil (Brady and Weil, 2008). Other soil parameters showed a gradual decline with increasing depth of sampling, as also substantiated by Jobbagy and Jackson (2001) and Raina et al. (2013), who found topsoil concentrations of all nutrients were higher than in the lower soil profiles, where the elements were scarcer.

3.2. Boron fractions and their relationship with soil properties

3.2.1. Readily soluble boron (Rs-B)

For the uptake of plants, the readily soluble boron (Rs-B) is the most easily accessible fraction among all other fractions, which includes dissolved plus boron that has been non-specifically adsorbed on clay surfaces and other surfaces with variable charges (Keren et al., 1985). The soils collected from Illambazar block showed higher values varying between 0.25 and 0.43 mg kg^{-1} (mean 0.35±0.04 mg kg^{-1}), in surface soils compared to surface soils collected from the Bolpur block varying between 0.22 and 0.38 mg kg^{-1} (mean 0.30±0.04 mg kg^{-1}) (Table 3, 4). The mean values of 0.24 mg kg^{-1} and 0.25 mg kg^{-1} were observed in mid–surface layers in the soils of Bolpur and Illambaar blocks, respectively (Table 3, 4; Figure 1). The depth-wise decline of this B fraction was observed in all the soils under study. Sarkar et al., (2008) also observed similar type of trend. This pool in the surface soils on average contributes 1.16% of total B. Similar findings were also reported by Jin et al. (1987) and Tsadilas et al. (1994).

Readily soluble boron (Rs-B) is positively correlated to the pH and clay content in the surface, mid-surface, and sub-surface soil layers. It can be attributed to the fact that increased pH increases the negative charges of clay surfaces and other surfaces with variable charges. Similar findings were reported by Datta et al. (2002) and Karthikeyan and Shukla (2011). In Illambazar soil, both OC ($r=0.52^{**}$) and CEC ($r=0.47^{*}$) showed positive and highly significant correlations with Rs-B. In Bolpur soil also both OC ($r = 0.52^{**}$) and CEC ($r=0.49^{*}$) (Table 5, 6) showed similar significant positive correlations with Rs-B. However, Xu et al. (2001) reported a significant positive correlation of readily soluble boron form with both amorphous Fe and Al content along with CEC and OC content.

3.2.2. Specifically adsorbed boron (Sad-B)

The proportion of specially adsorbed boron (Sad-B), is

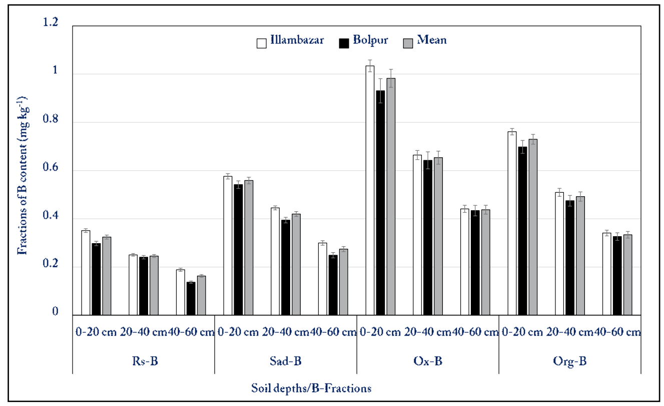

Figure 1: Depth-wise distribution of Rs-B, Sad-B, Ox-B, Org-B fractions of soil boron in the study area (Rs-B: Readily soluble boron; Sad-B: specifically adsorbed boron; Ox-B: Oxide bound boron; Org-B: Organically bound boron, Res-B: Residual boron; Tot-B: Total boron)

mostly dependent on the clay content of the soil since it is primarily adsorbed onto the edges of clay or linked with the amount of organic matter present in the soil (Jin et al, 1987). After Rs-B, it is the second-highest fraction that is accessible for plant consumption (Jin et al., 1987, Tsadilas et al., 1994). In surface (0–20 cm), mid-surface (20–40 cm) and sub-soil (40-60 cm) soils of Illambazar lock the ranges of sad-B fractions were 0.45 to 0.67 mg kg^{-1}, 0.38 to 0.53 mg kg^{-1} and 0.23 to 0.37 mg kg^{-1},respectively with their corresponding averages of 0.58, 0.45 and 0.30 mg kg^{-1} respectively (Table 3, Figure 1). However, in soils of Bolpur block the average contents of this B fraction in surface, mid-surface, and sub-surface soil were 0.54, 0.39, and 0.25 mg kg^{-1}, respectively, which was fluctuatedbetween 0.38 to 0.64, 0.25 to 0.48 and 0.14 to 0.37 mg kg^{-1} (Table 4, Figure 1). On average, this pool constitutes 2%, 1.33%, and 0·80% of total soil boron at the surface, mid-surface and sub-surface soil respectively. Similar results related to the contributions of this fraction to total soil boron were reported by Xu et al. (2001) and Padbhushan and Kumar (2015). This fraction was decreased with increasing depth of soil which may be due to decreasing organic carbon content and amorphous Fe and Al content with depth (Sarkar et al., 2008).

The specifically adsorbed boron (Sad-B) showed a significant and positive correlation with clay content in both soils of Illambazar ($r=0.43^{*}$) and Bolpur ($r=0.49^{*}$). According to Xu et al. (2001), the clay concentration, which had an impact on the B sorption process, might dominate the fraction that was specifically adsorbed. This fraction most likely results from the weakly binding sites of both organic and inorganic components and none of these constituents contributed exclusively towards this boron fraction (Hou et al., 1994). The Sad-B fraction of surface soil of Illambazar block showed significant and positively correlated with

OC (r=51[**]) and CEC (r=0.56[**]). In sub-surface soil (40-60 cm) of Illambazar showed a significant positive correlation between Sad-B and amorphous Fe (0.40[*]).

3.2.3. Oxide bound boron (Ox-B)

The oxide-bound boron (Ox-B) is linked with the oxides and hydroxides of Fe and Al. This fraction becomes tightly bound B at mineral surfaces as well as B that has isomorphously replaced by Al or Fe within the octahedral sheet of the minerals (Hou et al., 1996, McLaren and Crawford, 1973, Tessier et al., 1979, Shuman, 1985). This fraction of B, being less labile, is inaccessible to plants (Jin et al., 1987). Sorption of B in soil has revealed the importance of Al and Fe oxide minerals (Harada and Tamai, 1968, Bingham et al., 1971, Elrashidi and O'Connor, 1982). This pool accounts for <4% of total boron (Tot-B) in both Illambazar and Bolpur soils. Hou et al. (1994) also reported similar kind of contribution of this fraction to total boron fraction.

In comparison to Bolpur soils, the oxide-bound boron

Table 3: Status of different fractions of boron in soils of Illambazar block of Birbhum district, West Bengal

S.L. No.	Rs-B ($mg\ kg^{-1}$) at depth (cm)			Sad-B ($mg\ kg^{-1}$) at depth (cm)			Oxd-B ($mg\ kg^{-1}$) at depth (cm)		
	0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60
S1	0.36	0.25	0.21	0.53	0.42	0.3	0.98	0.66	0.43
S2	0.25	0.19	0.18	0.55	0.4	0.28	1.05	0.52	0.35
S3	0.34	0.26	0.19	0.54	0.45	0.24	0.86	0.65	0.38
S4	0.35	0.25	0.2	0.62	0.48	0.37	0.92	0.79	0.56
S5	0.37	0.28	0.21	0.65	0.51	0.34	1.18	0.85	0.52
S6	0.36	0.22	0.16	0.52	0.38	0.27	0.97	0.52	0.36
S7	0.33	0.24	0.14	0.61	0.53	0.32	1.01	0.58	0.35
S8	0.31	0.26	0.2	0.58	0.45	0.26	0.96	0.69	0.44
S9	0.28	0.21	0.16	0.55	0.4	0.29	1.04	0.64	0.47
S10	0.38	0.26	0.18	0.56	0.47	0.31	1.18	0.72	0.49
S11	0.36	0.29	0.23	0.62	0.49	0.36	1.15	0.66	0.54
S12	0.31	0.27	0.21	0.58	0.42	0.37	0.84	0.66	0.43
S13	0.38	0.26	0.19	0.56	0.48	0.32	1.35	0.78	0.51
S14	0.34	0.22	0.14	0.6	0.47	0.27	1.02	0.73	0.45
S15	0.37	0.24	0.18	0.53	0.42	0.26	0.92	0.75	0.44
S16	0.36	0.21	0.17	0.67	0.45	0.24	1.19	0.78	0.42
S17	0.35	0.24	0.14	0.52	0.44	0.33	0.95	0.51	0.33
S18	0.38	0.27	0.25	0.48	0.38	0.31	1.03	0.58	0.38
S19	0.31	0.24	0.17	0.64	0.43	0.35	1.07	0.52	0.37
S20	0.41	0.29	0.23	0.59	0.41	0.36	1.19	0.72	0.56
S21	0.39	0.27	0.15	0.66	0.48	0.25	0.94	0.65	0.43
S22	0.35	0.28	0.22	0.58	0.47	0.24	1.05	0.71	0.48
S23	0.34	0.23	0.17	0.56	0.43	0.23	1.13	0.62	0.4
S24	0.43	0.28	0.24	0.65	0.49	0.37	0.98	0.75	0.56
S25	0.36	0.25	0.2	0.45	0.38	0.25	0.89	0.57	0.33
Range	0.25-0.43	0.19-0.29	0.14-0.25	0.45-0.67	0.38-0.53	0.23-0.37	0.84-1.35	0.51-0.85	0.33-0.56
Mean	0.35	0.25	0.19	0.58	0.45	0.30	1.03	0.66	0.44
SD	0.04	0.03	0.03	0.06	0.04	0.05	0.12	0.1	0.07

Table 3: Continue...

SL. No.	Org-B (mg kg^{-1}) at depth (cm)			Res-B (mg kg^{-1}) at depth (cm)			Tot-B (mg kg^{-1}) at depth (cm)		
	0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60
S1	0.66	0.45	0.36	19.32	23.11	24.66	21.85	24.89	25.96
S2	0.71	0.49	0.28	23.52	26.42	28.43	26.08	28.02	29.52
S3	0.78	0.58	0.31	31.44	32.68	34.89	33.96	34.62	36.02
S4	0.74	0.46	0.3	28.26	32.55	34.32	30.89	34.53	35.75
S5	0.78	0.54	0.42	27.95	30.2	32.64	30.93	32.38	34.14
S6	0.68	0.45	0.29	23.77	26.35	28.04	26.3	27.92	29.13
S7	0.67	0.43	0.31	28.45	31.18	34.82	31.07	32.96	35.94
S8	0.73	0.4	0.28	29.09	35.96	36.3	31.67	37.76	37.48
S9	0.74	0.52	0.38	25.15	33.85	35.45	27.76	35.62	36.75
S10	0.72	0.46	0.32	29.37	34.61	35.84	32.21	36.52	37.14
S11	0.89	0.52	0.33	28.05	32.38	34.33	31.07	34.34	35.79
S12	0.65	0.47	0.36	25.09	30.28	33.21	27.47	32.1	34.58
S13	0.87	0.51	0.44	25.2	31.44	33.99	28.36	33.47	35.46
S14	0.85	0.45	0.38	27.85	29.57	31.52	30.66	31.44	32.77
S15	0.8	0.43	0.33	25.32	27.08	29.16	27.94	28.92	30.37
S16	0.79	0.66	0.35	28.25	30.43	32.77	31.26	32.53	33.96
S17	0.78	0.42	0.26	27.23	29.22	31.88	29.83	30.83	32.94
S18	0.75	0.57	0.34	25.35	32.44	34.32	27.99	34.24	35.61
S19	0.77	0.41	0.28	26.81	30.13	33.17	29.6	31.73	34.34
S20	0.88	0.73	0.49	31.07	32.09	33.08	34.14	34.24	34.72
S21	0.81	0.61	0.36	29.62	31.41	32.97	32.42	33.42	34.17
S22	0.71	0.55	0.31	25.33	27.18	28.91	28.02	29.19	30.16
S23	0.75	0.51	0.33	26.68	33.09	34.56	29.46	34.88	35.7
S24	0.82	0.63	0.43	31.51	35.77	36.5	34.39	37.92	38.1
S25	0.7	0.49	0.26	27.45	33.19	35.33	29.85	34.88	36.37
Range	0.65-0.89	0.40-0.73	0.26-0.49	19.32-31.51	23.11-35.96	24.66-36.50	21.85-34.39	24.89-37.92	25.96-38.10
Mean	0.76	0.51	0.34	27.08	30.9	32.84	29.81	32.77	34.11
SD	0.07	0.08	0.06	2.75	3.1	2.94	2.84	3.16	2.98

SL. No.: Sampling Location Number; Rs-B: Readily soluble boron; Sad-B: specifically adsorbed boron; Ox-B: Oxide bound boron; Org-B: Organically bound boron, Res-B: Residual boron; Tot-B: Total boron

contents in Illambazar soils were higher. The values of Ox-B fraction in the surface soils of Illambazar was varied between 0.84 and 1.35 mg kg^{-1} (mean 1.03±0.12 mg kg^{-1}); in mid-surface soil its content was varied between 0.51 and 0.85 mg kg^{-1} (mean 0.66±0.10 mg kg^{-1}) and in sub-surface soil or in lower depth (40–60 cm) it's range was 0.33 to 0.56 mg kg^{-1} (mean 0.44±0.07 mg kg^{-1}) (Table 3, Figure 1). However, the surface soil of Bolpur block had 0.93±0.25 mg kg^{-1} as its mean with minimum and maximum value of 0.61 and 1.44 mg kg^{-1}respectively (Table 4, Figure 1). Soils of both the Bolpur and Illambazar blocks showed a decreasing trend of its content with regards to soil depth. Significant positive relationship was observed between of oxide bound boron (Ox-B) fraction with clay (r=0.45*) and CEC (r= 0.66**) in sub-surface soils (40–60 cm) of Illambazar block. However, in surface soil of Bolpur block, Ox-B showed significant and positive correlations with OC (r=0.44*), CEC (r=0.41*) and amorphous Fe (r=0.40*). Similarly, a significant relationship of Ox-B with amorphous-Fe, and amorphous-Al were recorded in lower depths too. Our findings are similarly consistent with those of Colak et al. (2013).

3.2.4. Organically bound boron (Org-B)

The organically bound boron (Org-B) fractions in soils of both Illambazar and Bolpur blocks were decreased across the soil depth. In Illambazar soil, Org-B content was varied from 0.65-0.89, 0.40-0.73, and 0.26-0.49 mg kg^{-1} with 0.76, 0.51 and 0.34 mg kg^{-1} as their corresponding means in surface, mid-surface, and subsurface soils, respectively (Table 3, Figure 1). However, in Bolpur soil its content was varied from 0.39-0.95, 0.22-0.67, and 0.13-0.54 mg kg^{-1} with 0.76, 0.51 and 0.34 mg kg^{-1} 0.70, 0.47, 0.33 mg kg^{-1} as their corresponding means in surface, mid-surface, and subsurface soils, respectively (Table 4, Figure 1).

In all the soil depths the Org-B fraction showed a significant positive correlation with organic carbon content of both Illambazar and Bolpur soil. The Org-B also showed a positive correlation with CEC in the soils of both the Illambazar and Bolpur blocks. Datta et al. (2002) reported similar findings corroborating the above relationship. The vital association found between the organically bound B fraction and organic matter content suggested that organic matter was crucial in B adsorption and release in soils (Ranjbar and Jalali, 2013) and the organic carbon content greatly influences this fraction in soil (Karthikeyan and Sukla, 2011).

Table 4: Status of different fractions of boron in soils of Bolpur block of Birbhum district, West Bengal

SL. No.	Rs-B (mg kg^{-1}) at depth (cm)			Sad-B (mg kg^{-1}) at depth (cm)			Oxd-B (mg kg^{-1}) at depth (cm)		
	0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60
S1	0.22	0.17	0.13	0.43	0.32	0.21	0.61	0.42	0.32
S2	0.32	0.26	0.12	0.6	0.48	0.26	1.04	0.74	0.45
S3	0.36	0.21	0.14	0.58	0.39	0.25	1.08	0.88	0.58
S4	0.27	0.2	0.15	0.61	0.41	0.34	0.72	0.55	0.47
S5	0.29	0.21	0.16	0.62	0.39	0.25	0.68	0.48	0.29
S6	0.33	0.23	0.14	0.61	0.45	0.22	0.86	0.58	0.31
S7	0.26	0.21	0.17	0.52	0.39	0.23	0.77	0.45	0.34
S8	0.3	0.22	0.11	0.45	0.4	0.24	0.96	0.68	0.48
S9	0.32	0.18	0.13	0.64	0.36	0.27	1.43	0.85	0.65
S10	0.37	0.28	0.15	0.51	0.46	0.25	0.91	0.77	0.59
S11	0.28	0.2	0.16	0.43	0.36	0.21	0.82	0.48	0.36
S12	0.33	0.19	0.12	0.45	0.33	0.22	0.76	0.59	0.37
S13	0.29	0.24	0.18	0.59	0.42	0.27	0.62	0.61	0.48
S14	0.34	0.22	0.13	0.53	0.4	0.22	1.24	0.58	0.39
S15	0.35	0.25	0.11	0.45	0.35	0.19	1.14	0.81	0.53
S16	0.32	0.23	0.17	0.58	0.41	0.21	0.88	0.61	0.5
S17	0.29	0.23	0.11	0.55	0.41	0.26	1.34	0.92	0.45
S18	0.24	0.18	0.1	0.57	0.36	0.14	0.84	0.68	0.34
S19	0.25	0.2	0.16	0.58	0.35	0.28	0.62	0.32	0.23
S20	0.37	0.29	0.14	0.63	0.47	0.33	1.44	0.96	0.5
S21	0.35	0.27	0.17	0.38	0.25	0.16	0.74	0.58	0.44
S22	0.25	0.19	0.12	0.43	0.32	0.21	0.88	0.47	0.33
S23	0.32	0.28	0.15	0.64	0.46	0.28	0.66	0.42	0.35
S24	0.26	0.23	0.17	0.55	0.44	0.35	1.07	0.79	0.52
S25	0.38	0.29	0.18	0.61	0.48	0.37	1.16	0.84	0.58
Range	0.22-0.38	0.17-0.29	0.10-0.18	0.38-0.64	0.25-0.48	0.14-0.37	0.61-1.44	0.32-0.96	0.23-0.65
Mean	0.3	0.24	0.14	0.54	0.39	0.25	0.93	0.64	0.43
SD	0.04	0.04	0.02	0.08	0.06	0.06	0.25	0.18	0.11

Table 4: Continue...

SL. No.	Org-B (mg kg^{-1}) at depth (cm)			Res-B (mg kg^{-1}) at depth (cm)			Tot-B (mg kg^{-1}) at depth (cm)		
	0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60
S1	0.6	0.35	0.22	16.1	19.71	22.13	17.96	20.97	23.01
S2	0.79	0.58	0.36	20.25	23.92	25.33	23	25.98	26.52
S3	0.69	0.55	0.36	28.35	30.12	34.75	31.06	32.15	36.08
S4	0.77	0.48	0.34	25.25	26.56	30.08	27.62	28.2	31.38
S5	0.48	0.27	0.16	18.32	22.1	24.15	20.39	23.45	25.01
S6	0.79	0.42	0.34	16.28	19.4	23.01	18.87	21.08	24.02
S7	0.66	0.55	0.38	25.11	27.08	29.94	27.32	28.68	31.06
S8	0.71	0.47	0.31	24.39	27.06	28.32	26.81	28.83	29.46
S9	0.86	0.62	0.34	23.72	25.39	27.25	26.97	27.4	28.64
S10	0.64	0.48	0.32	28.17	31.84	32.36	30.6	33.83	33.67
S11	0.72	0.4	0.33	22.46	25.13	28.29	24.71	26.57	29.35
S12	0.78	0.54	0.3	27.54	30.21	34.37	29.86	31.86	35.38
S13	0.61	0.37	0.28	20.16	22.83	25.19	22.27	24.47	26.4
S14	0.45	0.22	0.13	27.45	30.12	32.38	30.01	31.54	33.25
S15	0.67	0.57	0.36	24.03	26.7	28.86	26.64	28.68	30.05
S16	0.8	0.44	0.37	22.73	25.85	28.56	25.31	27.54	29.81
S17	0.9	0.67	0.38	22.05	23.12	26.49	25.13	25.35	27.69
S18	0.39	0.42	0.33	24.44	27.65	30.07	26.47	29.29	30.98
S19	0.65	0.46	0.32	23.11	25.78	26.04	25.21	27.11	27.03
S20	0.81	0.58	0.37	28.17	31.19	33.62	31.42	33.49	34.96
S21	0.67	0.44	0.35	20.14	22.01	25.4	22.28	23.55	26.52
S22	0.6	0.37	0.25	20.08	21.68	23.39	22.24	23.03	24.3
S23	0.66	0.43	0.37	27.18	28.85	32.03	29.46	30.44	33.18
S24	0.95	0.57	0.35	28.1	30.12	33.19	30.93	32.15	34.58
S25	0.8	0.62	0.54	29.29	33.56	35.42	32.24	35.79	37.09
Range	0.39-0.95	0.22-0.67	0.13-0.54	16.10-29.29	19.40-33.56	22.13-35.42	17.96-32.24	20.97-35.79	23.01-37.09
Mean	0.7	0.47	0.33	23.71	26.32	28.82	26.19	28.06	29.98
SD	0.13	0.11	0.08	3.85	3.85	3.95	4.03	4.01	4.06

3.2.5. Residual boron (Res-B)

Boron held within primary (tourmaline) and secondary (colemanite) minerals is described as residual boron (Res-B). Residual boron is generally associated with silicates (Jin et al., 1987) and it accounts for the major portion of total soil boron.

In contrast to other fractions, the residual fraction increased with depth, with higher values obtained in lower depths than in surface soils. The increasing trend of Res-B with depth accounted for the increase in total B recoveries with increasing depth of sampling. In the surface soils of Illambazar block, it varied from 19.32 to 31.51 mg kg^{-1} as compared to range of 16.10 to 29.29 mg kg^{-1} in the soils of Bolpur block (Table 3, 4). The average values of Res-B content in surface, mid-surface, and subsurface soils were 27.08, 30.90, 32.84 mg kg^{-1} for Illambazar soil and 23.71, 26.32 and 28.82 mg kg^{-1} for Bolpur soil (Figure 2). The highest values of Res-B were obtained 32.84±2.94 mg kg^{-1} in soils of the Illambazar block.

In both soils under study, the residual boron (Res-B) content was significantly and positively correlated with clay, CEC, amorphous Fe, and amorphous Al content in surface soil. Similar findings have also been reported by Datta et al. (2002), who observed that residual boron was significantly

Table 5: Relationship between fractions of boron with soil properties of Illambazar

Boron Fractions	Soil properties (0–20 cm)						Soil properties (20–40 cm)					
	pH	Clay	OC	CEC	Am-Fe	Am-Al	pH	Clay	OC	CEC	Am-Fe	Am-Al
Rs-B	0.08	0.11	0.52**	0.47*	0.14	0.23	0.01	0.42*	0.24	0.40*	0.22	0.09
Sad-B	0.01	0.43*	0.51**	0.56**	0.37	0.33	0.11	0.26	0.08	0.37	0.27	0.19
Ox-B	-0.02	0.19	0.28	0.26	0.02	0.36	-0.14	0.28	0.39	0.38	0.16	0.25
Org-B	0.03	0.22	0.55**	0.53**	0.09	0.12	-0.33	0.27	0.58**	0.37	0.17	0.32
Res-B	0.14	0.43**	0.29	0.66**	0.42*	0.23	0.09	0.37	0.11	0.46*	0.20	0.07
Tot-B	0.14	0.44*	0.32	0.68**	0.42*	0.26	0.07	0.38	0.14	0.48*	0.21	0.09

Table 5: Continue...

Boron Fractions	Soil properties (40–60 cm)					
	pH	Clay	OC	CEC	Am-Fe	Am-Al
Rs-B	0.08	0.23	0.14	0.24	-0.08	0.29
Sad-B	0.16	0.37	0.15	0.42*	0.40*	0.30
Ox-B	-0.01	0.45*	0.35	0.66**	0.12	0.29
Org-B	-0.28	0.21	0.63**	0.42*	0.09	0.07
Res-B	0.05	0.28	0.07	0.35	0.06	0.11
Tot-B	0.04	0.30	0.09	0.38	0.07	0.12

Rs-B: Readily soluble boron; Sad-B: specifically adsorbed boron; Ox-B: Oxide bound boron; Org-B: Organically bound boron, Res-B: Residual boron; Tot-B: Total boron

Table 6: Relationship between fractions of boron with soil properties of Bolpur

Boron fractions	Soil properties (0–20 cm)						Soil properties (20–40 cm)					
	pH	Clay	OC	CEC	Am-Fe	Am-Al	pH	Clay	OC	CEC	Am-Fe	Am-Al
Rs-B	0.07	0.25	0.52*	0.49*	0.33	0.31	0.12	0.37	0.46*	0.38	0.35	0.21
Sad-B	0.06	0.49*	0.06	0.39	0.13	0.19	0.06	0.45*	0.44*	0.45*	0.24	0.14
Ox-B	-0.19	0.30	0.44*	0.41*	0.40*	0.13	-0.03	0.36	0.47*	0.50*	0.59**	0.19
Org-B	-0.65**	0.37	0.76**	0.39	0.28	0.02	-0.20	0.49*	0.56**	0.55*	0.50*	0.12
Res-B	0.11	0.56**	0.35	0.52**	0.51**	0.44*	0.13	0.49*	0.18	0.45*	0.44*	0.42*
Tot-B	0.08	0.58**	0.40*	0.55**	0.53**	0.43*	0.12	0.51**	0.22	0.48*	0.49*	0.42*

Table 6: Continue...

Boron fractions	Soil properties (40–60 cm)					
	pH	Clay	OC	CEC	Am-Fe	Am-Al
Rs-B	0.45*	0.13	0.22	0.02	0.09	0.23
Sad-B	0.12	0.61**	0.21	0.56**	0.16	0.35
Ox-B	-0.08	0.38	0.06	0.60**	0.35	0.28
Org-B	-0.06	0.61**	0.47*	0.49*	0.57**	0.24
Res-B	0.54**	0.17	0.11	0.38	0.46*	0.58**
Tot-B	0.16	0.58**	0.13	0.40*	0.47*	0.58**

Rs-B: Readily soluble boron; Sad-B: specifically adsorbed boron; Ox-B: Oxide bound boron; Org-B: Organically bound boron, Res-B: Residual boron; Tot-B: Total boron

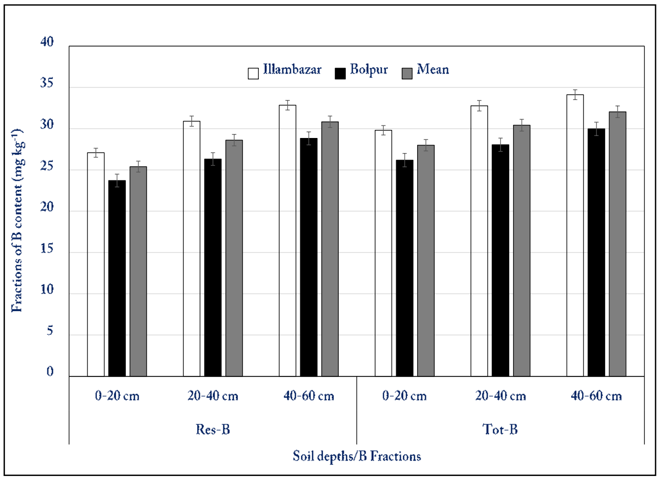

Figure 2: Depth-wise distribution of fractions of Res-B and Tot-B fraction of boron in the study area (Res-B: Residual boron; Tot-B: Total boron)

and positively correlated with clay, Al, Fe, and Al + Fe, which demonstrate that confirms that clay and sesquioxides are structurally formed by residual B. The increased content of residual B with increased depth accounted for the increase in total boron recoveries with increasing depth of soil sampling.

3.2.6. Total boron (Tot-B)

The total boron (Tot-B) content of the soil was calculated by adding all fractions; from readily soluble boron (Rs-B) to residual boron (Res-B). Similar to the residual B fraction, Tot-B fraction increased across the depth. The average values of Tot-B of Illambazar soil were 29.81, 32.77 and 34.11 mg kg^{-1} at the surface, mid-surface, and sub-surface soil respectively, whereas their values of Bolpur soil were 26.19, 28.06 and 29.98 mg kg^{-1} respectively (Table 3, 4, Figure 2). The correlation analysis between Tot-B and physico-chemical soil properties revealed that Tot-B positively and significantly correlated with clay content, CEC, amorphous-Fe, amorphous-Al content of the soil.

From the fractionation study, it was found that, the contribution of different B fractions towards Tot-B followed the order of Residual boron (Res-B)>>Oxide bound boron (Oxd-B)>Organically bound boron (Org-B)> Specifically adsorbed boron (Sad-B)>Readily soluble boron (Rs-B). This order of the contribution of the different fractions towards total B content in soil corresponds to the observation of Diana and Beni (2006).

3.3. Inter-relationships between different boron fractions

To understand the inter-relationships between different fractions, simple correlations were computed among the fractions revealing that almost B fractions in all the soils under study, irrespective of depth, showed a positive and significant correlation (Table 7, 8). Surface soils of Illambazar showed that Ws-B correlated significantly and

Table 7: Inter-relationship among the fractions of boron of Illambazar soil

B fractions	Rs-B	Sad-B	Ox-B	Org-B	Res-B	Tot-B
0–20 cm						
Rs-B	1.00					
Sad-B	0.14	1.00				
Ox-B	0.21	0.29	1.00			
Org-B	0.45*	0.36	0.48*	1.00		
Res-B	0.38	0.44*	0.03	0.49*	1.00	
Tot-B	0.41*	0.47*	0.09	0.53**	0.99**	1.00
20–40 cm						
Rs-B	1.00					
Sad-B	0.36	1.00				
Ox-B	0.37	0.52**	1.00			
Org-B	0.34	0.03	0.34	1.00		
Res-B	0.32	0.23	0.21	0.24	1.00	
Tot-B	0.34	0.26	0.25	0.28	0.99**	1.00
40–60 cm						
Rs-B	1.00					
Sad-B	0.37	1.00				
Ox-B	0.50*	0.48**	1.00			
Org-B	0.33	0.34	0.68**	1.00		
Res-B	0.10	0.21	0.22	0.10	1.00	
Tot-B	0.13	0.24	0.26	0.14	0.99**	1.00

Rs-B: Readily soluble boron; Sad-B: specifically adsorbed boron; Ox-B: Oxide bound boron; Org-B: Organically bound boron, Res-B: Residual boron; Tot-B: Total boron

Table 8: Inter-relationship among the fractions of boron of Bolpur soil

B fractions	Rs-B	Sad-B	Ox-B	Org-B	Res-B	Tot-B
0–20 cm						
Rs-B	1.00					
Sad-B	0.17	1.00				
Ox-B	0.49*	0.23	1.00			
Org-B	0.23	0.18	0.43*	1.00		
Res-B	0.44*	0.19	0.40*	0.18	1.00	
Tot-B	0.48*	0.23	0.47*	0.24	0.99**	1.00
20–40 cm						
Rs-B	1.00					
Sad-B	0.57**	1.00				
Ox-B	0.39	0.39	1.00			
Org-B	0.28	0.27	0.67**	1.00		

Table 8: Continue...

B fractions	Rs-B	Sad-B	Ox-B	Org-B	Res-B	Tot-B
Res-B	0.38	0.42*	0.43*	0.35	1.00	
Tot-B	0.41*	0.45*	0.48*	0.40*	0.99**	1.00
40-60 cm						
Rs-B	1.00					
Sad-B	0.41*	1.00				
Ox-B	0.06	0.36	1.00			
Org-B	0.22	0.38	0.45*	1.00		
Res-B	0.11	0.41*	0.46*	0.39	1.00	
Tot-B	0.11	0.42*	0.49*	0.42*	0.99**	1.00

Rs-B: Readily soluble boron; Sad-B: specifically adsorbed boron; Ox-B: Oxide bound boron; Org-B: Organically bound boron, Res-B: Residual boron; Tot-B: Total boron

positively with the organic fraction (Org-B) (r=0.45*), and there is a positive and significant correlation between Org-B and Oxd-B (r= 0.48*). The Res-B was significantly (p<0.01) and positively correlated with total boron (r = 0.99**). This relationship is explainable, for residual B is the major contributor to total B (Datta et al., 2002). Total B also correlated significantly and positively with Rs-B (r=0.41*) and Sad-B (r=0.47*).

In surface soils of the Bolpur block, Rs-B showed a significant and positivecorrelation with Oxd-B (r=0.49*), Res-B (r=0.44*), and Tot-B (r=0.48*). Similarly, Oxd-B exhibiteda significant and positive correlation with Org-B (r=0.43*), Res-B (r=0.40*), and Tot-B (r=0.47*). The highly positive and significant correlation between Res-B and Tot-B was also observed in the surface soils of Bolpur block (r=0.99**). These findings are in good agreement with the observations of Gupta et al. (1985), Datta et al. (2002), Sarkar et al. (2008).

4. CONCLUSION

The vertical distribution of boron fractions was mainly affected pH, clay content, organic matter, CEC, amorphous Fe and amorphous Al contents of soil. The residual boron (Res-B) contributed the highest towards total soil B (Tot-B) followed by oxide-bound boron (Oxd-B)> organically bound boron (Org-B)>specifically adsorbed boron (Sad-B)>readily soluble boron (Rs-B). Almost all the B fractions showed a significant positive correlation among themselves. The findings will be useful for fertilizer recommendations of B-deficient lateritic soils (Alfisols).

5. FURTHER RESEARCH

Further studies are required to investigate the release kinetics of different fractions of boron in lateritic soil.

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