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Trends in key soil parameters under conservation agriculture-based sustainable intensification farming practices in the Eastern Ganga Alluvial Plains

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Abstract. Key soil parameters, organic matter, soil pH and plant nutrients determine the capacity of a soil to sustain plant and animal productivity. Conservation agriculture (CA) and crop diversification or intensification may change these soil parameters positively or negatively, which eventually affect long-term sustainability. We monitored these key soil properties (at depths of 0–15 and 15–30 cm) under CA-based sustainable intensification practices: zero-till (ZT), and crop residue retention, and crop rotations on Inceptisols and Entisols in the Eastern Ganga Alluvial Plains from 2014 to 2017. The rainfall of this sub-tropical region is 1273–3201 mm. Soil organic carbon (C) ranged within 0.46–1.13% and generally followed (positive) rainfall gradients. At all sites, the soil under ZT tended to have higher organic C than conventional tillage (CT). Soil pH_{H2O} ranged within 5.7–7.8 across the region. At all sites, soil pH generally decreased under ZT compared to CT. This was most marked at some acidic soil sites where pH decreased by up to 0.4 units; the lower the initial soil pH, the higher was the decrease in pH under ZT practice. In contrast, the reverse trend was observed for soil organic C. Partial nutrient balances for N, P and K in rice–wheat and rice–maize systems were positive for N and P (<50 kg ha^{-1}) but negative for K (up to 90 kg ha^{-1}) under both tillage practices; more so under ZT practice even though crop residues were retained. Changes under ZT provide an opportunity to maintain soil organic C. However, remediation measures such as liming and efficient use of fertilisers are required for long-term sustainability of the farming systems in this agriculturally important region of South Asia.

Additional keywords: cropping systems, maize, partial nutrient balance, rice, soil organic C, soil pH, South Asia, wheat.

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Introduction

Conservation agriculture (CA) and crop diversification or intensification are the major components of the emerging farming systems for ensuring food security in South Asia (Jat *et al*. 2014; Islam *et al*. 2019). These practices include minimum or zero-till (ZT), crop residue retention on the soil surface, crop rotations and crop intensification to optimise resource and energy use, and sustain or enhance food production. This is of utmost importance in the eastern part of South Asia, the Eastern Ganga (Gangetic) Alluvial Plains, where the population is large (over 400 million) and mostly agrarian with small landholdings (≤1 ha per household), and chronic rural poverty is widespread (Ericksen *et al*. 2011).

A CA-based sustainable intensification (CASI) program, initiated in 2014–15 in the Eastern Ganga Alluvial Plains in two districts each of Nepal, Bangladesh and Bihar and West

Bengal in India. Islam *et al*. (2019) evaluated the performance of two major farming systems, rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) and rice–maize (*Zea mays* L.), in terms of crop yields and water use for two crop rotation cycles in the eight districts of the Eastern Ganga Alluvial Plains. The crops were grown either using traditional conventional tillage (CT) or a variation of CASI practices. The CT practice consists of 4–5 ploughings to <15 cm depth for land preparation in both puddled transplanted rice (PTR) and in the following CT wheat or CT maize. Of the three CA-based practices, one partial CASI practice combined PTR–ZT wheat or PTR–ZT maize. Two full CASI practices examined unpuddled transplanted rice (UPTR)–ZT wheat or ZT maize, and direct-seeded rice (DSR)–ZT wheat or ZT maize (Islam *et. al.* 2019). They reported that although the CASI practices did not significantly affect rice yields, both wheat and maize yields increased by ~5% using these practices compared to CT farming practice. In general, these findings confirm those of others in this region (Jat *et al*. 2014; Gathala *et al*. 2015) and elsewhere (Aryal *et al*. 2016) in South Asia. However, Islam *et al*. (2019) found large variability in crop yields among the eight districts and suggested that this could be due to differences in land and soil types, and soil properties. They suggested that monitoring soil properties and nutrient status is the key to relating variation in crop yields in the Eastern Ganga Alluvial Plains. Moreover, soil properties such as pH, organic matter and nutrient status may change following CASI practices, as observed elsewhere (Dalal *et al*. 2011; Choudhary *et al*. 2018).

Key soil parameters, soil organic matter, pH and plant nutrients reflect both inherent and dynamic soil properties, and are governed by physical, chemical and biological processes in soil (Karlen *et al*. 2003); these parameters are differently affected by CASI practices as by CT practices (Choudhary *et al*. 2018). Soil organic matter affects soil physical properties such as soil aggregation, chemical properties such as nutrient sinks and sources and their transformations, and biological properties such as microbial activity (energy and nutrient supply and physical habitat) for nutrient cycling (Gathala *et al*. 2017). Soil pH is the single most dominant factor, which affects a range of chemical and biological processes and soil functions (Karlen *et al*. 2003). These include acidification, nutrient cycling and availability, element toxicity and biological activity, and hence plant growth (Vargas Gil *et al*. 2009) and crop yield. Further, plant available N, P and K are major nutrients that affect crop productivity and the long-term sustainability of a farming system (Wanjari *et al*. 2004), especially with crop intensification using CASI practices, resulting in increased yields (Islam *et al*. 2019) and, therefore, increased nutrient removal (Roy *et al*. 2003).

Tillage, crop residue retention and fertilisation mainly affect soil organic matter (C and N) by manipulating the organic matter input, quality and placement, as well as decomposition, resulting in higher amounts of organic matter in soil under ZT, residue retention and fertilisation compared to the CT practice (Alvarez 2005; Dalal *et al*. 2011; Somasundaram *et al*. 2017). Crop intensification, which increases crop residue input, may further enhance soil organic matter in CASI farming systems. Limited data suggest that any change in soil organic matter is dependent on the farming system. For example, a rice–wheat rotation had much less effect on soil organic C than a wheat–maize system in slightly alkaline soils (Choudhary *et al*. 2018); although less is known about the effect of these farming systems on acidic soils in the Eastern Ganga Alluvial Plains. Increase in soil organic C under CASI practice also affects soil pH. For example, Dalal (1989) reported a negative relationship between soil organic C and pH in the top 10 cm of soil depth after 13 years of ZT residue retention in a N-fertilised wheat experiment on a Vertisol; that is, as organic C increased in soil under the ZT practice, soil pH decreased. The effect of ZT on soil pH on other soils and cropping systems is inconsistent because long-term N fertilisation usually has a much greater effect on reducing soil pH than ZT practice, especially in the top 10 cm in a clayey Vertisol (Dalal *et al*. 1991). However, in a coarse-textured (sandy and sandy loam) soil with low buffer capacity, especially in a high-rainfall environment, ZT practice may adversely affect soil pH, especially in already acidic soils in the Eastern Ganga Alluvial Plains, as found elsewhere (Guo *et al*. 2010).

Crop diversification or intensification under CASI practices increases crop yields and farming system productivity (Islam *et al*. 2019) and is likely to increase N, P and K uptake from soil and removal in the grain produced, resulting in nutrient depletion in soil (Wanjari *et al*. 2004; Surekha and Satishkumar 2014). Nutrients can be replaced by balanced fertiliser application (Jahan *et al*. 2016); however, typical fertiliser regimes represent incomplete replacement (e.g. N and P only). However, excess application of a nutrient may lead to accumulation in, or loss from, soil resulting in economic loss as well as adverse environmental impacts. For sustainable intensification of farming systems, besides monitoring trends in soil pH and organic C, information is required on the nutrient balance so that appropriate remedial action can be taken to reduce crop yield losses as well as adverse impacts on soil health and the environment. Therefore, we monitored soil properties such as pH, organic matter and plant nutrients in response to introduction of CASI practices – ZT, crop residue retention and intensified crop rotations – compared to a CT practice on Inceptisols and Entisols between 2014–15 and 2016–17, as a component of a sustainable and resilient farming systems intensification research program (Islam *et al*. 2019). The objectives of this study were to monitor (i) soil organic matter and soil pH, (ii) available P and K and (iii) partial N, P and K balance, following the introduction of CASI practices, including crop diversification or intensification compared to a CT practice in eight selected districts of the Eastern Ganga Alluvial Plains.

Materials and methods

Climate and site description

Eight districts in the Eastern Ganga Alluvial Plains were selected for this study. The study sites included two districts each in Nepal (Dhanusha and Sunsari), Bihar (Madhubani and Purnea) and West Bengal (Coochbehar and Malda) in India, and Bangladesh (Rangpur and Rajshahi). All sites had a slope of <3% (Fig. 1). The climate of the region varies from subhumid in the western portion (Dhanusha and Madhubani) to per-humid in the eastern portion (Coochbehar and Rangpur) of the study area

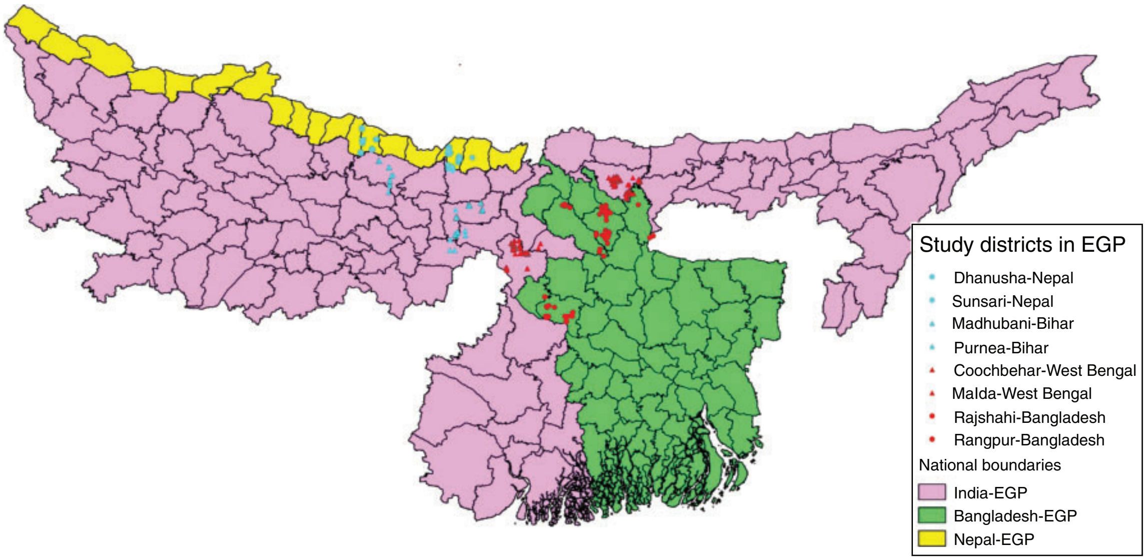

Fig. 1. The Eastern Ganga Alluvial Plains (EGP) study area showing the field trial sites (*) in Bangladesh-EGP, India-EGP and Nepal-EGP.

Table 1. Mean annual temperatures and rainfall in eight districts of Eastern Ganga Alluvial Plains

District (country)	Mean annual temperature (°C)	Mean annual rainfall (mm)
Rangpur (Bangladesh)	24.9	2192
Madhubani (Bihar, India)	24.7	1273
Coochbehar (West Bengal, India)	25.4	3201
Dhanusha (Janakpur) (Nepal)	24.3	1552
Sunsari (Itahari) (Nepal)	24.4	2007
Purnea (Bihar, India)	24.8	1427
Malda (India)	25.4	1750
Rajshahi (Bangladesh)	25.8	1448

Table 2. Tillage practice, cropping systems and fertiliser rates used in eight districts of Eastern Ganga Alluvial Plains

See Islam *et al*. (2019) for details about different fertiliser rates in some districts

Tillage system	Cropping system	Fertiliser rate (N : P : K, kg ha^{-1})
1. Puddled rice (PTR)–conventional till (CT) maize or wheat	a. PTR–CT maize b. PTR–CT wheat	Rice 150 : 30 : 85 Wheat 145 : 45 : 50 Maize 250 : 50 : 150
2. PTR–zero till (ZT) maize or wheat	a. PTR–ZT maize b. PTR–ZT wheat	
3. Unpuddled rice (UPTR)–ZT maize or wheat	a. UPTR–ZT maize b. UPTR–ZT wheat	
4. Direct-seeded rice (DSR)–ZT maize or wheat	a. DSR–ZT maize b. DSR–ZT wheat	

(Table 1). Mean annual temperature varies from 24.3°C in the north-west (Dhanusha) to 25.8°C in the south-east (Rajshahi); there is a temperature variation of only 1.5°C in the whole region (Table 1). However, mean annual rainfall varies from <1300 mm in the west (Madhubani) to >3000 mm in the north-east (Coochbehar) (Table 1).

From each district, five clusters of villages were selected for this study and at each village, trials at two farmers' fields were established in 2014–15, thereby up to 10 farmers participated in field trials in each district. Each trial contained treatments evaluating three rice crop establishment practices (PTR (top 15–20 cm depth), UPTR and DSR) during the monsoon season, and two tillage practices (CT and ZT) for two crops (wheat and maize) in the dry season: (1a) PTR–CT maize and (1b) PTR–CT wheat; (2a) PTR–ZT maize and (2b) PTR–ZT wheat; (3a) UPTR–ZT maize and (3b) UPTR–ZT wheat; and (4a) DSR–ZT maize and (4b) DSR–ZT wheat (Table 2). In Coochbehar and Malda districts, wheat was replaced by lentil (*Lens culinaris* L.) at some nodes (Islam *et al*. 2019). However, these few trials were not considered in this rice–maize and rice–wheat farming systems study. The rice crop received up to 150 kg N ha^{-1}, 30 kg P ha^{-1} and 85 kg K ha^{-1}; and correspondingly wheat received up to 145, 45 and 50, and maize up to 250, 50 and 150 (Table 2). A detailed description of the agronomic practices for each experimental treatment is given in Islam *et al*. (2019).

Crop yields for two full years (four crops) of the field trials between 2014 and 2017 seasons were collated in a final research synthesis report (Gathala 2018), and summarised in Islam *et al*. (2019).

Soil and plant sampling and analysis

Soil samples were collected from the field trials in the 2014–15 and 2016–17 seasons from rice–wheat and rice–maize farming systems from both CT and CASI treatments, as described by Gaydon and Dalal (2015). Briefly, four to five representative soil samples were randomly taken from each field (field size

< 0.25 ha, typically ~0.1 ha) at 0–15 and 15–30 cm depths and composited for each depth. In the 2016–17 season, additional soil samples were taken at 0–5 and 5–10 cm depths at two district nodes: Coochbehar and Malda. The soil samples were gently broken up, visible plant materials removed and the soil dried at room temperature (20–30°C) for 3–5 days. The air-dried samples were ground to pass a 2-mm sieve for soil pH, and available P and K measurements, and further ground to <0.1 mm for soil organic C and total N measurements.

Soil $\mathrm{pH}_{(1:2.5)}$ was measured in a soil suspension obtained by shaking 20 g of air-dried soil sample and 50 mL of deionised water in a 100-mL bottle for 1 h (Jackson 1962). Available P was determined as Bray–Kurtz P1 (0.03 M NH_4F in 0.025 M HCl) in soils with pH < 7 (Bray and Kurtz 1945). For soils with pH > 7, available P was determined in an extraction solution of 0.5 M $NaHCO_3$ adjusted to pH 8.5 (Olsen *et al*. 1954). For the district comparison, available P values measured using the Bray and Kurtz (1945) procedure were converted into equivalent available P measured by the Olsen *et al*. (1954) procedure using the relationship of Kurtz–Bray P1 = 1.27 × Olsen P + 11.68, $R^2 = 0.895$, reported by Sarker *et al*. (2014) for this region. Available K was determined in the soil extracted in 1 M NH_4Cl solution at pH 7 (Knudsen *et al*. 1982). Hot-water soluble C was determined by the procedure of Sparling *et al*. (1998). The organic C of the soil samples was determined by the chromic acid digestion procedure of Walkley and Black (1934) and total N was determined following the Kjeldahl digestion procedure (Bremner and Mulvaney 1982). All values were reported as mean ± standard error of the mean (s.e.m.). Since bulk density values at 0–15 cm depth, measured using 5-cm steel rings, were similar under tillage as well as in different rotations ($1.36 \pm 0.03\ \mathrm{Mg\ m^{-3}}$), the results can be considered to be reported on an equivalent soil mass basis.

For plant N, P and K analysis, grain and straw samples were collected at the crop harvest for the Coochbehar and Malda nodes only; grain and straw yields were recorded for all districts. The samples were dried at 65°C for at least 48 h, and ground to <1 mm. The ground plant samples were analysed for N in Kjeldahl digest, and P and K in acid digest (Jones and Case 1990). Total N, P and K taken up by the grain (grain yield × nutrient concentration) and straw (straw yield × nutrient concentration) were calculated. Following the procedure of Roy *et al*. (2003), the partial nutrient balance was calculated as the difference between the amount of nutrient added in fertiliser and that removed from the field in the grain as well as the straw unless it was retained or returned to the field, for example in the ZT treatment. The partial nutrient balances were not calculated in all districts due to lack of data on grain N, P and K concentrations.

Statistical analysis

Paired *t*-test was used to determine significant differences in mean values of the attributes between tillage (CT vs ZT) and farming systems (rice–wheat vs rice–maize) with two degrees of freedom. The treatment significant differences were compared with the least significant difference, usually at $P < 0.01$ and $P < 0.05$.

Results

Initial soil properties in 2014–15

Soil pH

Soil pH (0–15 cm depth) ranged within 4.7–8.6 for all districts, and the mean values varied from 5.7 in the Rangpur and Coochbehar to 7.8 at Rajshahi (Table 3). In general, the Rangpur, Madhubani and Coochbehar soils were acidic (pH < 6) and Malda and Rajshahi soils were alkaline (pH > 7). At Madhubani, 87% of the sites had pH < 5.5, classifying these sites as very acidic (Tandon 2005), whereas Rangpur had 10% and Coochbehar 18% of sites in this category. At Rajshahi, Malda and Purnea, >70% of sites were neutral or slightly alkaline (pH 6.5–7.5); only 5% of sites were alkaline (pH > 8.5), and these sites were limited to Purnea.

Soil organic C and total N

Soil organic C (0–15 cm depth) varied substantially in Dhanusha (0.2–2.21%) and Malda (0.4–1.8%). Sunsari had the highest mean soil organic C values (1.09%) and Purnea the lowest (0.46%) (Table 3). Purnea also had highest proportion of sites (36%) with low levels of soil organic C (<0.5%) (Tandon 2005), followed by Dhanusha, with 26% low in organic C. However, >70% of sites in Rangpur, Coochbehar, Malda and Sunsari contained >0.75% organic C, which is considered in the high range for this region (Tandon 2005).

Similar to soil organic C, total N (0–15 cm depth) varied most in Dhanusha (0.02–0.19%) and least in Purnea (0.03–0.05%) (Table 4). The proportion of sites within a

Table 3. Average soil pH, organic C (range, mean ± s.e.m.) and texture (0–15 cm depth) in eight districts of Eastern Ganga Alluvial Plains (2014–15)

The numbers of samples are listed in parentheses

District	Soil pH		Soil organic C (%)		Texture
	Range	Mean	Range	Mean	
Rangpur (34)	4.7–7.1	5.7 ± 0.06	0.51–1.37	0.99 ± 0.04	Sandy loam
Madhubani (15)	5.0–6.5	5.8 ± 0.18	0.35–0.61	0.49 ± 0.03	Sandy loam
Coochbehar (24)	5.3–7.1	5.9 ± 0.12	0.30–1.69	1.13 ± 0.08	Sandy loam
Dhanusha (50)	5.1–7.7	6.4 ± 0.09	0.20–2.21	1.08 ± 0.09	Sandy loam
Sunsari (38)	5.5–7.2	6.5 ± 0.12	0.42–1.78	1.09 ± 0.09	Sandy clay loam
Purnea (16)	5.4–7.5	6.9 ± 0.28	0.36–0.54	0.46 ± 0.03	Sandy clay loam
Malda (10)	5.8–8.7	7.1 ± 0.31	0.4–1.8	1.07 ± 0.12	Sandy clay loam
Rajshahi (43)	6.5–8.6	7.8 ± 0.07	0.36–0.89	0.62 ± 0.02	Sandy clay loam

Table 4. Average soil total N, extractable P and exchangeable K (range, mean ± s.e.m.) at 0–15 cm depth in eight districts of Eastern Ganga Alluvial Plains (2014–15)

The numbers of samples are listed in parentheses; nd, no data

District	Soil total N (%)		Available P (mg kg^{-1} soil)		Available K (mg kg^{-1} soil)	
	Range	Mean	Range	Mean	Range	Mean
Rangpur (34)	0.04–0.12	0.08 ± 0.002	3.4–122.9	69.0 ± 9.5	39–183	76 ± 6
Madhubani (15)	0.03–0.06	0.05 ± 0.005	6.9–10.3	8.1 ± 0.5	nd	nd
Coochbehar (24)	0.03–0.17	0.12 ± 0.008	14.1–63.9	37.2 ± 3.3	41–101	68 ± 3
Dhanusha (50)	0.02–0.19	0.10 ± 0.008	1.2–40.5	9.2 ± 1.4	18–374	129 ± 10
Sunsari (38)	0.04–0.15	0.07 ± 0.006	2.2–42.8	15.5 ± 4.1	25–128	52 ± 8
Purnea (16)	0.03–0.05	0.04 ± 0.003	9.1–13.8	11.3 ± 0.6	99–265	188 ± 24
Malda (10)	0.05–0.15	0.11 ± 0.008	15.7–38.9	31.6 ± 2.2	81–131	97 ± 5
Rajshahi (43)	0.04–0.09	0.06 ± 0.002	3.4–53.1	14.1 ± 1.8	23–339	76 ± 7

district with low total N was similar to the soil organic C concentration distribution.

Available P and K

Available P (0–15 cm depth) varied by more than one order of magnitude at Dhanusha and Rajshahi with 1.2–40.5 and 3.4–53.1 mg kg^{-1} soil, respectively (Table 4). However, mean available P was lowest at Madhubani (8.1 ± 0.5 mg kg^{-1} soil) and highest at Rangpur (69.0 ± 9.5 mg kg^{-1} soil). More than 70% of sites at Dhanusha and Madhubani were low in available P (<10 mg kg^{-1}) (Tandon 2005), with the reverse the case for sites at Sunsari and Malda (>25 mg kg^{-1}).

Similar to available P, available K (0–15 cm depth) also varied by more than one order of magnitude at Dhanusha and Rajshahi with 18–374 and 23–339 mg kg^{-1} soil respectively (Table 4). Mean available K was highest at Purnea (188 ± 24 mg kg^{-1} soil) and lowest at Sunsari (52 ± 8 mg kg^{-1} soil) (Table 4). In three out of the eight districts, >80% of sites contained low available K (<108 mg kg^{-1}) (Tandon 2005). These were Coochbehar (80%), Sunsari (89%) and Rajshahi (83%). Only a few sites (5% at Rangpur and 2% each at Rajshahi and Dhanusha) had high available K (>280 mg kg^{-1}).

Changes in soil properties after three years of CASI farming systems

Tillage practices

Due to inconsistency in rice crop establishment in Treatment 4 (DSR), we compared the tillage effects on soil properties from Treatments 1 (CT practice) and 3 (ZT practice) at all sites except Rajshahi where data were not collected. The soil pH at 0–15 cm depth was significantly lower under ZT than CT after three years of CASI farming systems only at Madhubani, although it generally tended to be lower at most sites (Table 5). This lack of a stronger trend in soil pH across all sites may be due to the large variability in farmers' fields at most sites. In contrast, for example, when a site at the Regional Research Station, Tarahara in Sunsari district, Nepal, was monitored over a three-year period, soil pH remained significantly lower under ZT compared to CT practice (Fig. 2). Importantly, the ZT results in a more stratified soil profile, and therefore net acidification caused by farming practices could be detected earlier at shallower depths. For example, at Coochbehar sites, soil pH at 0–5 cm was lower under ZT than CT (5.45 vs 5.81, $P < 0.05$) but not at greater depths. Moreover, at Madhubani and Rangpur, soil pH was also significantly lower under ZT than CT at 15–30 cm depth (Fig. 3). In contrast, at Rangpur, tillage practices had no significant effect on soil pH at 0–15 cm depth, possibly due to the regular application of dolomite at Rangpur sites only (Jahan and Gurung 2017 and A Hossain pers. comm.).

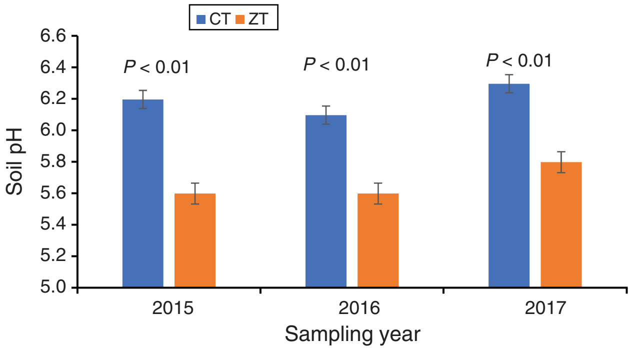

Fig. 2. Effect of tillage practice (CT and ZT) on soil pH ($n = 3$) at 0–15 cm depth over a three-year period at the Regional Research Station, Tarahara, Sunsari district, Nepal. Tillage effect was significant.

Soil organic C concentrations (0–15 cm) were significantly higher under ZT than CT at Madhubani, Coochbehar and Malda but similar at other sites (Table 5). At Sunsari, even at the research station site monitored over a three-year period, organic C concentration showed inconsistent trends under the ZT relative to CT (Fig. 4*a*), reflecting the high variability of soil organic C concentrations in these districts. However, consistent differences in soil total N between ZT and CT were found at the research station site of Tarahara in Sunsari district, Nepal (Fig. 4*b*), possibly because unlike soil organic C, total N was less affected by the labile fraction of soil organic matter. It is possible, therefore, that the labile fraction of soil organic C, such as hot-water soluble C, may be a more sensitive indicator to changes in tillage practices. For example, hot-water soluble C was 29% higher in soil under ZT than CT in Coochbehar district (282 ± 34 vs 219 ± 31 mg C kg^{-1}) and 36% higher in Malda district (281 ± 31 vs 245 ± 27 mg C kg^{-1}).

Plant available P was significantly affected by tillage practice only at Malda (Table 6), where it was higher under ZT than CT. Available K was similar in soil under both tillage practices in all districts (Table 6). However, monitoring of soil at the research station site of Tarahara in Sunsari district, Nepal, over a three-year period showed that available K concentration remained lower under ZT than CT (Fig. 5).

Cropping systems

Generally, soil pH was not significantly affected by the cropping systems although soil pH tended to be lower in the rice–maize than the rice–wheat system. For example, at Coochbehar, soil pH (0–15 cm) under rice–maize was 5.3 ± 0.14 whereas that under rice–wheat it was 5.6 ± 0.16 ($P = 0.03$); the corresponding pH values at Malda were 7.0 ± 0.22 and 7.2 ± 0.26 ($P = 0.22$) at 0–5 cm depths. Similar trends were also noted at 5–10 cm depths. At Coochbehar, soil pH under rice–maize was 5.6 ± 0.17 compared to 5.8 ± 0.17 ($P = 0.13$) for rice–wheat; the corresponding pH values at Malda were 7.5 ± 0.20 and 7.6 ± 0.26 ($P = 0.36$) at 5–10 cm depths for the 2016–17 sampling.

Soil organic C concentrations in both the rice–wheat and rice–maize systems were essentially similar in all districts at 0–15 cm depths. At 0–10 cm depths, however, organic C was significantly ($P < 0.05$) higher in soil under rice–maize (1.16 ± 0.08%) than rice–wheat (1.06 ± 0.07%) at Malda. This was also reflected in soil organic C fractions and hot-water extractable C ($P < 0.04$). Total N concentration followed trends similar to that of soil organic C (Fig. 6).

The cropping systems had no significant effect on available P at either 0–10 or 0–15 cm depths. However, available P at 0–5 cm depth was significantly ($P < 0.02$) lower in soil under rice–maize (45.3 ± 6.0 mg kg^{-1}) than rice–wheat (52.1 ± 5.1 mg kg^{-1}) at Coochbehar at 2017 sampling. A similar trend was observed at Malda, although differences were not significant, with corresponding values of 65.5 ± 8.5 and 71.1 ± 7.7 mg kg^{-1}.

Available K concentrations were not significantly affected by cropping systems at any depths (0–5, 5–10, 0–10 cm or

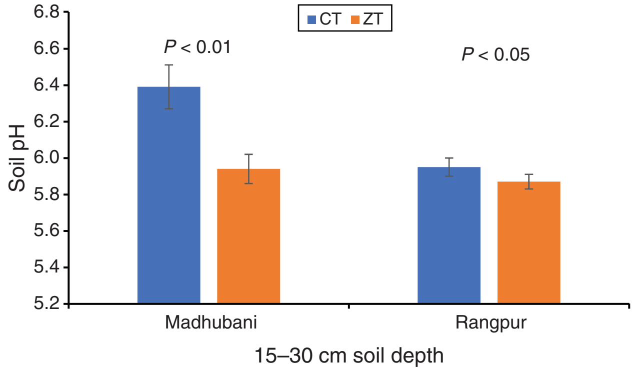

Fig. 3. Effect of tillage practice (CT and ZT) on soil pH at 15–30 cm depth in Madhubani (n = 15) and Rangpur (n = 34) districts after three years of farming system trials. Tillage effect was significant.

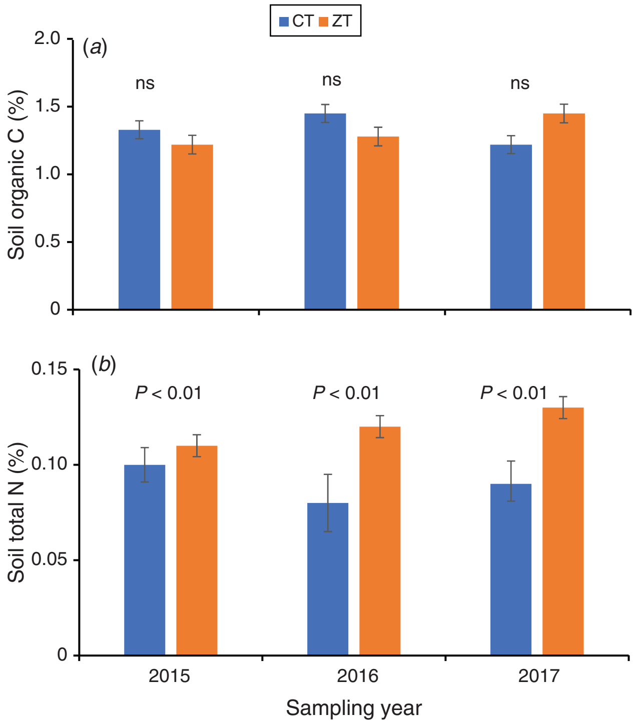

Fig. 4. Effect of tillage practice (CT and ZT) on (*a*) soil organic C (n = 3) and (*b*) total soil N (n = 3) at 0–15 cm depth for a three-year period at the Regional Research Station, Tarahara, Sunsari district, Nepal.

Table 5. Changes in soil pH and organic C (mean ± s.e.m.) at 0–15 cm depth under ZT after three years in seven districts of Eastern Ganga Alluvial Plains (2017)

The numbers of paired samples for each tillage practice are listed in parentheses; nd, no data were collected from Rajshahi sites; ns, not significant

District	Soil pH			Soil organic C (%)		
	CT	ZT	Sig. level	CT	ZT	Sig. level
Rangpur (34)	5.87 ± 0.04	5.85 ± 0.03	ns	0.93 ± 0.04	0.93 ± 0.04	ns
Madhubani (15)	5.86 ± 0.11	5.44 ± 0.18	0.01	0.49 ± 0.03	0.54 ± 0.03	0.05
Coochbehar (10)	5.63 ± 0.08	5.53 ± 0.18	ns	1.00 ± 0.11	1.19 ± 0.12	0.01
Dhanusha (41)	6.39 ± 0.17	6.37 ± 0.15	ns	1.10 ± 0.21	1.12 ± 0.19	ns
Sunsari (32)	5.95 ± 0.12	6.07 ± 0.09	ns	0.97 ± 0.06	0.94 ± 0.05	ns
Purnea (16)	6.97 ± 0.10	6.96 ± 0.11	ns	0.51 ± 0.06	0.51 ± 0.06	ns
Malda (10)	7.25 ± 0.22	7.19 ± 0.20	ns	1.06 ± 0.09	1.16 ± 0.09	0.08
Rajshahi	nd	nd		nd	nd	

Table 6. Changes in available P and K (mean ± s.e.m.) at 0–15 cm depth under ZT after three years in six districts of Eastern Ganga Alluvial Plains (2017)

The numbers of paired samples for each tillage practice are listed in parentheses; nd, no data were collected from the Madhubani and Rajshahi sites; ns, not significant

District	Available P (mg kg^{-1})			Available K (mg kg^{-1})		
	CT	ZT	Sig. level	CT	ZT	Sig. level
Rangpur (34)	72.9 ± 12.6	66.6 ± 11.4	ns	50 ± 2.5	49 ± 1.8	ns
Madhubani	nd	nd		nd	nd	
Coochbehar (10)	38.6 ± 4.9	42.1 ± 4.1	ns	51 ± 4.8	53 ± 4.4	ns
Dhanusha (10)	8.6 ± 2.3	9.0 ± 2.4	ns	144 ± 15.5	136 ± 12.8	ns
Sunsari (32)	16.8 ± 1.2	16.4 ± 1.1	ns	54 ± 2.0	53 ± 2.3	ns
Purnea (8)	10.9 ± 0.7	11.3 ± 0.7	ns	198 ± 15.5	201 ± 15.4	ns
Malda (10)	20.9 ± 4.0	23.2 ± 4.3	0.01	68 ± 3.9	65.5 ± 5.1	ns
Rajshahi	nd	nd		nd	nd	

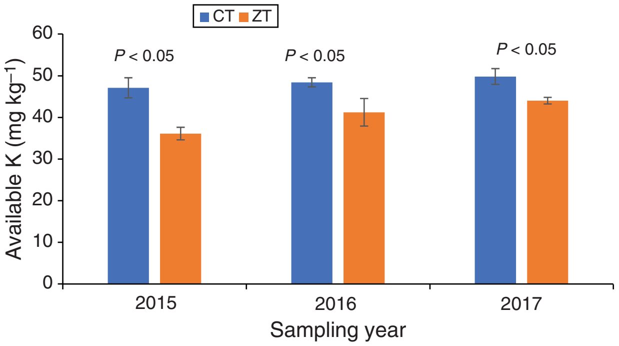

Fig. 5. Effect of tillage practice (CT and ZT) on soil available K ($n = 3$) at 0–15 cm depth over a three-year period at the Regional Research Station, Tarahara, Sunsari district, Nepal. Tillage effect was significant.

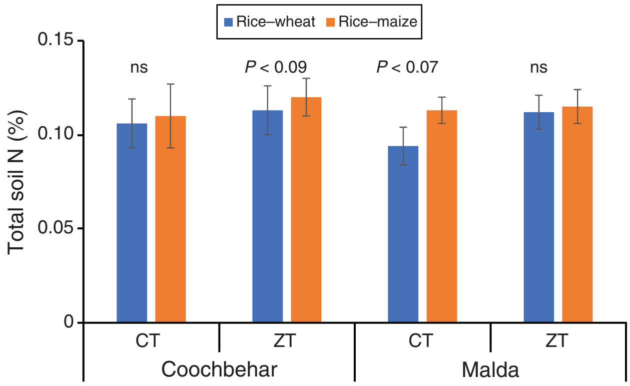

Fig. 6. Effect of tillage practices (CT and ZT) and farming systems (rice–wheat and rice–maize) on total soil N (0–10 cm) at Coochbehar ($n = 8$) and Malda ($n = 10$) districts. ns, not significant.

Table 7. Grain and straw or stover yields (mean ± s.e.m.) of rice–wheat and rice–maize in Coochbehar and Malda districts in 2016–17

The numbers of paired samples for each tillage practice are listed in parentheses. *Significant at $P < 0.05$

District	Crop rotation	Crop	Grain yield (t ha^{-1})		Straw or stover yield (t ha^{-1})	
			CT	ZT	CT	ZT
Coochbehar	Rice–wheat (19)	Rice	3.47 ± 0.12	3.55 ± 0.13	6.31 ± 0.20	6.23 ± 0.19
		Wheat	3.51 ± 0.13	3.59 ± 0.11	5.45 ± 0.17	5.59 ± 0.22
	Rice–maize (21)	Rice	3.58 ± 0.11	3.63 ± 0.12	6.51 ± 0.20	6.26 ± 0.18
		Maize	9.67 ± 0.26	9.77 ± 0.32	10.87 ± 0.17	11.53 ± 0.19
Malda	Rice–wheat (19)	Rice	4.59 ± 0.15	4.67 ± 0.15	7.92 ± 0.42	7.78 ± 0.46
		Wheat	3.50 ± 0.19	3.56 ± 0.20	5.86 ± 0.23	5.29 ± 0.27
	Rice–maize (19)	Rice	4.81 ± 0.16	4.78 ± 0.15	8.30 ± 0.27	7.97 ± 0.38
		Maize	7.21 ± 0.20	8.11 ± 0.42*	8.68 ± 0.28	10.00 ± 0.53*

0–15cm). Available K tended to be lower in rice–wheat than rice–maize system. At 0–5 cm depth, Coochbehar contained 69 ± 10 mg kg^{-1} available K in soil under rice–maize and 64 ± 7 mg kg^{-1} under rice–wheat; the corresponding values at Malda were 85 ± 11 and 68 ± 5 mg kg^{-1}.

Partial nutrient balance

Grain yields, wheat or rice straw, or maize stover yields of the rice–wheat and rice–maize systems under CT and ZT were similar except that the maize grain and stover yields under ZT were higher than CT in Malda (Table 7). Partial N, P and K balances for the rice–maize and rice–wheat systems under CT and ZT were calculated for the Coochbehar and Malda sites in 2017; at both sites N and P had a positive balance (20–40 kg ha^{-1}) but K had a negative balance, especially for rice–maize (>50 kg ha^{-1}) (Fig. 7*a*, *b*). In the rice–maize system, K balance was more negative under ZT than CT at both sites (up to 90 kg ha^{-1}). Unfortunately, the partial nutrient balances were not calculated at the other district sites, due to lack of data on grain N, P and K concentrations.

Discussion

Effect of ZT farming systems on soil pH, organic C and available P and K

The soil analyses in all districts showed a wide range in soil pH, organic C and P and K nutrient resource distribution between farms due to their level of management and production, with varying amounts of nutrients applied among farmers. These factors resulted in development of varying soil pH, organic C and fertility levels in the fields (Table 3).

In general, sites in the higher rainfall region with predominantly sandy loam soils were more acidic (Coochbehar and Rangpur) than the lower rainfall and relatively finer textured sandy clay loam soils (Malda, Rajshahi and Purnea), although acidic soils at Madhubani and to a lesser extent in the adjoining Dhanusha district were associated with inherently acidic parent material. Relatively coarse-textured soils, which predominate in the Eastern Ganga Alluvial Plains, are poorly buffered with slightly acidic to moderately or strongly acidic pH, as found elsewhere (Guo *et al.* 2010). Further, ZT with crop residue retention favours better soil structure and continuity of soil pores compared to CT (Dalal 1989). This results in a greater loss of non-acidic cations through rapid leaching, especially in the high-rainfall humid regions, including Coochbehar and Rangpur. It is also likely that the relatively greater crop residue retention in ZT, especially on acidic soils, will contribute to further acidification by producing acids or acidic products during organic matter decomposition (Dalal *et al.* 1991). In poorly buffered sandy soils, especially those already acidic, it takes only a small amount of acid addition to further lower soil pH (Fig. 8*a*).

In addition to the parent material and rapid leaching of non-acidic cations, the management of cropping lands also contributes to soil acidification by several mechanisms such as the removal of alkalinity (non-acidic cations) in the harvested grain, and application of ammonium or ammonium-producing N fertiliser (Guo *et al.* 2010). Intensification of cropping (increase in crop intensity) accompanied by application of additional N fertiliser, and increased crop yields under the ZT system (CASI practice), increases the rate of alkalinity removal – which may further accelerate the rate of soil acidification under ZT because significant acidification may occur with increasing fertiliser N application (Guo *et al.* 2010).

The soil organic C concentration varied due to climate and edaphic factors, as well as management practices (Mandal *et al.* 2007). In general, soil organic C concentrations increased from west to east and from south to north, following the total annual rainfall, a similar result to those reported by others (Jenny and Raychaudhuri 1960; Saiz *et al.* 2012).

Although ZT was practised for only three years at these field trial sites, there was an increasing trend noted in soil organic C compared to the CT practice (Fig. 8*b*). It may take ≥5 years to observe a clear trend in soil organic C concentration change after a change in tillage practices (Alvarez 2005). However, the labile C fraction of soil organic matter, such as hot-water soluble C, provided an early indication of potential effects of

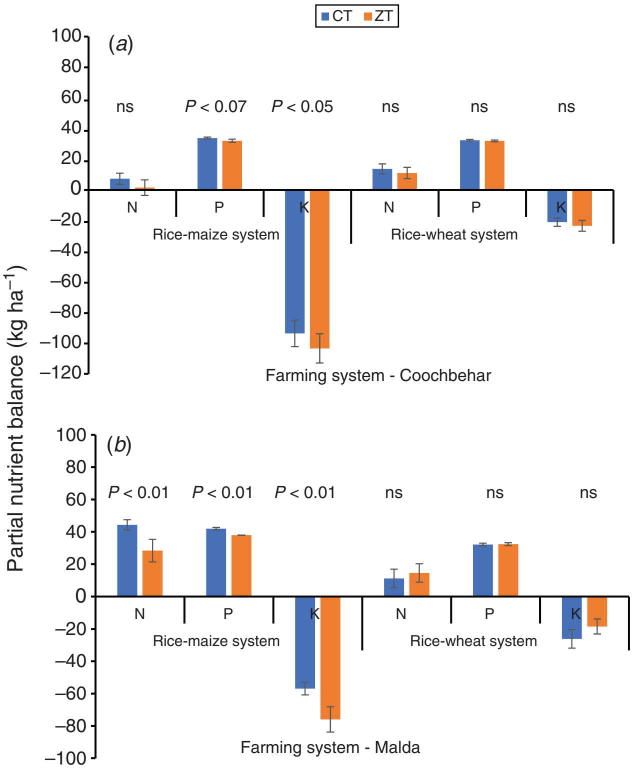

Fig. 7. Partial nutrient balance for the rice–wheat and rice–maize systems under ZT and CT practices for 2017 in (*a*) Coochbehar (n = 16 for rice–maize, n = 19 for rice–wheat) and (*b*) Malda (n = 20 for rice–maize, n = 19 for rice–wheat) districts, West Bengal, India.

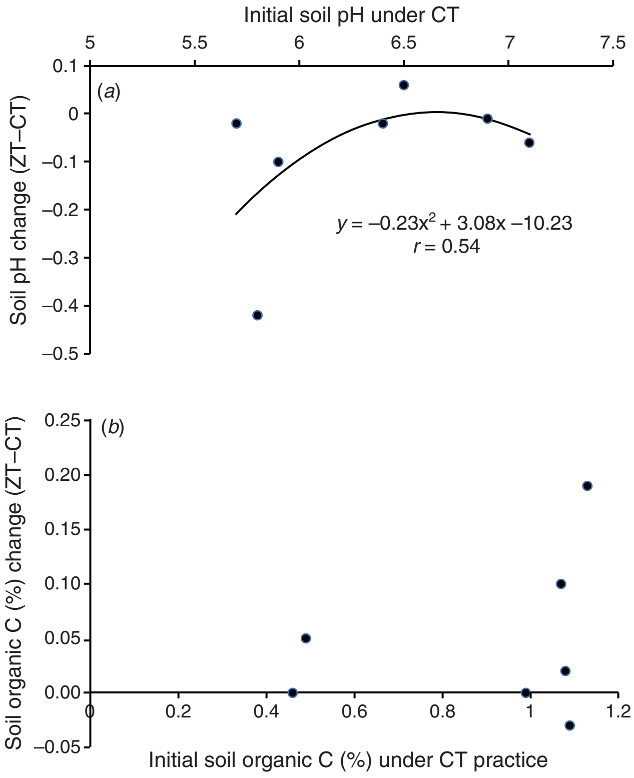

Fig. 8. Changes in (*a*) soil pH and (*b*) soil organic C from the CT to ZT practice in seven districts after three years.

ZT on soil organic C in this study, and also observed elsewhere (Sparling *et al*. 1998; Haynes 2005). Moreover, higher total N in soil under ZT than CT (Fig. 4*b*) may lead to sequestration of organic C in these soils (Knicker 2011). In ZT practice, retention of crop residue on or near the soil surface increases organic C input to the soil, and the minimal disruption of soil aggregates also encourages the retention of organic C and reduces organic C decomposition (Six *et al*. 2000; Dungait *et al*. 2012). If these field trial sites are maintained for a longer term under continuous ZT then further monitoring will likely reinforce these early findings.

In general, rice–maize tended to have lower pH than the rice–wheat system. The maize crop received 170 kg N ha^{-1} whereas only 120 kg N ha^{-1} was applied to the wheat crop in Coochbehar. Moreover, maize grain yield was ~8 t ha^{-1} compared to only ~3.5 t ha^{-1} for wheat (Table 7). Therefore, both the higher N rate and the removal of greater quantity of non-acidic cations through grain removal in the maize crop tended to lower pH in the soil under ZT compared to CT (Thomas *et al*. 2007; Guo *et al*. 2010). Conversely, soil organic C (and total N, Fig. 6) tended to be higher in soil under ZT than CT, primarily because of higher crop residue inputs from maize (~10 t ha^{-1}) than wheat (~5.5 t ha^{-1}) (Table 7). Similar to our results, Mandal *et al*. (2007) concluded from results of five long-term experiments (7–36 years) that more than 2.9 t C ha^{-1} or 7.25 t ha^{-1} of crop residue (containing ~40% C) is required to increase soil organic C in subtropical India. This is also consistent with the findings of Campbell *et al*. (1996) that the amount of crop residue returned to soil was positively related with soil organic C in a clay soil.

Tillage practice did not affect available P except at Malda where soil under ZT had higher available P than under CT (Table 6), possibly due to lower P fertiliser dissolution resulting from the higher pH here compared to the other districts. Although agronomic P imbalances in crop lands across the world occur in the long term (MacDonald *et al*. 2011), the short-term effects of changing tillage practices on available P are less clear. Because applied P in soil is relatively immobile, long-term P application would likely result in accumulation and stratification of available P under ZT in the top 15 cm layer compared to that under CT due to soil incorporation (Grove *et al*. 2007; Thomas *et al*. 2007). Banding of fertiliser may improve maize yields by concentrating P in the surface layer (Alam *et al*. 2018).

Soil available (exchangeable) K in the farmers' fields in all districts were not affected by tillage practice, although at a research station site (Tarahara in Sunsari district, Nepal) the soil under ZT contained less available K than under CT (Fig. 5). Large variability across all districts precluded the measurement of significant short-term tillage effects on farmers' fields. On the research station, the observed tillage effects may be due to increase in K removal in the greater production from the research station although the return of crop residue to soil will lessen the depletion of K (Zhao *et al*. 2014).

Effect of farming systems on partial balance of N, P and K

Partial nutrient balance is a simple approach that can identify substantial imbalances (either deficit or excess) that may occur for an individual field, as well as the major flows of nutrients in a farming system (Roy *et al*. 2003; Mueller *et al*. 2014; Das *et al*. 2018). Partial nutrient balance provides a first approximation to evaluate the sustainability of the farming systems, as crop intensification increases the uptake and removal of nutrients from soil. For example, a negative nutrient balance needs to be addressed before crop yields are adversely affected (Singh *et al*. 2005). In this study, in both the rice–maize and rice–wheat systems, N and P had a positive balance, but K had a negative balance under both CT and ZT practices. This is evidenced by higher total N but lower available K in the soil under ZT than CT (Figs 5 and 6). If the negative K balance is also accompanied by a declining trend in available K (0–15 cm) – for example, in Rangpur, Coochbehar and Sunsari districts (Tables 4 and 6) – and reaches a critical level (<108 mg K kg^{-1} soil, Tandon 2005), then K fertiliser application will be required. However, positive N balance in the cropping system is likely lead to both economic loss for farmers and also contribute to soil acidification. In other cropping systems, however, Jahan *et al*. (2016) reported negative N balance for an intensive rice–potato–mungbean crop rotation in Bangladesh.

Negative K balance for crops in South Asia is widespread (Singh *et al*. 2005; Surekha and Satishkumar 2014). In this study, the rice–maize had a larger negative K balance (~90 kg ha^{-1}) than the rice–wheat system (~40 kg ha^{-1}), due primarily to larger K removal in the maize crop than the wheat; rice yields were similar in both farming systems (Islam *et al*. 2019). Even in the rice–wheat system, Hossain *et al*. (2016) observed a decline in available K (0–15 cm), indicating that the applied rate of K fertiliser application was inadequate to meet crop demands. In addition to fertiliser K application, the return of crop residues to soil would significantly contribute to the K available to following crops and might reduce negative K balance in farming systems (Singh *et al*. 2005; Thomas *et al*. 2007). Thus, partial nutrient balance often provides an early warning for a potential risk to the long-term sustainability of a farming system.

Conclusion

Long-term sustainability of these cereal-based farming systems in the Eastern Ganga Alluvial Plains is essential for food security of the region. This sustainability depends on the sustainable conservation and use of natural resources, particularly soils in the subhumid and humid to per-humid environments. This region is prone to soil acidification due to the poorly buffered sandy and sandy loam soils, and to the leaching of a significant fraction of rainfall (1273–3201 mm). The CASI practices, including ZT, crop residue retention and crop rotation improve soil organic matter and preserve continuity of soil pores, which further enhance leaching and may potentially accelerate soil acidification. Combined with increasing N fertiliser rates for crop intensification, this provides a conducive environment for insidious soil acidification. Since most of the soils in this region are already in the acidic pH range and the early trends in this study point towards increasing acidification, remedial actions are urgently required. This is indeed a challenge for ameliorating acidic soils under ZT practice (minimal soil disturbance). Because the use of ammonium-N fertiliser is a substantial contributor to soil acidification, more efficient N use practices will be an important component of the management of soil acidification. For example, the inclusion of legumes in rotation will reduce fertiliser N requirements, slowing acidification. However, as farming system intensification results in increasing acidification due to increased grain and N removal, more efficient N management alone, including that from legume-N, is unlikely to prevent acidification, and increased lime or dolomite applications will be needed to overcome the challenge of acidification. Without remediation, acidification may become a considerable constraint to sustainable and resilient farming systems in this region.

The partial nutrient balance for rice–maize and rice–wheat farming systems suggests that the sustainability of yields in crop intensification under the CASI (including ZT) practice requires larger K inputs than that under CT practice. Further, other crop nutrients including micronutrients (Zn and B) may also be depleted in these soils and, therefore, these nutrients require monitoring so that timely remedial measures can be taken, as this may pose a long-term threat to sustainable farming systems and food security in the Eastern Ganga Alluvial Plains of South Asia.

Conflicts of interest

The authors declare no conflicts of interest.

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