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Special Issue Article

Conservation Agriculture in Cereals Systems in the Indo-Gangetic Plains: Impacts on Productivity, Resource-use Efficiency and Soil Properties

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ABSTRACT

Conservation agriculture (CA)-based experiments were conducted at various locations in Indo-Gangetic Plains (IGP) of India in rice-based and other cropping systems. A triple ZT system at IARI, New Delhi, involving zero tillage DSR (ZTDSR) with green gram (GG) residue (GGR)- ZT wheat (ZTW)/ZT mustard (ZTM) with rice residue (RR) – ZTGG with wheat residue (WR)/ mustard residue (MR) (GGR+ ZTDSR - RR+ZTW/ZTM-WR/MR+ ZTGG) gave 29% and 45% higher system productivity and 27 and 54% higher system net returns in rice-wheat and rice-mustard cropping systems compared to the TPR-Conventional wheat/maize system, respectively. Similarly, the system productivity in maize-wheat-green gram under CA was higher compared to conventional tillage system. Another study in Karnal showed that the exclusion of tillage in DSR could reduce energy input by 41% and save irrigation water by 26% compared to conventional puddled transplanted rice (CT-R). In Jabalpur, the similar system, *i.e.*, DSRZT+ crop residue (R)+ *Sesbania* (S)- ZTW+R- ZTGG (green gram) +R led to higher irrigation and total water productivities of by 74% and 25%, respectively over the DSRCT+S-CTW-ZTGG system. Zero tillage had lowest bulk density (1.51 Mg/m^3) and soil resistance to penetration (1.48 MPa), but had the highest infiltration rate (0.44 cm h^{-1}), which indicated an improvement in soil physical conditions under CA. Higher SOC (0.84%), available N and P and micro-nutrient (Zn, Cu, and Mn) contents were also recorded under CA. The CT or minimum tillage in rice followed by conventional maize with recommended dose of fertilizer and residue mulch @ 6t ha^{-1} resulted in higher N_2O emission compared to other treatments. However, when minimum tillage in rice was followed by ZT maize with similar fertilizer inputs but no residue, lowest emission was recorded. CA-based RWS or diversification of the RWS with suitable crops may be recommended for the IGP of India, and also in similar agro-ecologies of the tropics and sub-tropics for higher productivity, resource-use efficiency and better soil properties. Inclusion of a legume, preferably green gram during summer months would provide additional yield and income, and bring more sustainability in this system.

Key words: Conservation agriculture, crop yields, rice-wheat system, diversification, resource-use efficiency, soil properties

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Introduction

Conventional agricultural system is facing a host of problems such as declining (input) factor productivity, degradation of soil health, declining/ stagnating crop yields and farm income, global warming, declining biodiversity, secondary salinization and sodicity, susceptibility to climatic variability; and air and ground water pollution (Humphreys *et al.*, 2010; Gathala *et al.*, 2011; Das *et al.*, 2014; Bhattacharyya *et al.*, 2018; Modak *et al.*, 2019). The Indo-Gangetic Plains (IGP) plays a crucial role for ensuring food security of India. Rice-wheat system (RWS) is the predominant cropping system in this region, occupying ~10.5 Mha area (Das *et al.*, 2018, 2020). However, the sustainability of RWS, which is more resource-intensive, is under threat due to several problems like declining ground water table, deteriorating soil health, deficiency/ imbalance/loss of nutrients, and environmental pollution (Gathala *et al.*, 2011a; Chauhan *et al.*, 2012). Most of these emerging problems could be solved/ managed by the adoption of Conservation agriculture (CA). In India, the CA occupied ~ 1.50 M ha area is mostly engaged in the rice-wheat cropping system of the IGP. The CA can conserve and make more efficient use of natural resources through integrated management of available soil, water and biological resources combined with external/manmade inputs (Kassam *et al.*, 2018; Mohammad *et al.*, 2018). It offers numerous benefits: enhanced crop productivity and profitability; reductions in fossil fuel use, GHGs emission, soil erosion, yield variability, and carbon losses; and improved soil structure and water retention, and carbon sequestration (Das *et al.*, 2018; Mondal *et al.*, 2019). Despites these benefits, adoption of CA is not impressive in India. Non-availability of desired CA technologies, machineries, inadequate knowledge on complete CA package, inadequate policies (lack of priority, promotion and incentives for adoption), and social constraints like strong belief in ploughing are constraints/issues, which hinder the spread of CA in India.

Some component practices of the CA could be zero till direct-seeded rice (ZTDSR), brown manuring (BM) of *Sesbania aculeata* or *Crotalaria juncea*, crop/rice residue (RR) retention, and ZT wheat (ZTW). The RWS needs to be diversified as well with non-rice crops to minimize the irrigation water use, which could be as remunerative as rice. Therefore, studies were designed and carried out across locations of the Indian IGP with the objectives: (i) to replace conventional transplanted rice (TPR) with suitable DSR-based system, involving CA; and (ii) to diversify the RWS with inclusion of suitable crops during rainy (*kharif)*, winter (*rabi)* or summer (*zaid*) season.

Materials and Methods

Five CA-based experiments were undertaken for three years in rice-based (*i.e.*, rice-wheat; rice-mustard during 2013-14 to 2015-16) and wheat-based (maize-wheat; cotton-wheat; pigeonpea-wheat during 2011-12 to 2013-14) cropping systems at ICAR-Indian Agricultural Research Institute, New Delhi. A set of four CA/CT treatments each under rice-based systems (Table 1) and under wheat-based systems (Table 6) were evaluated for system productivity and economics for three years. Similar experiments on rice-wheat-green gram cropping system were undertaken under CA at ICAR-Directorate of Weed Research, Jabalpur, comprising treatments of ZTDSR with crop residue and *Sesbania* co-culture and CT (Table 2). Experiment was also conducted for five years (2015-2020) at ICAR-Central Soil Salinity Research Institute, Karnal, Haryana in RWS in a well-drained reclaimed sodic soil, with CT rice (puddled transplanted rice) - CT wheat with 100% residue removed from both crops (CT-R), reduced till DSR- reduced till wheat with 1/3rd residue incorporation in both crops (RT+R), ZTDSR – zero-tillage wheat (ZTW) with 1/3rd residue retention in both crops (ZT+R), and reduced till DSR-ZTW with 100% rice residue mulched (RT-R/ZT+R) (Table 3). A long-term effect of CA practice on maize-wheat-green gram system was also evaluated at ICAR-Indian Institute of Wheat and Barley Research (IIWBR), Karnal, Haryana. Whole wheat and maize residues produced in respective plots were kept as residue. After picking of pods, greengram residue was

Table 1. System productivity (rice equivalent yield; REY) and net returns under CA-based rice-wheat and rice-mustard cropping systems (mean of three years) in Delhi

Treatment	Rice-wheat		Rice-mustard	
	Productivity (REY) (t/ha)	Net returns ($\times 10^3$ Rs/ha)	Productivity (REY) (t/ha)	Net returns ($\times 10^3$ Rs/ha)
Direct-seeded rice (DSR) – zero-till wheat (ZTW)/zero-till mustard (ZTM)	10.05^{b*}	115.0^{b*}	8.08^{c*}	81.0^{c*}
Wheat residue (WR)/ mustard residue (MR) DSR – rice residue (RR) + ZTW/ZTM	9.93^{b}	112.5^{b}	9.04^{b}	96.8^{b}
Green gram(GG) residue (GGR) + DSR - RR+ ZTW/ ZTM-WR/MR+ ZTGG	13.18^{a} (10.73)‡ (29.2%)†	138.4^{a} (125.1)‡ (27.1%)†	13.70^{a} (10.28)‡ (45.4%)†	133.0^{a} (101.7)‡ (53.9%)†
TPR-CTW/CTM	10.20^{b}	108.9^{b}	9.42^{b}	86.4^{c}
P-value	<.0001	0.0421	<.0001	<.0001
Contrast (CA vs CT)				
CA	11.56^{a}	125.5^{a}	11.37^{a}	103.6^{a}
CT	10.20^{b}	108.9^{b}	9.42^{b}	86.4^{b}
P-value	<.0001	0.0414	<.0001	<.0001

‡ indicates system productivity and net returns without considering green gram's yield and economics; †indicates per cent increase in system productivity and net returns under rice-wheat and rice-mustard systems (including green gram) compared to TPR-CTW/CTM system;
*Means followed by different lowercase letters within a column differed significantly ($P \leq 0.05$) as per Tukey's Honest Significant Difference test.

Table 2. System crop and water productivities and economics of the rice-wheat-green gram cropping system under CA in Jabalpur

Treatment	System productivity (REY) (t/ha)	Net return ($\times 10^3$Rs/ha)	System irrigation water productivity (kg grain/mm-ha)	System water productivity (kg grain/mm-ha)
DSR CT+*Sesbania* (S)-CTW-ZTGG	10.42^{b*}	126.0^{c*}	19.3^{b*}	6.8^{b*}
DSR CT+ crop residue(R)+ S-CTW+ R – ZTGG+R	11.36^{a}	132.0^{c}	25.2^{a}	7.9^{a}
DSR ZT+S-ZTW-ZTGG	10.51^{b}	140.0^{b}	19.5^{b}	6.9^{b}
DSR ZT+R+S-ZTW+R-ZTGG+R	11.64^{a}	149.0^{a}	25.9^{a}	8.1^{a}
TPR-CT-fallow	8.34^{c}	98.0^{d}	16.2^{c}	5.8^{c}

*Means followed by different lowercase letters within a column differed significantly ($P \leq 0.05$) as per Tukey's Honest Significant Difference test.

either removed from the CT system or retained after spraying with glyphosate+paraquat in CA system. Similarly, 15 CA-based demonstrations were conducted on wheat under RWS in villages of Karnal District, Haryana in winter during 2015-16 to 2019-20. Wheat cultivar HD 2987, HD 3086, BISA 921 and PBW 723 were sown with 125 kg seed ha^{-1} using turbo happy seeder. Another two CA experiments reported are being undertaken in rice-green gram (Table 4) and rice-maize (Table 5) systems at ICAR-National Rice Research Institute (NRRI) since 2015 to compare the overall impact on productivity, soil health, and greenhouse gases (GHGs) emissions. Main

Table 3. System productivity and net returns of rice-wheat system under CA treatments (mean of five years) in Karnal

Treatment	System productivity (t/ha)	Net returns ($\times 10^3$ Rs/ha)
CT-R	12.38[bc*]	147.6
RT+R	13.03[a]	161.8
ZT+R	11.96[c]	152.6
RT-R/ZT+R	12.65[ab]	157.9

[*]Means followed by different lowercase letters within a column differed significantly (P≤0.05) as per Tukey's Honest Significant Difference test.

Germany), infiltration rate by double-ring infiltrometer, soil aggregates by Yoder apparatus, available water content by gravimetric method. Similarly, standard procedures were followed to determine soil organic carbon (Walkley and Black 1934), available N (Subbiah and Asija, 1956), available P (Olsen *et al.*, 1954), available K (Jackson, 1973), and soil micro-nutrients (Lindsay and Norvell, 1978). The emission of greenhouse gases was estimated as per Gupta *et al.* (2016).

Contrast analysis was also done for better comparison between CA and CT. All data were analyzed using the analysis of variance technique using PROC GLM in the statistical software package SAS 9.3 (SAS Institute, Cary, NC).

Table 4. System productivity of rice-green gram cropping system under the CA across 5 years in Cuttack

Tillage practices (T)	System productivity (t/ha)				
	2015-16	2016-17	2017-18	2018-19	2019-20
CTDSR-CTGG	7.26	6.99	7.55	8.75	7.63
ZTDSR-ZTGG	6.68	6.32	6.69	7.95	6.72
ZTTPR-ZTGG	7.26	7.15	7.65	8.70	7.85
LSD (P≤0.05)	NS	0.40	0.26	0.21	0.23

Table 5. System productivity in rice-maize system and N_2O emission in maize in Cuttack (after 3 years of CA)

Treatment	System (R-M) productivity (t/ha)	N_2O (kg/ha) in maize	kg CO_2 eq./ha
Minimum till rice(MTR)+ 100%N- zero till maize (ZTM)+RDF	11.78	0.69	206.6
MTR+100%N-ZTM+RDF+ residue mulch 3t/ha (RM 3)	12.11	1.00	299.0
MTR+100%N-ZTM+RDF+ residue mulch 6t/ha (RM6)	12.35	1.25	371.5
Conventional till rice (CTR)+100%N - conventional till maize (CTM) + RDF	12.85	0.90	268.2
CTR+100%N-CTM +RDF+RM3	14.12	1.15	341.7
CTR+100%N-CTM+RDF+RM6	13.84	1.44	428.1
LSD (P=0.05)	1.073	0.024	11.63

plot treatments comprising of ZTDSR followed by (*fb*) ZT green gram (ZTDSR-ZTGG); ZT (non-puddled) mechanical transplanted rice *fb*ZT green gram (ZTTPR-ZTGG), and CT rice –CT green gram (CTDSR-CTGG) were superimposed with three green gram varieties, *viz.*, IPM 2-3, IPM 02-14 and local check.

Soil parameters were evaluated by following standard methods, e.g. bulk density by core method, penetration resistance by manual cone penetrometer (Eijkelkamp Agrisearch Equipment,

Results and Discussion

Crop and system productivity and profitability

Rice-based cropping systems (rice-wheat-green gram, rice-wheat/mustard/green gram)

A triple ZT system with three crops (rice, wheat/mustard, green gram) residue, which involved ZTDSR with green gram (GG) residue

(GGR)- ZT wheat (ZTW)/ZT mustard with rice residue (RR) – ZTGG with wheat residue(WR)/ mustard residue(MR) (GGR+ZTDSR - RR+ZTW/ ZTM-WR/MR+ ZTGG) resulted in 29% and 45% higher system productivity and 27% and 54% higher system net returns in rice-wheat and rice-mustard cropping system, respectively compared to the conventional TPR-CTW/CTM, (Table 1). Contrast analysis revealed that the CA had led to significantly higher system productivity and net returns in both the systems. The triple ZT system having additional yield of green gram gave higher system yield and net returns over conventional system for three-times higher support price in green gram compared to rice and wheat, even though it involved higher cost of cultivation due to additional cost of growing green gram in summer. Rice and wheat crops together also gave 0.53 t ha^{-1} higher system productivity and Rs. 16,200 ha^{-1} higher net returns; and rice and mustard crops together gave 0.86 t ha^{-1} higher system productivity and Rs. 15,300 ha higher net returns compared to the conventional system. Thus, the addition of residues of three crops including a legume besides controlling weeds and nematodes (Baghel *et al.*, 2020), might have led to better soil conditions (Mondal *et al.*, 2019; Modak *et al.*, 2020), prolonged moisture retention (Das *et al.*, 2020), higher C and N sequestration (Bhattacharyya *et al.*, 2015), and availability of nutrients, which facilitated better growth and higher yields. In Jabalpur, DSRZT+ crop residue (R)+ *Sesbania* (S) co-culture -ZTW+R –ZT green gram with residue (ZTGG+R) resulted in significantly higher system productivity (11.64 t ha^{-1}) and net returns (Rs 1,49,000 ha) than other treatments except the DSRCT+R+S-CTW+R-ZTGG+R (system productivity (Table 2)). Inclusion of green gram considerably increased system productivity by 25-40% irrespective of tillage and residue retention over the TPR-CTW-fallow system. Higher system productivity in DSR ZT+R+S-ZTW+R-ZTGG+R system was mainly due to the combined effect of higher yield in wheat and green gram. Higher system profitability accrued mainly due to additional harvest of green gram, saving in cost of production like tillage, water, coupled with higher crop yields (Choudhary, 2016). The study in Karnal revealed that the reduced till DSR-reduced till wheat (with 1/3rd residue incorporation in both crops) (RT+R) resulted in higher system productivity and net returns compared to puddled transplanted rice-CT wheat with whole or 100% residue removed from both crops (CT-R) (Table 3), It remained comparable with the reduced till DSR- ZTW with whole or 100% rice residue mulched (RT+R/ ZT+R). This treatment (RT+R) also fetched Rs 14247 ha-1 higher system net returns. In another experiment on rice-green gram system in Cuttack, Odisha revealed that ZTTPR-ZTGG system resulted in consistently higher system productivity from 2nd year onwards (Table 4). However, in rice-maize system conventional (CTR+100%N-CTM +RDF+RM3) led to significantly higher system productivity than all minimal till systems with same level of inputs or residue (Table 5). Other CT system like CTR+100%N-CTM+RDF+ RM6 was comparable with CTR+100%N-CTM +RDF+RM3. In this context, the results of 15 CA-based demonstrations trials on wheat under the rice-wheat system in villages of Karnal district indicated that although wheat yields were comparable between CA (5.95 t ha^{-1}) and CT (6.02 t ha^{-1}) system (Fig. 1), the lower cost and saving of time in tillage operation made the CA advantageous over the CT system. Chaudhary *et al*. (2019) reported that the ZT with surface residue retention was more beneficial in terms of energy, time and cost effectiveness. Also, the adoption of ZT+ residue retention in wheat under the rice-wheat system could improve wheat yield

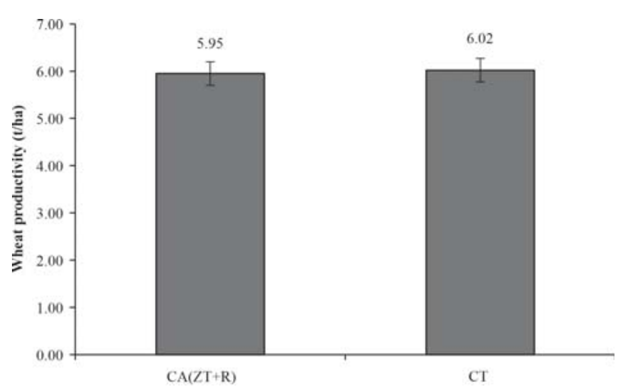

Fig. 1. Comparative performance of CA and CT system on wheat productivity under rice-wheat system in Karnal (mean of 15 demonstrations)

by advancing time of wheat sowing and reducing weed infestation, particularly *Phalaris minor* Retz. (Chaudhary *et al.*, 2019).

Diversified cropping systems (cotton/pigeon pea/ maize-wheat)

In cotton-wheat and pigeon pea-wheat systems, ZT permanent broad bed with residue (PBB+R), ZT flat bed with residue (ZTFB+R) and ZT permanent narrow bed with residue (PNB+R) were comparable with each other on system productivity (in wheat equivalent yield) and net returns (Jat *et al.*, 2013; Das *et al.*, 2014, 2018), compared to conventional till flatbed (CTFB) system (Table 6). However, among all CA practices, the PBB+R was the most superior in these regards. This implied that cotton-wheat and pigeon pea-wheat systems responded more or less uniformly/ equally to these three CA systems. In contrast, in the maize-wheat system, the CA-based PBB+R and ZTFB+R were comparable with each other and gave higher system productivity and net returns than CTFB and PNB+R system. Contrast analysis also revealed that the CA system was superior to CT and gave higher system productivity and net returns in maize-wheat (13%), cotton-wheat (27%) and pigeon pea-wheat (10%) systems. The improvement in system productivity might be attributed to the compound effect of ZT and residue, leading to lower weed interference (Susha *et al.*, 2018) and greater nutrients availability, improved soil physical properties (Mondal *et al.*, 2019), better aeration, efficient nutrient and water use in CA over the CT (Das *et al.*, 2014, 2018). Both crops residue in each system added organic C to soil on decomposition and led to improvement in SOC, N, and other nutrients (Das *et al.*, 2018; Modak *et al.*, 2019, 2020). Another study evaluating showed higher maize yield in CA (8.77 t/ha) compared to CT (8.52 t ha^{-1}) in maize-wheat system in Karnal (Fig. 2). Improved physicochemical conditions of soil in CA (Das *et al.*, 2013), resulting in better growth of maize might be responsible for higher productivity under the CA. Wheat yields in CA (6.10 t ha^{-1}) and CT (6.17 t ha^{-1}) were similar, but the maize-wheat system's wheat equivalent yield was marginally higher in CA (14.26 t ha^{-1}) compared to CT (14.16 t ha^{-1}). Rice yields could be are lower under CA (Chhokar *et al.*, 2014) and therefore, maize-wheat-green gram system could be a better option under the CA.

Resource-use efficiency

The adoption of CA-based RWS over the years led to savings in N by 25% (60 kg N ha^{-1}) and labour by 33% (Table 7). Cotton-wheat system saved irrigation water by 60%, N by 25% (68 kg N/ha) and labour by 13 %. Similarly, CA-

Table 6. System productivity (wheat equivalent yield; WEY) and net returns under CA-based maize-wheat, cotton-wheat and pigeon pea-wheat systems in Delhi (mean of 3 years)

Treatment	Maize-wheat		Cotton-wheat		Pigeon pea-wheat	
	Productivity (WEY) (t ha^{-1})	Net returns (×10^3 Rs ha^{-1})	Productivity (WEY)(t ha^{-1})	Net returns (×10^3 Rs ha^{-1})	Productivity (WEY) (t ha^{-1})	Net returns (×10^3 Rs ha^{-1})
CT FB	8.28^{c*}	107.6^{b*}	10.78^{b*}	117.5^{b*}	9.45^{b*}	97.5^{b*}
PNB+R	9.03^{b}	118.5^{b}	13.58^{a}	161.8^{a}	10.32^{a}	112.6^{a}
PBB+R	9.58^{a}	130.7^{a}	14.07^{a}	164.7^{a}	10.47^{a}	116.0^{a}
ZTFB+R	9.54^{a}	132.1^{a}	13.53^{a}	161.7^{a}	10.48^{a}	115.2^{a}
P-value	<.0001	0.0073	0.0001	0.0046	0.0008	0.0424
Contrast (CA vs CT)						
CA	9.38^{a}	127.1^{a}	13.73^{a}	162.8^{a}	10.42^{a}	114.6^{a}
CT	8.28^{b}	107.6^{b}	10.78^{b}	117.5^{b}	9.45^{b}	97.4^{b}
P-value	0.0006	0.0163	0.0263	0.0421	0.0123	0.0239

[*]Means followed by different lowercase letters within a column differed significantly (P≤0.05) as per Tukey's Honest Significant Difference test.

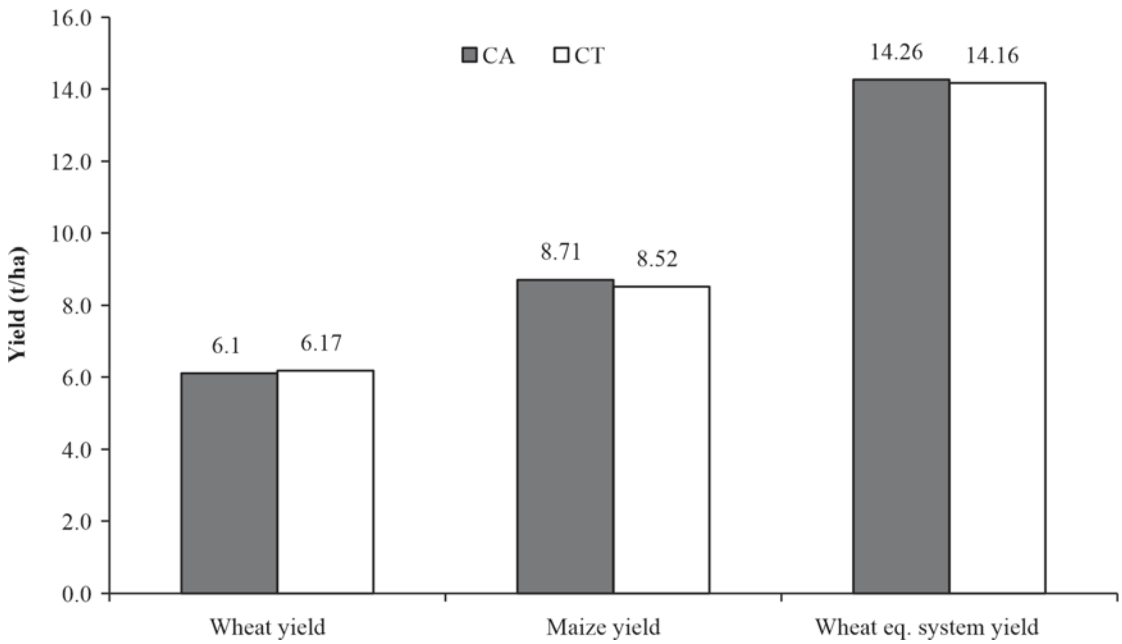

Fig. 2. Comparative performance of CA and CT on productivity of maize-wheat system in Karnal (mean of 4 years)

Table 7. Resources saving under CA-based cropping systems in Delhi

Resources	Cropping system	Savings
Irrigation water	Cotton-wheat (ZT+PBB+R)	60.3%
(compared to TPR-CTW)	Pigeon pea-wheat (ZT+PBB+R)	67.9%
	Maize-wheat (ZT+FB+R)	63.5%
Nitrogen (compared to CT)	Cotton-wheat (ZT+PBB+R)	25% (~67.5 kg N ha^{-1})
	Maize-wheat (ZT+FB+R)	25% (~67.5 kg N ha^{-1})
	Rice-wheat (MBR+DSR - RR+ ZTW/ ZTM-WR/MR+ ZTGG)	25% (~60 kg N ha^{-1})
Labour (compared to CT)	Cotton-wheat (CA treatment)	13.1% (cotton 8.1%+wheat 5%)
	Maize-wheat (CA treatment)	10% (maize 5%+wheat 5%)
	Pigeon pea-wheat (CA treatment)	15.6% (pigeon pea 10.6%+wheat 5%)
	Rice-wheat (CA treatment)	32.7% (rice 25%; wheat 7.7%)

based maize-wheat system saved 64% irrigation water, 25% N and 10% labour (Saad *et al.*, 2016). Another study in Karnal showed that input energy was maximum in CT-R (23,481 MJ ha^{-1}), while minimum in ZT+R (13,763 MJ ha^{-1}) (Table 8). No tillage operations in DSR and wheat could reduce energy input in ZT+R by 41% compared to CT-R. Direct seeding of rice with scheduling of irrigation water at 5 days after disappearance of ponded water (ZT+R) led to a saving of 26% irrigation water compared to CT-R in rice. Under the rice-wheat-green gram system in Jabalpur, the DSRZT+crop residue (R)+*Sesbania* (S)-ZTW+R-ZTGG+R resulted in higher system water productivity (irrigation and the total) by 74% and 25%, respectively compared to DSRCT+S-CTW-ZTGG system (Table 2). Higher grain yield and lower amount of irrigation water required due to reduction in water loss in this system played roles in improving water productivity (Choudhary, 2015; Saad *et al.*, 2016).

Table 8. Resource savings in rice-wheat system under CA-based treatments compared to CT

Treatment	Total energy consumption (MJ ha^{-1}) and savings (in parentheses)*	Irrigation water applied (mm) and savings (in parentheses)*
CT-R	23481	1072
RT+R	16948 (27.8%)*	813 (24.2%)*
ZT+R	13763 (41.4%)	791 (26.2%)
RT-R/ZT+R	14496 (38.3%)	761 (29.0%)

Table 9. Soil physical properties across CA-based treatments compared to CT

Treatments	Bulk density (Mg m^{-3})	Penetration resistance (MPa)	Infiltration rate (cm hr^{-1})	Water stable aggregates (%)	Available water content (%)
CT-R	1.56[a*]	2.33[a*]	0.16	29.2	13.1
RT+R	1.52[b]	1.93[b]	0.38	49.5	14.2
ZT+R	1.51[b]	1.48[c]	0.44	55.4	14.4
RT-R/ZT+R	1.53[b]	1.50[c]	0.38	52.3	14.3

[*]Means followed by different lowercase letters within a column differed significantly (P≤0.05) as per Tukey's Honest Significant Difference test.

Soil physical and chemical properties

Long term experiments in Karnal recorded improvement in soil physical properties in CA in RWS. The ZT+R practice resulted in lowest bulk density (1.51 Mg/m^3) and soil penetration resistance (1.48 MPa) with highest infiltration rate (0.44 cm/ha) (Table 9). McGarry *et al.* (2000) reported similar results for zero and traditional tillage practice. Similarly, water stable aggregates and available water content were higher under this practice than in CT-R (Radford *et al.*, 1995; Aggarwal *et al.*, 2017; Mohammad *et al.*, 2018). Another long-term study in maize-wheat-green gram system showed that the CA plots had lower soil resistance to penetration compared to CT (Fig. 3). Our findings are in conformity with

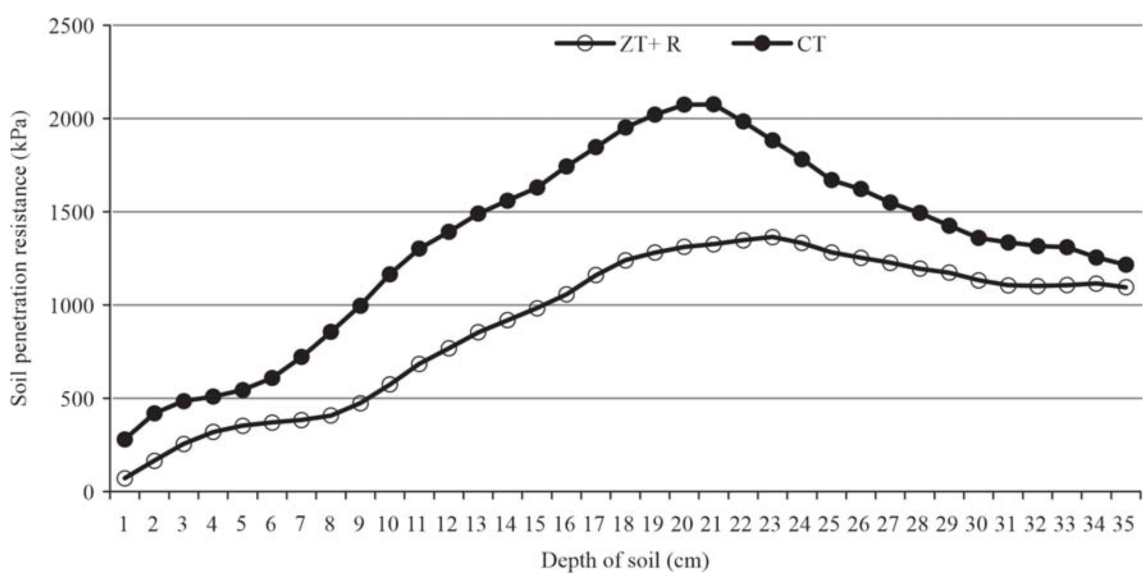

Fig. 3. Effect of tillage and residue management on soil penetration resistance in maize-wheat-green gram system in Karnal

Table 10. Soil chemical properties under different conservation agriculture practices

Treatments	SOC	N	P	K	Zn	Cu	Fe	Mn
	(%)	(kg ha^{-1})			(mg kg^{-1})			
CT-R	0.58^{b*}	115.0^{b*}	24.8^{bc*}	227.7^{a*}	2.94^{b*}	1.77^{a*}	24.45^{ab*}	4.26^{c*}
RT+R	0.82^{a}	127.4^{a}	22.9^{c}	244.5^{a}	5.39^{a}	1.96^{a}	21.91^{b}	6.41^{b}
ZT+R	0.84^{a}	124.1^{a}	30.2^{ab}	254.0^{a}	5.78^{a}	1.83^{a}	20.61^{b}	8.01^{a}
RT-R/ZT+R	0.85^{a}	130.0^{a}	39.8^{a}	245.7^{a}	6.71^{a}	1.88^{a}	29.80^{a}	8.26^{a}

[*]Means followed by different lowercase letters within a column differed significantly (P≤0.05) as per Tukey's Honest Significant Difference test.

Mondal *et al.* (2019) and Aggarwal *et al.* (2017). Lower penetration resistance facilitated better root growth of crops in this system (Mondal *et al.*, 2019). The CA also improved soil moisture retention (both at 0.33 and 15 bar) and available water content compared to CT-R (Table 9), and soil organic carbon (SOC) (Table 10). The CA-based systems [RT-R/ZT+R (0.85%), ZT+R (0.84%), RT+R (0.82%)] resulted in significantly higher SOC than CT-R (0.58%). Similar improvement in SOC in CA plot has been observed earlier (Bhattacharyya *et al.*, 2015; Das *et al.*, 2018; Modak *et al.*, 2019, 2020). Besides, the RT-R/ZT+R and ZT+R plots resulted in higher availability of N and P in soil compared to CT-R, while no effect was observed on the soil available K. Soil micro-nutrients such as Zn, Cu and Mn content under different CA treatments varied from 5.39-6.71, 1.83-1.96, and 6.41-8.26 mg kg^{-1} compared to 2.94, 1.77 and 4.26 mg kg^{-1} soil in CT-R. In contrast, Fe content was higher in CT-R (24.45 mg/kg) treatment than in CA-based treatments.

Greenhouse gases emission

The CT system (CTR+100% N-CTM +RDF+RM6) and minimum till system with same level of input or residue resulted in significantly higher emission of N_2O compared to other treatments. The lowest emission was recorded in MTR+100%N-ZTM+RDF with no-residue. Higher emission of N_2O in the former treatment led to higher amount of kg CO_2 equivalence ha^{-1}, which ultimately was responsible for higher global warming potential (Gupta *et al.*, 2016).

Conclusions

The CA-based rice-wheat-green gram cropping system and the diversified cotton/ pigeon pea/maize–wheat systems could be a possible substitute for their respective conventional system. Inclusion of legume green gram during summer would bring more sustainability to these systems. Adoption of CA would lead to higher productivity, profitability, and resource-use efficiency, and improve soil health in the Indian IGP. However, the difficulty in farmers' house-hold level availability of required seeder machines/ tractors, efficient herbicides to curb weeds, somewhere yield penalty (as perceived) in the initial years are the main hindrance to the success of this practice. Proven resource-efficient CA practice, better government policies for supply of timely and scale-appropriate CA machineries, incentives for promotion of CA technologies and subsidies to farmers for growing crops under CA, however, can overcome this and facilitate better adoption of the CA practice in the IGP of India.

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