Conservation agriculture in intensive rice cropping reverses soil potassium depletion

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ORIGINAL ARTICLE

Conservation agriculture in intensive rice cropping reverses soil potassium depletion

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Abstract Intensive cropping in the Eastern Gangetic Plain has progressively depleted soil potassium (K) over time due to negative K balances. There is limited understanding of how alternative soil and crop management practices under Conservation Agriculture (CA) will alter the soil K pools in such soils. We hypothesized that long-term CA will reduce K depletion in soils through recycling and storing soil K. A split plot experiment with two factors—(A) soil disturbance (strip planting = SP and conventional = CT), and (B) residue retention (low, LR = 20 cm and high, HR = 50 cm) commenced in 2010 with three crops per annual cycle for 24 consecutive crops. Soil samples were then collected in December 2018 at 0–5, 5–15, 15–30, 30–45 and 45–60 cm to analyse fractions of K along with soil physical and chemical properties. All K fractions were higher in SP (by 300, 26, 7.8 and 2.4 mg kg^{-1} for total, non-exchangeable, exchangeable and soil solution K, respectively) than in CT while HR was higher (by 267, 243, 18, 28.8 and 15.9 mg kg^{-1} for total, mineral non-exchangeable, exchangeable and soil solution K, respectively) than in LR. While increased crop residue retention recycled more K to the soil which partly explains higher concentrations in K fractions, both increased residue retention and decreased soil disturbance increased SOC that can positively increase exchangeable K. Hence, the core components of CA, minimal soil disturbance and increased residue retention, resulted in larger K pools in soil and appear to be effective means for reversing negative K balances in these intensive rice-based cropping systems.

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Introduction

Intensive cropping systems may cause heavy depletion of soil K in the long term even on soils with high inherent K status (Dobermann et al. 1998; Panaullah et al. 2006; Islam et al. 2016). Moreover, the use of K fertilizers on farms was often not adequate leading to negative input–output balances (Salam et al. 2014; Islam et al. 2022a). The shift to high yielding varieties of rice, hybrid maize, potato and wheat accelerated the removal of K from the soil in the Eastern Gangetic Plain (EGP). Consequently, soil phytoavailable K status in Bangladesh declined by 25–37% over the last decades due to the negative K balance in the intensive cropping systems (Hasan et al. 2020 and Ali et al. 1997). Elsewhere, net K losses ranged from 18 to 44 kg K ha^{-1} year^{-1} in the rice–wheat cropping pattern at Parwanipur, Nepal on a loamy sand soil (Gami et al. 2001), from 63.3 to 85.2 kg K ha^{-1} year^{-1} in the rice–wheat cropping pattern at Bhairhawa, Nepal on a silt loam soil (Regmi et al. 2002) and from 63 to 151 kg K ha^{-1} year^{-1} in the Indo-Gangetic Plains, Ludhiana, India (Yadvinder-Singh et al. 2005; Singh et al. 2003). Since intensive rice-based cropping on the EGP is important for food security in South Asia, declines in soil K supply cannot be overlooked. Indeed, declining trends of yields in rice, wheat and many other corps has been attributed in part to the deterioration of K nutrition which was caused by inadequate K fertilization (Salam et al. 2014).

Potassium buffering in soils is largely determined by the clay content and its dominant mineralogy. The extent of weathering of primary K-bearing minerals, the chemical pathways through which weathering takes place, as well as the dynamic equilibrium between various K fractions in soils influence the K-supplying capacity in the short and long term. The intensive rice-based rotation in the EGP results in short fallow periods and periodic drying-wetting of the soils between crops, both of which can accelerate mineral transformations with possible implications for K supply (Alam et al. 2016; Haque et al. 2016). Based on the degree of availability to crops, soil K can be classified into (Darunsontaya et al. 2012): (a) Soil solution K which is usually considered the primary source of K absorbed by plant root; and its concentration is a function of soil K buffering capacity, past cropping and K fertilization practices; (b) Exchangeable K which is adsorbed by the negative charges on soil clay and organic matter surfaces; (c) Non-exchangeable K which is held as fixed ions in the interlayer space of illite-type and weathered biotite or muscovite clay minerals; (d) Mineral K which is found in K-bearing minerals in soils depending primarily on the parent material. Soil solution and exchangeable potassium are in equilibrium and collectively known as the readily available potassium pool (Shaikh et al. 2007) while the last two are considered non-labile but are responsible for the long-term supply of K to plants (Askegaard et al. 2003).

Crop residue retention can increase soil organic matter and is especially important for recycling K due to the relatively high proportion of shoot K uptake that remains in unharvested residues of crops (Boehm and Anderson 1997; Whitbread et al. 2000). For instance, 80–85% of crop K uptake was in cereal straw (Whitbread et al. 2000; Singh et al. 2003). When crop residues are removed from fields a negative K balance was found by Whitbread et al. (2003). Conservation Agriculture (CA) is an emerging crop production system in the EGP, which emphasizes increased crop residue retention whereas currently in the EGP almost 80% of crop residue is removed (Bell et al. 2019). In addition, Kushwaha et al. (2001) found that minimum tillage (MT) practices and residue retention under the principles of CA can reverse the declining trend in soil quality and increase values of soil organic C and total N (11.1 vs 7.8 and 1.33 vs 0.87 g kg^{-1} soil, respectively) relative to conventional tillage and residue removal. The reduced tillage together with increased residue retention resulted in the maximum increase in microbial biomass C and N (82–104% over control). However, CA effects on soil K dynamics and distribution in the soil profile have not been reported.

The present study was carried out to: (i) determine the magnitude of K fractions in soil under long term CA vs conventional practices and (ii) examine the relationship of K fractions to other soil properties under long term intensive rice-based CA and conventional agricultural practices. Improved understanding of the forms of K in soil and their interrelationships will underpin long term availability of K in soils to crops and the management of K balance in the intensive cropping systems of the EGP.

Materials and methods

Site description

Location, morphological characteristics and taxonomical class of the experiment soil

The experiment was conducted at Alipur, Durgapur, Rajshahi in northwest of Bangladesh (24^0 29′ 02.0'' N and 88^0 46′ 53.7'' E). The site comprised Calcareous Grey Floodplain soil classified as a Typic Haplaquept and Arial/Sara soil series (Huq-Shoaib, 2013; USDA 2014), occurring on the High Ganges River Flood Plain (Brammer et al. 1988). The particle size distribution, textural class and some chemical properties of the experimental soil by depth are given in Table S1. Details of the experiment site were previously reported by Alam et al. (2016) and Islam et al. (2022b). The clay minerals of the soils are mostly mica and smectite, interstratified mica-vermiculite-smectite and kaolinite-smectite (Moslehuddin et al. 1999).

Experimental design and soil sampling

Starting in 2010, the experiment was laid out in a split plot design with two factors: factor A, soil disturbance practices (strip planting (SP) and conventional tillage (CT)) and factor B, residue retention (low residue (LR, 15 cm) and high residue (HR, 50 cm) under an annual triple-cropped pattern with four replications and a diversified cropping sequence (Suppl. 1). In SP, the seeds or seedlings were sown/transplanted in 3 cm wide strips separated by 27 cm of undisturbed soil for lentil and 17 cm for rice crop using a Versatile Multi-Crop Planter (VMP). Conventional tillage was done by 3–4 rotary tillage operations. Low residue involved keeping about 20 cm of the standing rice crop residue in the field during harvesting. High residue involved keeping 50 cm of standing rice residue during harvesting. In the SP system, the crop residue was mostly retained as standing stubble or on the soil surface while the same amount of residue was incorporated into the soil by repeated rotary tillage in CT system.

Composite soil samples were collected by an auger (5 cm diameter) from 0–5, 5–15, 15–30, 30–45 and 45–60 cm depth from each replicated plot after the harvest of T. Aman rice of the 2017–18 crop cycle. There were nine auger holes per plot for each composite sample. For the determination of the soil bulk density (BD), two depths (0–5 and 5–15 cm) was sampled by 5 cm diameter core sampler per plot (Black 1965).

Soil sample processing and analysis

The collected soil samples were air dried at room temperature, mixed thoroughly, crushed and screened through a 10-mesh sieve. Before crushing, stones, visible roots and insects were removed. Soil solution K was determined by extracting the soil with 0.01 M $CaCl_2$ solution (1:10 ratio) following the method described by Houba et al. (1986). Exchangeable K was determined by shaking the soil with NH_4OAc solution (1:10 ratio) and adjusting pH to 7 as described by Knudsen et al. (1982). For non-exchangeable K, the 1 M HNO_3 extractable K was estimated by using flame photometer in a 1:10, soil: acid suspension boiled for 10 min as described by Knudsen et al. (1982). Non-exchangeable K was calculated by subtracting soil solution K and exchangeable K from the HNO_3 extractable K. The amount of total K was measured by acid digestion method (acid mixture ($HClO_4$:H_2SO_4: HNO_3 at the ratio of 2:1:5) as described by Page *et. al*. (1982). The amount of K in the mineral lattice was calculated by subtracting soil solution K, exchangeable K and non-exchangeable K from total K. Soil organic carbon was determined by Walkley and Black (1934) method. Soil pH were measured using the methods suggested by Chapman (1965). The amount of total N was determined by a Semi-micro Kjeldahl method (Bremner and Mulvaney 1982) and available *P* was determined by the Olsen method (Olsen and Sommers 1982). Bulk density was measured by core sampler method (Black (1965). Soil texture was determined following the hydrometer method (Bouyocos 1927).

Statistical analysis

The significance of treatment effects on the soil K pools and K balance was determined by analysis of variance (ANOVA) based on split plot and split-split plot designs. The soil depth effect was determined by analysis (ANOVA) for a Repeated Measures Design. Treatment means were separated by Duncan's Multiple Range Test (DMRT) using the statistical package Statistix 10 at 5% level of significance. Pearson's correlations were used to evaluate the relationships among the K fractionations and with other properties of soil.

Results

Potassium fractions

Solution K

Tillage, residue retention and soil depth each significantly influenced the soil solution K concentration (Table 1), but there was no significant interaction effect. Soil solution K concentration was significantly higher in SP (16.3 mg kg^{-1}) than in CT (13.9 mg kg^{-1}). High residue significantly increased soil solution K (15.9 mg kg^{-1}) relative to LR (14.3 mg kg^{-1}). On the other hand, sub surface soils (5–15 and 15–30 cm) contained significantly higher soil solution K (17.2 and 17.4 mg kg^{-1} soil) than other depths.

Exchangeable K

Exchangeable K was significantly influenced only by the main effects of tillage, residue retention and soil depth (Table 1). Exchangeable K content increased in SP (45.1 mg kg^{-1}) relative to CT (37.3 mg kg^{-1}) and with HR retention. Soil at 5–15 cm had significantly higher exchangeable K (43.8 mg kg^{-1}) than others depths which had no regular trend.

Non-exchangeable K

The non-exchangeable K concentration was significantly influenced by tillage, residue retentions and

Table 1 Effect of tillage, residue retention and soil depth on total K, mineral K, non-exchangeable K, exchangeable K and soil solution K (SSK) concentration in soil (depth 0–60 cm)

Factors and treatments		Total K (mg kg^{-1})	Mineral K (mg kg^{-1})	Non-exch. K (mg kg^{-1})	Exch. K (mg kg^{-1})	SSK (mg kg^{-1})
Tillage	CT	5329	4922	356	37.3	13.9
	SP	5629	5186	382	45.1	16.3
	LSD at 0.05	284	–	21.6	2.59	1.39
Residue retention	LR	5346	4933	360	39.3	14.3
	HR	5613	5176	378	43.1	15.9
	LSD at 0.05	154	146	12.2	3.55	0.924
Soil depth	0–5 cm	5089	4689	346	39.9	13.9
	5–15 cm	5553	5115	377	43.8	17.2
	15–30 cm	5725	5274	389	43.3	17.4
	30–45 cm	5814	5379	377	42.4	15.7
	45–60 cm	5217	4815	354	36.6	11.3
	LSD at 0.05	193	192	24	1.78	1.27
Level of significance	Tillage (T)	*	ns	*	*	*
	Residue (R)	**	*	*	*	*
	Depth (D)	***	***	**	***	***
	T X R	ns	ns	ns	ns	ns
	T X D	ns	ns	ns	ns	ns
	R X D	ns	ns	ns	ns	ns
	T X R X D	ns	ns	ns	ns	ns

Legends: *SP* strip planting and *CT* conventional tillage; *HR* high residue, *LR* low residue, LSD ($P < 0.05$), *SSK* soil solution K.
*$P<0.05$; **$P<0.01$; $P<0.001$; ns = not significant

Table 2 Effect of tillage, residue retention and soil depth on bulk density, and the stock of total K, total SOC, total N in soils (depth 0–15 cm)

Factors and treatments		BD (g cm^{-3})	Total K (t ha^{-1})	Total SOC (t ha^{-1})	Total N (t ha^{-1})
Tillage	CT	1.37	5.36	7.91	0.99
	SP	1.34	5.62	9.41	1.06
	LSD at 0.05	0.01	-	0.903	0.05
Residue retention	LR	1.38	5.39	8.19	0.99
	HR	1.33	5.6	9.13	1.06
	LSD at 0.05	0.01	0.198	0.331	0.038
Soil depth	0–5 cm	1.34	3.42	8.25	1.09
	5–15 cm	1.37	7.57	9.07	0.96
	LSD at 0.05	0.012	0.169	0.404	0.035
Level of significance	Tillage (T)	**	ns	*	*
	Residue (R)	***	*	**	**
	Depth (D)	**	*	***	***
	T×R	*	***	*	ns
	T×D	ns	ns	*	*
	R×D	ns	ns	ns	ns
	T×R×D	*	*	ns	ns

Legends: *SP* strip planting and *CT* conventional tillage; *HR* high residue, *LR* low residue, *BD* bulk density, *SOC* soil organic carbon, *TN* total nitrogen, LSD ($P < 0.05$).

*$P<0.05$; **$P<0.01$; $P<0.001$; ns = not significant

soil depths (Table 1), but there were no significant interaction effects. Non-exchangeable K concentration was significantly higher in SP (382 mg kg^{-1}) than in CT (356 mg kg^{-1}). HR retention also significantly increased non-exchangeable K (378 mg kg^{-1}) concentration relative to LR (360 mg kg^{-1}). Soil at 15–30 cm contained significantly higher non-exchangeable K (389 mg kg^{-1}) than others depths which had no regular trend with depth.

Mineral K

Residue retentions and soil depths significantly influenced the mineral K content (Table 1), but there were no significant tillage or interaction effects. High residue significantly increased mineral K (5176 mg kg^{-1} soil) relative to LR (4933 mg kg^{-1}). Sub surface soil (15–30 and 30–45 cm depth) contained significantly more mineral K (5274 and 5379 mg kg^{-1}*)* than others depths and lowest value was 4689 mg kg^{-1} in surface soil (0–5 cm).

Other soil properties

Bulk density

The bulk density responded significantly to tillage, residue retention, depth, tillage by residue and the tillage by residue by depth interactions (Table 2), but there was no significant effect of tillage with depth or residue with depth. Conventional tillage showed the higher BD (1.37 g cm^{-3}) than SP (1.34 g cm^{-3}) (0–15 cm depth). High residue retention significantly decreased BD (1.33 g cm^{-3}) relative to LR (1.38 g cm^{-3}) (0–15 cm depth). On the other hand, surface soil (0–5 cm) showed significantly lower BD (1.34 g cm^{-3}) than sub surface soil (5–15 cm) which had a BD of 1.37 g cm^{-3}. Bulk density ranged from 1.31 g cm^{-3} in SP with HR at 0–5 cm to 1.42 g cm^{-3} in CT with LR at 5–15 cm (Fig. 1a).

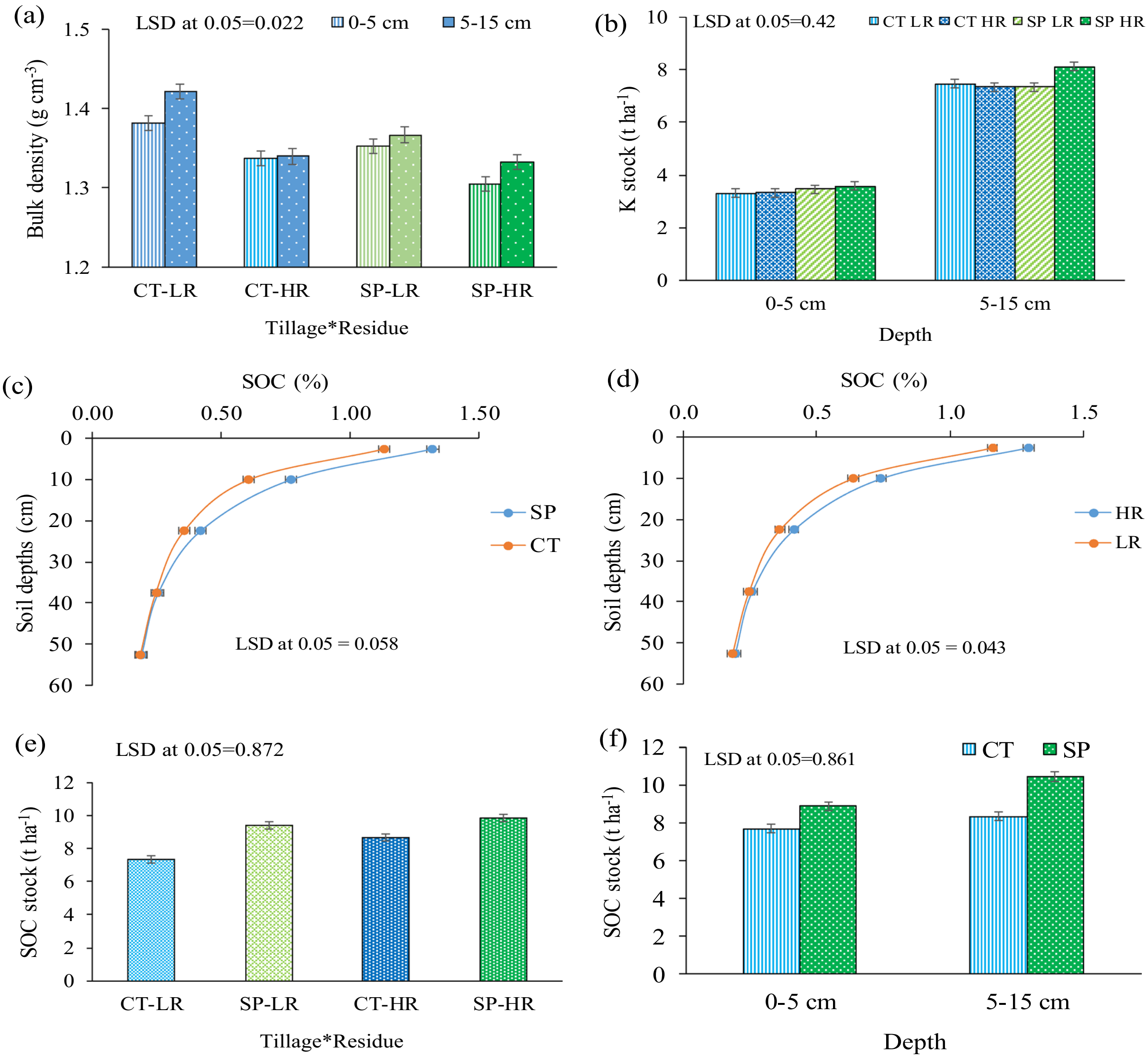

Fig. 1 Bulk density (**a**), K stock (**b**), soil organic carbon (**c**, **d**) and soil carbon stock (**e**, **f**) as affected by soil depth, tillage and residue treatments. [*Legends*: *SP* strip planting and *CT* conventional tillage; *HR* high residue, *LR* low residue. Error bars represent SE ($P<0.05$); Means ($n=4$) shown]

Total Potassium stock in soils

Tillage, residue retention, soil depth and the residue by soil depth interaction significantly influenced the total K stock in soils (Table 2). High residue retention increased the total K (5.60 t ha^{-1}) stock in soils at 0–15 cm relative to LR (5.39 t ha^{-1}). The highest K (8.51 t ha^{-1}) obtained from 5–15 cm depth in SP with HR and the lowest (3.30 t ha^{-1}) in 0–5 cm depth for CT with LR (Fig. 1b).

Total soil organic carbon concentration and stock

Tillage, residue retention, soil depth, tillage by depth and residue by depth interactions significantly influenced the SOC content in soils (Table S3). At

0–5, 5–15 and 15–30 cm, SP and HR had significantly higher SOC (1.32 vs 1.13, 0.77 vs 0.61 and 0.42 vs 0.36%, respectively and 1.30 vs 1.16, 0.74 vs 0.64 and 0.41 vs 0.36%, respectively) than CT and LR respectively but at 30–45 and 45–60 cm there were no significant difference between them (Fig. 1c, d).

Tillage, residue retention, soil depth and interaction effects of tillage by residue and tillage by soil depth significantly influenced the SOC stock in soils (Table 2). High residue with SP (9.89 t ha^{-1}) contained higher SOC stock than LR (7.36 t ha^{-1}) (Fig. 1e) with CT. The SOC stock was 15% higher at surface soil (0–5 cm) and 25% higher at sub-surface soil (5–15 cm) in SP than in CT (Fig. 1f).

Total nitrogen concentration and stock in soils

Residue retention, soil depth, tillage by depth and residue by depth interactions significantly influenced the TN concentration in soils (Table S3). SP had significantly higher TN (1.72 vs 1.53, 0.072 vs 0.068 and 0.069 vs 0.063%, respectively) than CT at 0–5, 5–15 and 15–30 cm depth, but at 30–45 and 45–60 cm there were no significant difference between them (Fig. 2a). At all depths, HR had higher TN than CT (Fig. 2b).

The positive effects of SP on TN stock in soils were evident at 0–5 cm depth but not at 5–15 cm (Fig. 2c). High residue showed the higher total N (1.06 t ha^{-1}) stock in soils than LR (0.99 t ha^{-1}) (Table 2).

Correlation matrix of K fractionations and other properties of soil

All K fractions were positively and significantly correlated with each other but especially between total K and mineral K and between exchangeable K and SSK (Table 3). Bulk density was negatively correlated with exchangeable K but not with other fractions. Total K and mineral K were significantly and negatively correlated with SOC but other K fractions were not correlated with SOC. Similarly, TN was negatively correlated with total K and mineral K but not with other K fractions. Total K, mineral K and non-exchangeable K were significantly and positively correlated with pH but other fractions were not. In case of *P*, the total K and mineral K were negatively and significantly correlated with *P* and other K fractions were not. (Table 3).

All the K fractions (total K, mineral K, non-exchangeable K, exchangeable K and soil solution K) were positively and significantly correlated with clay. Except for exchangeable K, all other K fractions were positively correlated with silt. On the other hand, all the soil K fractions were negatively correlated with sand (Table 3).

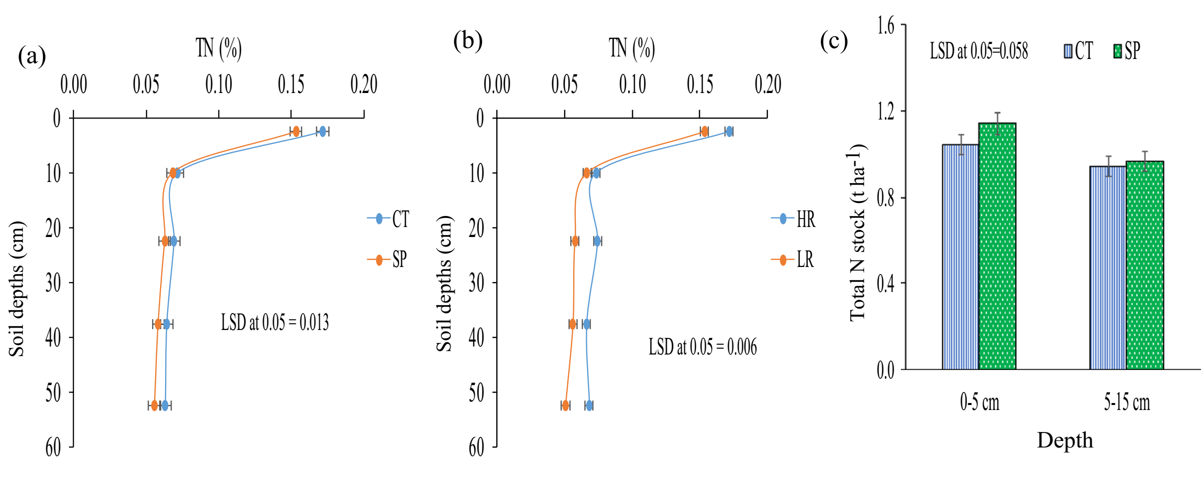

Fig. 2 Total nitrogen (TN) (**a**, b) and TN stock (**c**) as affected by soil depth, tillage and residue treatments. [*Legends*: *SP* strip planting and *CT* conventional tillage; *HR* high residue, *LR* low residue. Error bars represent SE ($P < 0.05$). Means ($n = 4$) shown]

Table 3 Correlation matrix of different K fractions and with other soil properties, soil texture and K input from residue

Parameters	Total K	Mineral K	Non-exch. K	Exch. K	SSK
Total K					
Mineral K	0.99***	–			
Non-exch. K	0.499***	0.41***	–		
Exch. K	0.41***	0.37***	0.45***	–	
SSK	0.43***	0.40***	0.40***	0.71***	–
BD	−0.33 ns	−0.32 ns	−0.19 ns	−0.40*	−0.29 ns
pH	0.51**	0.49**	0.37**	0.24 ns	0.19 ns
SOC	−0.26*	−0.26*	−0.15 ns	0.16 ns	0.08 ns
TN	−0.26*	−0.26*	−0.16 ns	0.08 ns	−0.09 ns
P	−0.28*	−0.28*	−0.13 ns	0.14 ns	0.04 ns
Sand	−0.65***	−0.63***	−0.48**	−0.49**	−0.62***
Silt	0.46**	0.45**	0.39*	0.27 ns	0.37*
Clay	0.62***	0.60***	0.41**	0.53***	0.65***
K input from residue	0.34**	0.33**	0.25*	0.36***	0.26*

Legends: Total K, Total potassium; Mineral K, Mineral potassium; Non-exch. K, Non exchangeable potassium; Exch. K, Exchangeable potassium, SSK, Soil Solution potassium, BD, Bulk Density, pH, soil pH, SOC, Soil Organic Carbon, TN, Total Nitrogen and P, extractable Phosphorus. LSD ($P < 0.05$)

*$P < 0.05$; **$P < 0.01$; $P < 0.001$; ns = not significant

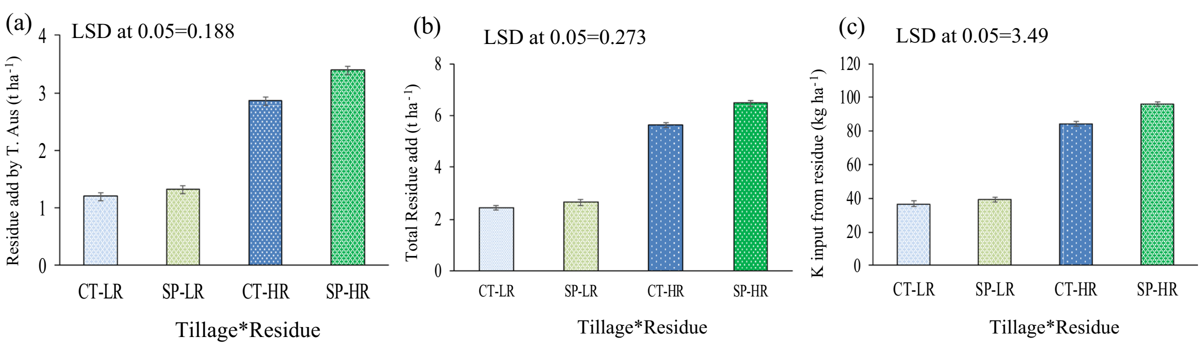

Fig. 3 The mass of crop residue retained after T. Aus rice (**a**), the combined mass of rice residue (**b**) and K input from residue (**c**) as affected by soil depth, tillage and residue treatments. [*Legends*: *SP* strip planting and *CT* conventional tillage; *HR* high residue, *LR* low residue. Error bars represent SE (P < 0.05); Means (n = 4) shown]

Effect of residue retention on K inputs

The T. Aus rice residue addition was significantly higher in SP-HR (3.40 t ha^{-1} year^{-1}) than in CT-LR (1.20 t ha^{-1} year^{-1}) (Fig. 3a). In case of T. Aman rice, more residue was retained in SP (2.21 t ha^{-1} year^{-1}) and HR (2.93 t ha^{-1} year^{-1}) than in CT (2.01 t ha^{-1} year^{-1}) and LR (1.28 t ha^{-1} year^{-1}), respectively (Table 4). The total residue addition was significantly the highest in SP-HR (6.49 t ha^{-1} year^{-1}) followed by CT-HR (5.64 t ha^{-1} year^{-1}) and the lowest in CT-LR (2.44 t ha^{-1} year^{-1}) (Fig. 3b).

Residue K concentrations were unaffected by tillage, residue retention or their interaction in T. Aus rice and T. Aman rice (Table 4). Tillage, residue retention and their interaction effects significantly influenced on K input from residues of T. Aus rice and T. Aman rice (Table 4). The added K in retained rice residues was significantly higher in SP-HR (96 kg ha^{-1} year^{-1}) followed

Table 4 Effect of tillage and crop residue retention on residue retained, K concentration in residue and K inputs from residue in the Lentil – T.

Factor and Treatments		Residue retention (t ha^{-1})			Potassium concentration (%)		K addition from residue (kg ha^{-1} $year^{-1}$)
		T. Aus	T. Aman	Total	T. Aus	T. Aman	
Tillage	CT	2.03	2.01	4.04	1.48	1.53	60.7
	SP	2.35	2.21	4.56	1.46	1.49	67.7
	LSD at 0.05	0.111	0.176	0.096	–	–	0.636
Residue retention	LR	1.26	1.28	2.54	1.47	1.51	37.9
	HR	3.13	2.93	6.06	1.47	1.51	90.5
	LSD at 0.05	0.154	0.174	0.256	–	–	3.44
Level of significance	Tillage (T)	**	*	***	ns	ns	***
	Residue (R)	***	***	***	ns	ns	***
	T×R	*	ns	*	ns	ns	*

Aus rice –T. Aman rice cropping pattern

Legends: *SP* strip planting and *CT* conventional tillage; *HR* high residue, *LR* low residue, LSD ($P < 0.05$).

*$P<0.05$; **$P<0.01$; $P<0.001$; ns = not significant

by CT-HR (85 kg ha^{-1} $year^{-1}$) than with CT-LR (37 kg ha^{-1} $year^{-1}$) (Fig. 3c).

All K fractions showed positive and significant correlation with K input from residue (Table 3), which indicated that when the amount of residue increased, all forms of K, but especially exchangeable K, increased (Fig. 4 a, b, c, d and e).

Discussion

In the present study, the results support our hypothesis that two principles of Conservation Agriculture (CA) were possible solutions to reverse the detrimental effect of intensive cropping on depletion of soil K. Here, decreased soil disturbance and increased crop residue retention, practiced for 24 consecutive crops, both enhanced soil K fractions in the 0 to 15 or 0–30 cm layers. Effects were independent but likely related in both cases to the increased accumulation of soil organic matter and increased recycling of crop residues. In the following discussion, we deal firstly with the effects of increased residue retention which can be related both to increased recycling of K as well as to soil organic matter accumulation. The subsequent section deals with likely effects of minimum soil disturbance, i.e. strip planting, on accumulation of organic matter pools and associated K fractions. Finally, we discuss the implications of these results for reversing the long-term decline in soil K status in intensively cropped areas due to prolonged negative K balances.

Crop residue retention increased available K

Higher crop residue retention increased all fractions of soil K regardless of soil disturbance levels and soil depths. The higher available K in the root zone due to increased residue retention was attributed to increased recycling of K, increased soil organic matter content and to the retention of more K ions in non-exchangeable and exchangeable fractions. In the present study, annual increases in crop residue retention were 3.5 t ha^{-1}, and these returned 52.6 kg K ha^{-1} to the soil. Hence, an increase in 270 mg K kg^{-1} of the total K fraction after 8 years (24 crops) of increased residue retention is plausible based only on the extra K input. Crop residues contain large quantities of K, and their recycling can markedly increase K availability in soils (Chatterjee and Mondal 1996; Sarkar 1997). Bayer et al. (2009) also added that the long-term input of different types of crop residues to soils managed under minimum tillage associated with crop rotation increased the C pools. Long term straw management was reported to increase exchangeable K, non-exchangeable K and SOC (124 mg kg^{-1}, 175 mg kg^{-1} and 24.0 g kg^{-1} respectively) in comparison with the unfertilized control treatment (49.0 mg kg^{-1},

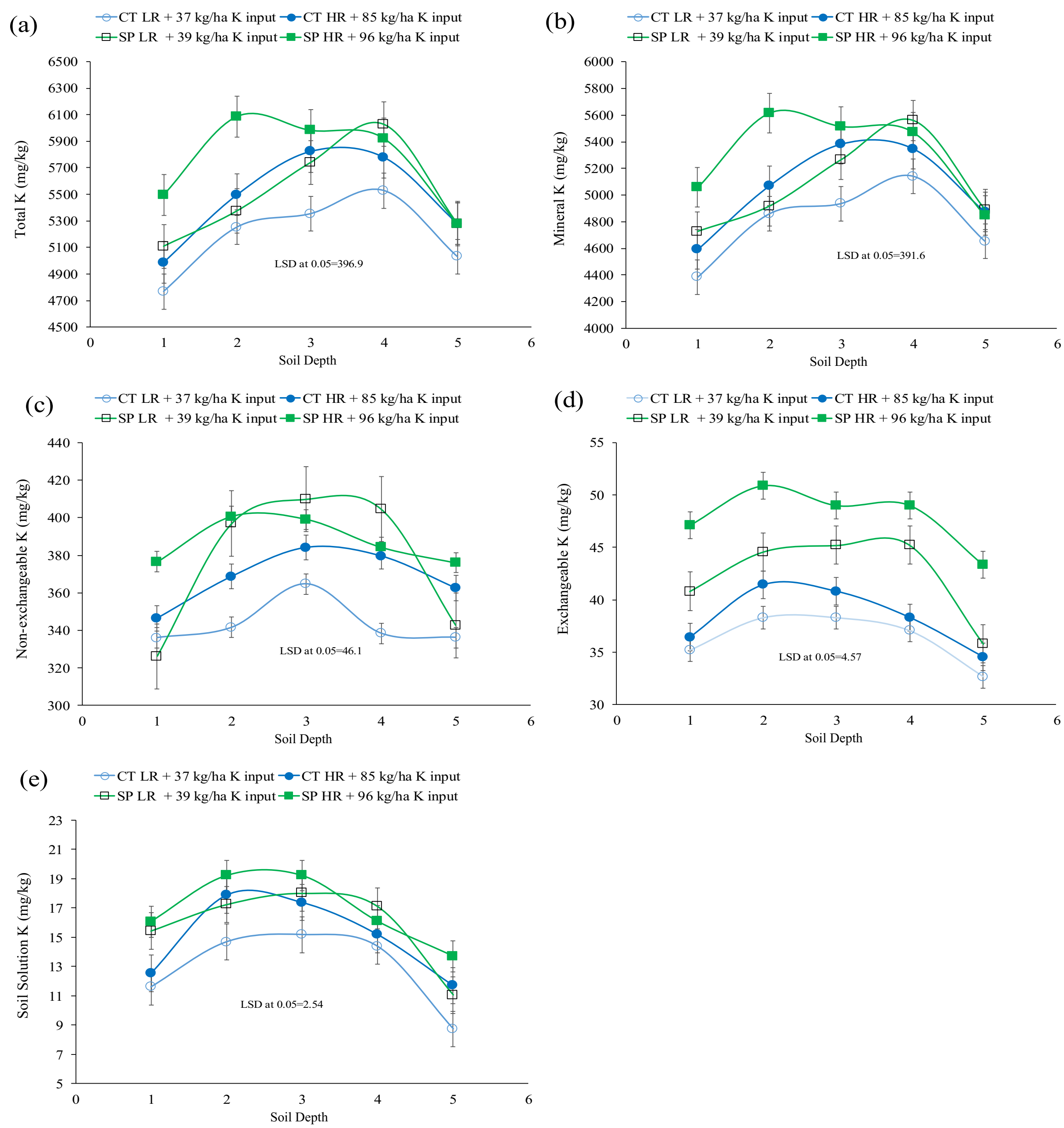

Fig. 4 Total K (**a**), mineral K (**b**), non-exchangeable K (**c**), exchangeable K (**d**) and soil solution K (**e**) as affected by total K input from residue and soil depth. [*Legends*: *SP* strip planting and *CT* conventional tillage; *HR* high residue and *LR* low residue; Soil depth 1 = 0–5 cm, depth 2 = 5–15 cm, depth 3 = 15–30 cm, depth 4 = 30–45 cm and depth 5 = 45–60 cm. Error bars represent SE ($P < 0.05$); Means ($n = 4$) shown]

165 mg kg^{-1} and 19.3 g kg^{-1} respectively) in reddish paddy soil (Liao et al. 2013). Moreover, incorporation of crop residues at a rate of 4.5 t ha^{-1} substantially reduced the K depletion from the soil under rice–wheat cropping patterns in the north-western part of Bangladesh (Miah et al. 2008).

Soil K dynamics and K release to the soil solution is strongly connected to soil organic matter content and clay mineralogy. K adsorption on the surfaces of clay minerals influences K leaching and plant availability (Taiwo et al. 2018). Similarly, organic matter addition to soils controls soil K dynamics and release. In addition, organic matter interacts with clay minerals primarily on the external planar positions (Sarkar et al. 2018), resulting in a potential increase in the K-selective sorption on clay minerals. Poonia et al. (1986) and Wang and Huang (2001) suggested that organic matter considerably promoted the initial K adsorption and had more easily accessible adsorption sites for K compared with mineral constituents of the soils. Hence, with increased crop residue retention and the accumulation of SOC, as reported here, there may have been an increase in retention of exchangeable K, which in time may increase the non-exchangeable K fraction associated with the inter-layers of illite clay minerals.

On the other hand, SP-LR appeared to deplete non-exchangeable K in the surface soil more than CT-LR. Strip planting and LR increased the yield of lentil and rice and of rice straw even though the same amount of inorganic K was utilized in both cases. Hence, SP-LR appears to acquire more K from non-exchangeable K forms in the soil. According to Srinivasarao and Khera (1994), up to 80% of the total K requirements of plants can be fulfilled by the non-exchangeable form of soil K. In the present case, at least part of the increased K uptake in crop produce with SP-LR appears to have been supplied by non-exchangeable K resulting in its declining level in the top soil over time.

However, total and mineral K values in the profile were not determined at the start of this experiment so it is not clear whether the higher total and mineral K reserves associated with increased residue retention was due to higher residue K input, or to less depletion of soil K.

Minimum soil disturbance enhanced K retention in the soil

Changing soil management from CT to SP maintained higher levels of all soil K fractions regardless of the residue retention levels. Minimum soil disturbance stratifies soil K due to less mixing and shallower disturbance of soil which results in less K from crop residues and from fertilizer being re-distributed or mixed at depth. Secondly, minimum soil disturbance allows the accumulation of soil organic matter which increases the cation exchange capacity of the soil that in turn helps to enhance K retention in the soil. The decrease in soil disturbance over 24 successive crops resulted in an extra 0.5 t of organic matter/ha/year added to the soil and an extra 7 kg of K per ha per year recycled to the soil. Combined these two processes partly explain the accumulation of K fractions after long term SP in the present study. Jaskulaska et al. (2020) reported that the content of available K was significantly higher in SP (283 mg kg^{-1}) compared to CT (256 mg kg^{-1}). Rahman et al. (2008) observed higher values for exchangeable K in no tillage (0.67 cmol kg^{-1}) than in CT (0.57 cmol kg^{-1}) or with soil puddling (0.45 cmol kg^{-1}).

The SP treatment increased the K concentration in soil solution that may also lead to increases in the non-exchangeable K pool in soil. Potassium fixation occurs when K^+ ions are sorbed on the highly charged sites of the interlayers of 2:1 type silicate clay (Vermiculite and mica) minerals (Pettygrove et al. 2011) and this fixation increase with the increase of soluble K concentration in soil solution (Arfin and Tan 1973; M. Najafi Ghiri and Ali Abtahi 2012). Kovar and Barber (1990) and Chen and Mackenzie (1992) also observed that application of K in combination with N in their experiments resulted in an increase in K + fixation in soils containing 2:1 mineral such as illite, vermiculite, and mica. However, total and mineral K values in the profile were not determined at the start of this experiment so the higher total and mineral K reserves due to SP may be due to less depletion in the soils than conventional tillage as these intensive cropping systems tend to have negative K balances (Madhukar et al. 2017).

Implications for management of K fertilizers

Negative K balances are prevalent in many cropping systems globally (Ma and Bell 2020). The substantial rise in global potash fertilizer prices in 2021–2022 (World Bank report, commodity markets outlook, October 2021) will exacerbate the tendency of farmers to under supply K fertilizer. In the intensively cropped rice-based systems of the EGP, annual removal of K in grain and straw from three crops per year averages 218 – 232 (Lentil-T. Aus rice -T. Aman rice) and 405–412 (Potato-Maize-T. Aman rice) kg/ha per year (data not shown). For some time, soil K reserves have supplied the imbalance between input and output. The depletion of soil K due to negative K balances maybe uneven in the soil profile. At the surface with fertilizer supply and crop residues returned to the soil surface, available soil K levels may appear to be maintained over time. The negative K balance may therefore be reflected in declining subsoil K levels which are often not measured or monitored (e.g. Ma et al. 2022). Indeed, in the current study we found the positive effects of minimum tillage and of increase crop residue retention expressed in higher levels of K fractions as deep as 30 cm in the profile. In the absence of baseline total and mineral K values in the profile for the start of this experiment, it is not possible to determine whether there has been continuous depletion of subsoil K reserves due to negative K balances.

The present results suggest that for intensive cropping, CA practice or increasing crop residue retention in conventional farming, are available strategies for smallholder farmers to reverse negative K balances without resorting to large increases in K fertilizer rates. However, to make that change, strategies need to be developed to replace crop residues in the farming system with other inputs. For example, animal feeds need to be produced through fodder production plots rather than relying on the collection of plant residues from cropping fields. Housing for livestock can be improved with concrete floor pads and collection ponds for manure and residue which can then be recycled onto farms to minimise the loss of K and other nutrients. Rural electrification or the supply of cheap cooking gas for farm households would replace the need for collection of crop residue and manure as fuel for cooking. However, even with these interventions the need for additional K fertilizer inputs seems inevitable in these intensive cropping systems. Farmers' reluctance to increase K fertilizer rates needs to be addressed by systematic programmes to demonstrate profitable investments in K fertilizer and in using balanced nutrient inputs so that farmers understand the profitability implications of correcting K imbalance. Refined guidelines on the risk of K leaching and the amounts of K leached under different cropping systems and rainfall scenarios would be useful also. This should lead to research on split applications or slow release forms of K which would minimise K leaching. The intensive cropping system may benefit from inclusion of deep-rooted crops that are able to absorb K from deep in the profile and recycle it to the surface. In the EGP, for example, there are rainfed regions where deep-rooted chickpea can be grown in the Rabi season with a potential for recycling of K for the benefit of following rice crops.

The positive benefits of increase crop residue retention in the current study were obtained even though only 40 to 50% of the crop residue was retained. That portion is currently determined by the small-scale machinery used for planting in CA systems with two-wheel tractors (Haque et al. 2015). Small-scale machinery has limited clearance height which means they are unable to operate and maintain standard planting depths and soil cover of seed when the residue levels are more than 50% of crop height. A shift towards four-wheel tractor-based CA planting in the EGP over time may facilitate retention of higher levels residue with positive impacts on the recycling of K and other nutrients from crop residues. That change would be a positive impact on multiple aspects of soil health and nutrient balance including the maintenance of adequate levels of plant-available K and decreasing soil bulk density. However, four-wheel tractor-based planting may have other impacts on soil physical properties such as subsoil compaction that would need to be examined.

Conclusions

The status of K fractions in the upper 15 to 30 cm layer was positively influenced by reduced soil disturbance and by increased crop residue retention. The main hypothesis of this study was supported since SP practice and HR retention significantly increased K pools and other properties in soils along with soil organic carbon. It may be concluded that SP practice with and without HR retention is a suitable option to increase K pools as well as soil organic carbon and total N in soils and to be an effective method for improving soil K availability, reversing negative K balance and enhancing K cycling in the intensively cropped rice-based systems.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Gender issues were also avoided in publishing this manuscript.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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