Conservation agriculture based sustainable intensification of basmati rice-wheat system in North-West India

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ABSTRACT
Continuous mono-cropping of rice-wheat (RW) system with conventional tillage (CT) based management practices have led to decline in soil health, groundwater table and farmers profit in north-west India. A medium-term (4 years) farmer’s participatory strategic research trial of basmati RW system was conducted to evaluate the effects of conservation agriculture (CA) based management practices on crop yields, water productivity, profitability and soil quality. Six treatments were compared varied in the cropping system, tillage, crop establishment and residue management. CA-based management under zero-till direct seeded rice-wheat-mungbean recorded 36% higher system yield than conventional till rice-wheat system (14.91 Mg ha\(^{-1}\)). CA-based rice-wheat system and rice-wheat-mungbean system saved ~35% irrigation water compared to conventional RW system (2168 mm ha\(^{-1}\)). Total water productivity (WP\(_{I+R}\)) was improved by 67% with CA-based rice-wheat-mungbean system (0.90 kg grain m\(^{-3}\)) over the conventional system. On system basis, 42% higher net return was recorded with CA-based rice-wheat-mungbean system compared to conventional system (USD 2570 ha\(^{-1}\)). Mungbean integration in basmati RW system contributed 29% share in system net returns across the treatments. Soil chemical and biological properties were improved by ~40% and 150%, respectively, with CA-based management system.

Introduction
The rice-wheat (RW) cropping system occupies 13.5 Mha area of Indo-Gangetic Plains (IGP), 10.3 Mha of which is in the Indian IGP and providing food for more than 400 million people of South Asia (Kumar et al. 2018). High productivity of RW system with conventional management practices in IGP is at the cost of over-exploitation of natural resources like groundwater, soil and energy (Choudhary et al. 2018a). The groundwater table in central Punjab and parts of Haryana states decreasing with a speed of ~1.0 m a\(^{-1}\) between the year 2000 and 2006 (Humphreys et al. 2010). The productivity and sustainability of this system are threatened because of the inefficiency of traditional/conventional practices, natural resource degradation (especially land, water and energy), in-situ crop residue burning (nutrient loss) and socio-economic changes (Chauhan et al.

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In North West India farmers preferred to grow basmati rice because of its high economic values due to its aromatic quality. Cultivation of basmati rice occupies about 2.1 Mha in the country and the two states of Punjab and Haryana account ~80% of the total basmati rice produced in India (APEDA 2014).

The time window (turn-around time) between rice harvesting and wheat seeding is very limited (hardly 7–10 days). Within this time frame, management (removing/incorporation) of residues generated from rice field is very difficult; therefore open-field burning of rice residue is the common practice in North-West (NW) India. Crop residue burning results in nutrient loss of 100% C, 80% N, 25% P, 20% K and 50% S (Sharma et al. 2015) and causes increased concerns over public health and environmental problems (GHG emissions). In Haryana and Punjab, ~25 Mt of rice and wheat residues are being burned in-situ annually leading to a loss of about 10 Mt of C equivalent to a CO$_2$ load of about 35 Mt per year and a loss of about $1.2 \times 10^5$ tonnes of nitrogen (N) and the destruction of beneficial microflora of the soil (Yadvinder-Singh et al. 2015) with major implications for soil health and nutrient use efficiency (Jat et al. 2014). At harvest, rice straw contains ~12,500 MJ energy, 5–8 kg N, 0.7–1.2 kg P, 12–17 kg K and 0.5–1 kg S per ton while one ton of wheat residue contains ~12,500 MJ energy, 4–5 kg N, 0.7–0.9 kg P, and 9–11 kg K nutrients on dry weight basis (Yadvinder-Singh et al. 2015). Crop residues are indirect source of renewable energy and the primary source of organic matter (as C constitutes about 40% of the total dry biomass) that enriches the soil and provides stability to agricultural ecosystems. Recycling of crop residues reduces the terminal heat effect in wheat by buffering the soil temperature (lowered by 2–4°C) and moisture in NW India (Sharma et al. 2015).

The conventional practice of growing crops are input (nutrients, water and energy) intensive and contribute greatly to high cultivation costs, resulting in low economic returns in RW system (Aryal et al. 2016). In conventional tillage practices, the crop residues cannot be managed because of less turnaround time so farmers do not have any option except burning of crop residues. Therefore, efforts are increasingly devoted to conservation agriculture (CA) based management systems with three proven principles of minimum tillage, crop residue retention along with efficient crop rotations. The positive effects of CA-based agronomic management options like zero-tillage (ZT), crop establishment and crop residue recycling in RW system include high crop yields due to timely sowing of wheat, improved soil quality due to residue recycling and water saving due to less groundwater application (Kienzler et al. 2012; Jat et al. 2017; Kumar et al. 2018; Choudhary et al. 2018b). In addition, system intensification through the integration of short duration mungbean (Vigna radiata) may provide an opportunity to improve soil quality, increase protein yield and farmer’s profits. Inclusion of short duration mungbean (Vigna radiata) in RW systems helped in increasing farmers’ profits (Gathala et al. 2013) and soil quality (Jat et al. 2017; Choudhary et al. 2018b).

This study was conducted with the hypothesis of that recycling of crop residues with zero-tillage and system intensification in the RW system might increase crop productivity and soil quality while pumping less groundwater in North-West India. There is a paucity of literature available on the role of CA-based sustainable intensification in basmati RW system and their impact on soil quality and protein yield. The objective of this study was to assess the effect of ZT, crop establishment methods, residue recycling and cropping system intensification (through the inclusion of mungbean as relay or catch crop) on crop productivity, water saving, economic performance, soil quality and protein yield in basmati RW system in NW India.

**Material and methods**

**Experimental site characteristics**

A 4-year (2011–2012 to 2014–2015) on-farm study on CA-based sustainable intensification of basmati RW system was conducted at Taraori (Haryana), India (N 29°48’35; E 76°55’16) the heartland of basmati rice. The experimental field was under RW system since last 20 years. The surface
soil (0–15 cm) layer at the initiation of experiment was non-saline (electrical conductivity 0.34 dSm\(^{-1}\)) with pH 8.03 (1:2 soil: water) and contained 5.1 g Walkley-Black carbon kg\(^{-1}\), 151.1 kg available N ha\(^{-1}\), 16.1 kg extractable P ha\(^{-1}\) (Olsen et al. 1954) and 215.4 kg NH\(_4\)OAc-extractable K ha\(^{-1}\) (Knudsen et al. 1982).

**Climate and weather**

The climate of the experimental site representing semi-arid subtropical, characterized by hot summers (April–September) and cool winters (October–March) with an average annual rainfall of 650 mm of which more than 70% is received through southwest monsoon during the months of June to September. The minimum temperature of 0.2–4°C prevailed during the month of January, and the maximum temperature of 40–48°C was recorded during the month of June every year. Rice was grown during June to November and wheat during November–April and mungbean during April–June. The meteorological data for crop growing seasons are presented in Supplementary Fig. 1.

**Treatments and experimental design**

Six treatments included selected combinations of cropping systems, tillage and crop establishment, residue management and mungbean integration in basmati RW system. Treatment number and details with management protocols are described in Table 1. The experiment was laid out in a completely randomized block design with three replications.

**Soil analysis**

For soil sampling, each plot was divided into four grids. Within each grid cell, soil was collected from 0 to 15 cm soil depth using a core sampler from four spots and composited for analysis. These samples were air-dried and sieved through a 2 mm screen, and representative samples were taken for the analysis of various soil properties using standard protocols. Soil pH and electrical conductivity (EC) was determined in the saturation extract of 1:2 (soil:water suspension) solution as described by (Richards 1954). Soil organic carbon was analysed using rapid titration method (Walkley and Black 1934). Available N was determined by alkaline permanganate method (Subbiah and Asija 1956), available P by Olsen method (Olsen et al. 1954) and exchangeable K by flame photometer method (Knudsen et al. 1982). Soil microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) was estimated by chloroform fumigation method (Vance et al. 1987).

**Tillage and crop establishment**

Conventional puddled transplanted rice (PTR) involved six tillage operations that included 2 – dry harrowings, 3 – wet harrowings in 3–4 cm standing water (puddling) and 1-levelling followed by manual transplanting. In conventional till (CT) wheat, six tillage operations (2 – harrowings, 2 – ploughings with spring tyne harrow, and 1 – levelling) were used for fine seedbed preparation followed by seeding using appropriate seeder (see below). Tillage operations for CT mungbean after wheat harvest included 2 – harrowings and seeds were broadcasted followed by levelling to cover the seeds, while for relay seeded crop, pre-germinated seeds were manually broadcasted in standing wheat at the time of last irrigation in third to fourth week of March. In case of zero-till (ZT) plots, tillage was only confined to seeding using zero-till seed cum fertilizer drill, whereas in ZT with full residue retention plots, seeding was done by Turbo Happy Seeder (Sidhu et al. 2015) equipped with inverted T-type furrow openers for both direct seeded rice (DSR) and wheat. Description of tillage, crop establishment and residue management protocols for different crops are presented in...
Table 1. Treatment notations and description of management protocols (tillage & crop establishment and residue management) for different crops in basmati rice-wheat system.

| No. | Details | Basmati rice | Wheat | Mungbean | Basmati rice | Wheat | Mungbean |
|-----|---------|--------------|-------|----------|--------------|-------|----------|
| T1  | Conventional basmati rice-wheat (no residue) | Conventional till (CT) puddled transplanted rice (PTR) manual transplanting with random crop geometry | CT sown with seed-cum-fertilizer drill | NA | Residue removed | Residue removed | -NA- |
| T2  | Conventional basmati rice-wheat-mungbean (mungbean residue incorporated) | Same as in T1 | Same as in T1 | CT and sown with seed-cum-fertilizer drill (CTM) | Residue removed | Residue removed | 100% residue incorporated during puddling in rice (MRI) |
| T3  | Zero till basmati rice-wheat (no residue) | Zero till (ZT) direct dry seeded rice (DSR) sown with ZT multi crop planter | ZT, sown with ZT seed-cum-fertilizer drill | NA | Residue removed | Residue removed | -NA- |
| T4  | Zero-till basmati rice-wheat-mungbean (mungbean residue retained) | ZT-DSR sown with turbo happy seeder | Same as in T3 | ZT, relay broadcasting of soaked seeds immediately before last irrigation to wheat in March (RM) | Residue removed | Residue removed | 100% residue retained at surface (MR) |
| T5  | Zero till basmati rice-wheat with residue (both rice and wheat residues retained) | Same as in T4 | ZT, sown with turbo happy seeder | NA | 100% residue retained (WR) | 100% residue retained (RR) | -NA- |
| T6  | Zero till basmati rice-wheat-mungbean with residue (all residues retained) | Same as in T4 | Same as in T5 | Same as in T4 | Same as in T5 | Same as in T5 | Same as in T4 |

NA-Not applicable; i-incorporation; r-retention; PTR-puddled transplanted rice; CT-conventional till; ZT-zero-till; RM-relay mungbean; Rr-residue incorporation; Ri-residue retention; R-rice; W-wheat; M-mungbean; DSR-direct seeded rice.
Table 1. Sowing and harvesting dates for different crops over the years are presented in Supplementary Table S1.

**Crop varieties, seed rate and crop geometry**

Basmati rice variety Pusa1121, wheat variety DPW 621–50 and mungbean variety SML 668 were used over all the years of study. In PTR, 25-day-old rice seedlings were transplanted manually at 20 cm × 20 cm spacing. In zero-till direct seeded rice (ZTDSR) treatments, rice seeds were directly drilled at 20 cm row spacing with a seed rate of 20 kg ha⁻¹ using zero-till multi-crop planter (on without residue retention plots) and Turbo Happy Seeder (on residue retention plots) with inclined plate seeding mechanism. Wheat in CT plots was seeded using seed cum fertilizer drill fitted with fluted roller seeding mechanism at a row spacing of 20 cm with a seed rate of 100 kg ha⁻¹. In ZT plots, row to row spacing and seed rate were uniform across all the treatments but sowing was done using Turbo Happy Seeder. Mungbean seeds were broadcasted under CT plots at a seed rate of 20 kg ha⁻¹. In case of relay seeding, pre-germinated seeds of mungbean (8 h overnight soaking in water followed by 24 h wrapping/covering in a gunny bag under a shed) at a seed rate of 25 kg ha⁻¹ were broadcasted uniformly in standing wheat crop immediately before the last irrigation to wheat.

**Recycling of crop residues**

Entire above ground residues of wheat and rice were removed or retained as per the treatment description given in Table 1. Mungbean residue was incorporated in T2 before rice transplanting while it was retained in T4 and T6 before sowing of DSR. Whole residues of all the crops were retained in T5 and T6. A total of 57.33 and 64.11 Mg ha⁻¹ of crop residues was recycled in T5 and T6, respectively, in 4 years (Supplementary Table S2). The total mass of mungbean residue for 4 years was 5.51 and 5.93 Mg ha⁻¹ in T2 and T4, respectively.

**Weed management**

Selective and non-selective herbicides were used as and when required under both the crops. No herbicides were applied before seeding in CT plots, however, on ZT plots, non-selective herbicides glyphosate at 900 g a.i. ha⁻¹ were used to kill the weeds prior to DSR or wheat sowing. In PTR, pendimethalin (1000 g a.i. ha⁻¹) or butachlor (1500 ml a.i. kg ha⁻¹) were used as pre-emergence herbicide at one day after transplanting. In DSR, pre-emergence spray of pendimethalin (1000 g a.i. ha⁻¹) was done just one day after seeding followed by another herbicide mix spray of bispyribac + azimsulfuron (25 g + 17.5 g a.i. ha⁻¹, respectively), at 20–25 days after sowing to kill all grassy and broadleaf weeds, and sedges. For wheat, tank mix solution of sulfosulfuron + metsulfuron (32 g a.i. ha⁻¹) at 35 days after sowing was applied to control grassy as well as broadleaf weeds. No herbicide was used in mungbean in all the years as this crop had a smothering effect on the weeds.

**Nutrient management**

Both basmati rice and wheat crops were raised using recommended doses of fertilizers (Prasad 2012). Both the crops received 26 kg P ha⁻¹ and 50 kg K ha⁻¹. Whole of the P and K fertilizers (and 25 kg ZnSO₄ ha⁻¹ to rice only) were drilled at sowing/transplanting in the form of diammonium phosphate (DAP) and muriate of potash, respectively. The recommended dose of nitrogen (N) for basmati rice and wheat was 90 and 150 kg N ha⁻¹, respectively. While 80% of recommended N (72 kg N ha⁻¹ in rice; 120 kg N ha⁻¹ in wheat minus 23.5 kg N ha⁻¹ supplied through DAP) was applied as per the standard protocol described below, the remaining N (20% of total) as urea was given on the basis of normalized difference vegetation index (NDVI) using
GreenSeeker (Bijay-Singh et al. 2015). In PTR, a dose of 24 kg N ha\(^{-1}\) each was applied in two equal splits at 15 and 30 days after transplanting, whereas, in DSR the N was applied in three equal splits after every 15-day interval at 16 kg N ha\(^{-1}\). To wheat, N was top dressed in two equal splits (48 kg N ha\(^{-1}\) each) at 25 and 45 days after sowing. The remaining 20% N- (rice – 18 kg N ha\(^{-1}\); wheat – 30 kg N ha\(^{-1}\)) was applied across the year using hand-held optical sensor GreenSeeker based upon standard curves describing NDVI (normalized difference vegetation index) and Response Index (Bijay-Singh et al. 2011). GreenSeeker guided 20% of total N resulted in the variation in N dose varied from 82 to 90 kg ha\(^{-1}\) in rice and 138–150 kg ha\(^{-1}\) in wheat over the years and amongst the treatments.

**Irrigation water management**

Irrigation to PTR was applied as per the farmer’s practice, where plots were kept continuously flooded (5 ± 2 cm submergence) for initial 30 days after transplanting and subsequent irrigations were applied at the appearance of hairline cracks. However, in ZTDSR, the first irrigation was applied immediately after seeding and the second irrigation was applied 3–4 days after the first irrigation for better germination and the subsequent irrigations were applied as per IRROMETER (gauge-type soil tensiometer) reading of −20 to −30 kPa soil matric potential installed at 15-cm depth throughout the growth period. In wheat, irrigation was applied at −60 to −70 kPa soil matric potential. In mungbean irrigation was applied as and when required under both CT and relay seeded mungbean.

Irrigation water was measured with a Woltman® helical turbine water meter fitted at the source of tubewell outlet. For measurement of the amount of irrigation water, the water meter reading was recorded at start and end of irrigation. The amount of irrigation water applied was quantified (in mm ha\(^{-1}\)) using Equation (1) and Equation (2), while, irrigation water productivity (WP\(_I\)) and total water productivity (WP\(_{I+R}\)) using Equations (3) and (4), respectively, as below:

\[
\text{Volume of irrigation water (kilolitre ha}^{-1}\text{)} = \left( \frac{\text{Final water meter reading} - \text{Initial water meter reading}}{\text{Plot area in m}^{2}} \right) \times 10,000 \quad (1)
\]

\[
\text{Irrigation water (ha – mm)} = \frac{\text{Volume of irrigation water (kilolitre ha}^{-1}\text{)}}{10} \quad (2)
\]

\[
\text{WP}_I (\text{kg grain m}^{-3}) = \frac{\text{Grain yield (kg ha}^{-1}\text{)}}{\text{Irrigation water (m}^3\text{ha}^{-1}\text{)}} \quad (3)
\]

\[
\text{WP}_{I+R} (\text{kg grain m}^{-3}) = \frac{\text{Grain yield (kg ha}^{-1}\text{)}}{\text{Irrigation + rainfall water (m}^3\text{ha}^{-1}\text{)}} \quad (4)
\]

*Where, 1 ha-mm irrigation depth = 10 kilolitres = 10 m\(^3\); 1 m\(^3\) = 1000 litres*

**Data recording**

The data on crop management inputs such as tillage, fuel consumption, number of irrigations, herbicide, fertilizer, seed, labour use, pesticide application and their costs under each treatment were recorded for each crop. Crops were harvested manually from randomly selected 4 × 4 m\(^2\) quadrate from two places within each main plot for grain and straw yields. To express the overall impact of treatments system productivity was calculated on wheat equivalent yield (WEY) basis for basmati rice and mungbean grain yield. Grain yield of basmati rice and mungbean were recorded at 14% moisture basis. System productivity (Mg ha\(^{-1}\)) was computed using Equation (5).
WEY (t ha$^{-1}$) = \{Rice/Mungbean yield (Mg ha$^{-1}$) $\times$ Prices of Rice/Mungbean (INR Mg ha$^{-1}$)\} / Prices of Wheat (INR t ha$^{-1}$) \} \tag{5}

Where, INR is the India National Rupee (Supplementary Table S3)

**Protein yield**

Protein yield was calculated based upon the protein content in grain and grain yield of individual crops. Nitrogen content in the grain was determined by the method of Jackson (1973). Nitrogen content in the grain varied from 1.54% to 1.59% in wheat, 1.06–1.09% in rice and 3.84–3.87% in mungbean. Protein content was calculated by multiplying the estimated N content with a standard factor for each crop (5.95 for rice; 5.80 for wheat and 5.70 for mungbean) given by Bender (2006).

The system protein yield is the sum of protein yield from each crop in the cropping system. Annual adult protein demand equivalent was based on the 60 g person$^{-1}$day$^{-1}$ as per the recommendations of the Indian council of medical research (ICMR 2009).

**Economic analysis**

Economic analysis was calculated by considering variable costs including human labour, diesel consumption, cost of production inputs (planting, seed, fertilizer, pesticide, irrigation, harvesting, threshing, cleaning, etc.), marketing, etc. and revenues obtained as per the prevailing market prices of the commodity (grain and straw) over the different years (Supplementary Table S3). The cost of human labour used for seeding, irrigation, fertilizer and pesticide application and harvesting of crops was based on labour-days/ha assuming an 8-h working day (as per labour law of India). Net returns were calculated by deducting the total variable cost from the gross returns.

**Statistical analysis**

The data recorded for different crop parameters were analysed using analysis of variance (ANOVA) technique (Gomez and Gomez 1984) for randomized block design using SAS 9.1 software (SAS Institute 2001). Tukey procedure was used where ANOVA was significant, and the treatment means were compared at 5% level of significance.

**Results**

**Crop yields and system productivity**

**Basmati rice**

Basmati rice grain yield was significantly influenced by the CA-based management options in all the years except in 2013–2014 (Table 2). Conventional PTR (T1 and T2) produced significantly higher grain yield compared to DSR (T3-T6) in 2011–2012 and 2012–2013, except T6 performing similar to T1 in 2012–2013 (Table 2). In the fourth year (2014–2015), PTR (T1 and T2) and ZTDSR (T3 and T6) produced similar but significantly higher yields compared to T4 and T5 (Table 2). Mean rice grain yield (averaged across 4 yrs) was significantly higher by 5% for PTR (T1 and T2) compared to ZTDSR-based systems (T3 to T6) except T6, which yielded similar to T1. Inclusion of mungbean in full CA treatments (T4 and T6) showed no significant effect on rice yield, compared to T3 and T5 in all the years except in 2014–2015 when T4 and T6 produced significantly higher yield (pooled average) compared to T3 and T5 (Table 2).
Wheat
Tillage, crop establishment and residue management had significant effect on wheat grain yield across the years (Table 2). Grain yield of ZTW (T3 to T6), irrespective of residue management, was significantly higher compared to CTW (T1 and T2) in all the years, except T3, which yielded similar to CTW in 2012–2013 and 2014–2015 (Table 2). Pooled data generally followed a trend similar to that observed in individual years. Full CA treatment (T6) produced 15–19% (17.5%, averaged over 4 yrs) higher grain yield compared to CTW (T1). Integration of mungbean into ZT system (T6) showed no significant effect on wheat grain yield when crop residues were retained over T5. However, when basmati rice and wheat residues were removed, inclusion of mungbean (T4) significantly increased the wheat yield over T3 in all the years, except in 2012–2013.

Mungbean
Relay planting of mungbean (T4 and T6) produced grain yield similar to conventional sowing (T2) in all the years, except in 2013–2014 (Table 2).

System productivity (wheat equivalent yield)
Like grain yield of individual crops, different treatments had significant effect on system productivity (wheat equivalent yield) over the years (Table 2). Total system yield ranged from 12.95 Mg in T1 in 2011–2012 to 22.63 Mg ha⁻¹ in T6 in 2013–2014 across all treatments.
and the years (Table 2). Significantly higher system productivity was recorded with T6 in all the years, and it was on par with T4 in 2011–2012 and 2013–2014, and T2 in 2012–2013. CA-based system in T6 recorded 36% higher system productivity (4 yrs’ mean) compared to T1 (14.91 Mg ha⁻¹). Sustainable intensification of scented RW system with mungbean integration (T2, T4 and T6) recorded 24–26% (4 yrs’ mean) higher system productivity compared to corresponding no mungbean treatment (T1, T3 and T5).

Irrigation water use and productivity

Water use

Irrigation water use was significantly (p = 0.05) affected by tillage, crop establishment and mungbean integration in basmati RW system (Table 3). Irrigation water amount ranged from 1147 to 3174 mm ha⁻¹ in different treatments during four years of study. Significantly higher irrigation water was consumed in T2 compared to all the other treatments across the years as well as on pooled basis (Table 3). Treatments T5 and T6 recorded lower water use compared to other treatments in all the years. In T2, 11% more irrigation water (210 mm ha⁻¹) was applied because of additional irrigation needed for mungbean compared to T1. Similarly, irrigation water use in T4 and T6 which included mungbean was higher compared to T3 and T5, respectively. Mean (averaged across 4 yrs) irrigation water use was 37% lower compared to T1 and was closely followed by T6 with 33% savings.

Water productivity

Irrigation water productivity (WPᵢ) of basmati RW system in different treatments varied from 0.47 to 1.61 kg grain m⁻³ across the years. WPᵢ and total water productivity (WPᵢ₊R) were significantly higher with T6 compared to all treatments in all the years (Table 3). System WPᵢ was higher in the treatments which included mungbean (T2, T4 and T6) compared to their no mungbean treatments. System WPᵢ (4 yrs’ mean) was higher by 94, 56, 55, 35% with T6, T5, T4, and T3 compared to T1, respectively. System WPᵢ₊R followed the trend for WPᵢ and it varied from 0.39 to 1.08 kg grain m⁻³ across the years. Highest system WPᵢ₊R was recorded with T6 (0.90 kg grain m⁻³) compared to other treatments and it was 67% higher (4 yrs’ mean) than with T1. Both T4 and T5 recorded similar WPᵢ₊R but had almost 44% higher compared to T1.

Economic profitability

Net returns from each crop and system productivity of RW system were significantly affected by tillage, crop establishment, mungbean integration and residue management practices (Table 4).

Basmati rice

Net returns from basmati rice varied from USD 1189–2480 ha⁻¹ in different years (Table 4). T3 and T4 provided similar but significantly higher net returns compared to all other treatments in 2011–2012, while T5 and T6 were recorded significantly higher net returns compared to other treatments in 2012–2013. On the other hand, T3 recorded significantly higher net returns compared to other treatments in 2013–2014. In 2014–2015, net returns were generally similar for all the treatments, except T6 which provided significantly higher returns than T2. ZT basmati rice (T3 to T6) produced similar but significantly higher net returns (6%, averaged across 4 yrs) compared to PTR (T1 and T2) (Table 4).

Wheat

Net returns from CTW (T1 and T2) were significantly lower (USD 817–986 ha⁻¹) compared to ZTW with or without residues (T3-T6) (USD 983–1318 ha⁻¹) over all the years (Table 4). Net returns across treatments and years ranged from USD 817–986 and USD 983–1318 ha⁻¹ with CTW and ZTW,
Table 3. Total irrigation water use (mm ha\(^{-1}\)) and water productivity (kg grain m\(^{-3}\)) applied to basmati rice-wheat-mungbean system as influenced by different management protocols.

| Treatments\(a\) | 2011–2012 | 2012–2013 | 2013–2014 | 2014–2015 | Pooled average | 2011–2012 | 2012–2013 | 2013–2014 | 2014–2015 | Pooled average | 2011–2012 | 2012–2013 | 2013–2014 | 2014–2015 | Pooled average |
|-----------------|------------|------------|------------|------------|---------------|------------|------------|------------|------------|---------------|------------|------------|------------|------------|---------------|
| T1              | 1737\(b\) | 3014\(b\) | 1671\(b\) | 2249\(b\) | 2168\(b\)     | 0.75\(c\) | 0.47\(c\) | 1.05\(c\) | 0.66\(d\) | 0.69\(d\)     | 0.59\(b\) | 0.39\(c\) | 0.74\(b\) | 0.53\(c\) | 0.54\(d\)     |
| T2              | 1999\(a\) | 3174\(a\) | 1871\(a\) | 2465\(a\) | 2378\(a\)     | 0.81\(c\) | 0.57\(c\) | 1.13\(c\) | 0.76\(c\) | 0.78\(cd\)    | 0.63\(b\) | 0.47\(c\) | 0.76\(b\) | 0.59\(c\) | 0.60\(cd\)    |
| T3              | 1449\(cd\)| 1940\(d\) | 1259\(d\) | 1663\(d\) | 1578\(d\)     | 0.88\(c\) | 0.74\(b\) | 1.42\(b\) | 0.90\(bc\)| 0.96\(bc\)    | 0.67\(b\) | 0.56\(bc\)| 0.92\(a\) | 0.66\(bc\)| 0.70\(bc\)    |
| T4              | 1562\(c\) | 2041\(c\) | 1403\(c\) | 1843\(c\) | 1713\(c\)     | 1.07\(b\) | 0.86\(b\) | 1.59\(b\) | 1.02\(b\) | 1.10\(b\)     | 0.79\(a\) | 0.65\(b\) | 0.97\(a\) | 0.74\(b\) | 0.78\(b\)     |
| T5              | 1293\(d\) | 1579\(f\) | 1147\(e\) | 1438\(e\) | 1365\(f\)     | 1.01\(b\) | 0.94\(b\) | 1.61\(b\) | 1.03\(b\) | 1.12\(b\)     | 0.75\(a\) | 0.67\(b\) | 1.01\(a\) | 0.73\(b\) | 0.78\(b\)     |
| T6              | 1340\(d\) | 1699\(e\) | 1199\(de\)| 1539\(e\) | 1445\(e\)     | 1.25\(a\) | 1.09\(a\) | 1.89\(a\) | 1.27\(a\) | 1.34\(a\)     | 0.88\(a\) | 0.79\(a\) | 1.08\(a\) | 0.87\(a\) | 0.90\(a\)     |

\(a\)Refer Table1 for treatment description.

\(b\)Means followed by similar lowercase letters within a column are not significantly different (p = 0.05).
respectively (Table 4). Highest net returns (USD 985–1318 ha\(^{-1}\)) were recorded with T4 in all the years except in 2012–2013. Net returns with T4 were generally on par with T6, except in 2013–2014. On pooled basis (4 yrs’ mean), significantly higher net returns (USD 1166 ha\(^{-1}\)) were recorded with T4 compared to all other treatments and was closely followed by T6 (USD 1108 ha\(^{-1}\)). T4 and T6 recorded an average increase of 24% in net returns compared to CTW (average for T1 and T2).

**Mungbean**

Relay mungbean (T4 and T6) recorded significantly higher net returns than CT mungbean (T2) in all the years (Table 4). Net returns from relay mungbean were 15% higher (4 yrs’ mean) compared to CT crop. Residue management showed no significant effect on net returns in mungbean (T4 vs T6).

**System net returns**

System net returns ranged from USD 2160 to 4457 ha\(^{-1}\) across all the treatment and years depending upon the input and market prices (Table 4). Significantly lower net returns were recorded with conventional basmati RW system (T1) compared to all the other treatments in all the years of experimentation. T4 and T6 recorded significantly higher net returns compared to other treatments and the returns from the two were similar except in 2013–2014 when T4 provided significantly higher returns compared to T6. Integration of mungbean in CA-based RW system (T4

Table 4. Net returns (USD ha\(^{-1}\)) of basmati rice, wheat, mungbean and on system basis as affected by different management.

| Treatments\(^{a}\) | 2011–2012 | 2012–2013 | 2013–2014 | 2014–2015 | Pooled average |
|------------------|-----------|-----------|-----------|-----------|---------------|
| **Basmati rice** |           |           |           |           |               |
| T1               | 1189c\(^{b}\) | 1602b     | 2233d     | 1595ab    | 1655b         |
| T2               | 1198c      | 1607b     | 2303c     | 1575b     | 1671b         |
| T3               | 1278a      | 1513c     | 2480a     | 1785ab    | 1764a         |
| T4               | 1285a      | 1567bc    | 2408b     | 1799ab    | 1765a         |
| T5               | 1256b      | 1775a     | 2291c     | 1654ab    | 1744a         |
| T6               | 1269ab     | 1716a     | 2310c     | 1838a     | 1784a         |
| **Wheat**        |           |           |           |           |               |
| T1               | 971d       | 817c      | 978c      | 893c      | 915d          |
| T2               | 986d       | 883b      | 965c      | 864c      | 925d          |
| T3               | 1176bc     | 983a      | 1081b     | 990b      | 1058c         |
| T4               | 1318a      | 985a      | 1242a     | 1115a     | 1166a         |
| T5               | 1117c      | 1015a     | 1121b     | 1048ab    | 1076bc        |
| T6               | 1230ab     | 1029a     | 1119b     | 1052ab    | 1108b         |
| **Mungbean**     |           |           |           |           |               |
| T1               | NA         | NA        | NA        | NA        | NA            |
| T2               | 659b       | 628b      | 688b      | 744b      | 658b          |
| T3               | NA         | NA        | NA        | NA        | NA            |
| T4               | 764a       | 712a      | 806a      | 842a      | 756a          |
| T5               | NA         | NA        | NA        | NA        | NA            |
| T6               | 791a       | 719a      | 803a      | 827a      | 759a          |
| **System**       |           |           |           |           |               |
| T1               | 2160d      | 2419c     | 3211f     | 2489d     | 2570d         |
| T2               | 2759b      | 3119c     | 3957c     | 3184b     | 3255b         |
| T3               | 2455c      | 2496c     | 3562d     | 2775c     | 2822c         |
| T4               | 3269a      | 3265a     | 4457a     | 3757a     | 3687a         |
| T5               | 2373c      | 2790b     | 3412e     | 2702cd    | 2820c         |
| T6               | 3188a      | 3466a     | 4233b     | 3718a     | 3652a         |

\(^{a}\)Refer Table 1 for treatment description.

\(^{b}\)Means followed by similar lowercase letters within a column are not significantly different (p = 0.05).

NA – Not applicable
and T6) increased the system net returns by 29% (4 years’ mean) over no mungbean, irrespective of tillage and crop establishment treatments.

System protein yield

System protein yield generally followed the trend observed for system yield (Table 5). Protein yield ranged from 936 to 1086 and 769 to 873 kg ha\(^{-1}\) with and without mungbean integration, respectively (Table 5). T6 recorded significantly higher system protein yield compared to the other treatments in all the years except in 2011–2012 where it was on par with T4. Lowest protein yield was with T1 which was on par with T5 in 2011–2012, and with T3 in 2014–2015. On average (4 yrs’ mean), T6 provided 22% and 31% higher protein yield compared to T5 and T1, respectively. Mungbean increased the protein yield significantly compared to RW system alone. Averaged over 4 yrs, system protein yield in treatments with mungbean (mean for T2, T4 and T6) was 23% higher compared to no mungbean treatments (T1, T3 and T5). Basmati RW system intensification with mungbean could meet out the adult protein demand of 43 persons ha\(^{-1}\) yr\(^{-1}\) compared to 35 persons ha\(^{-1}\) yr\(^{-1}\) (4 yrs’ mean) without mungbean integration (T1, T3, T5).

Table 5. System-based protein yield (kg ha\(^{-1}\)) and adults protein demand equivalents as affected by as affected by management protocols in basmati rice-wheat-mungbean cropping system.

| Treatments\(^a\) | Protein yield and adult equivalents | 2011–2012 | 2012–2013 | 2013–2014 | 2014–2015 | Pooled average |
|------------------|-----------------------------------|-----------|-----------|-----------|-----------|----------------|
|                  | System protein yield (kg ha\(^{-1}\)) |           |           |           |           |                |
| T1               | 840c\(^b\) | 769e | 782e | 789e | 795f |   |
| T2               | 1007b | 968b | 936d | 946c | 964c |   |
| T3               | 873c | 801d | 807c | 801de | 820e |   |
| T4               | 1086a | 962b | 1032a | 998b | 1019b |   |
| T5               | 872c | 841c | 867b | 828d | 852d |   |
| T6               | 1083a | 1021a | 1041a | 1026a | 1043a |   |
|                  | Yearly protein demand (based on 60g d\(^{-1}\) adult\(^{-1}\)) equivalents for adults |           |           |           |           |                |
| T1               | 35c | 32e | 33e | 33e | 34f |   |
| T2               | 42b | 41b | 39b | 40c | 41c |   |
| T3               | 37c | 34d | 34d | 34de | 35e |   |
| T4               | 46a | 41b | 43a | 42b | 43b |   |
| T5               | 37c | 35c | 37c | 35d | 36d |   |
| T6               | 46a | 43a | 44a | 43a | 44a |   |

\(^a\)Refer Table 1 for treatment description.

\(^b\)Means followed by similar lowercase letters within a column are not significantly different (p = 0.05).

Table 6. Soil chemical and biological properties after 4 years of cropping cycles.

| Treatments\(^a\) | Organic carbon (g kg\(^{-1}\)) | Available N (kg ha\(^{-1}\)) | Available P (kg ha\(^{-1}\)) | Available K (kg ha\(^{-1}\)) | Microbial biomass carbon (µg g\(^{-1}\) dry soil) | Microbial biomass nitrogen (µg g\(^{-1}\) dry soil) |
|------------------|--------------------------------|------------------------------|-----------------------------|-----------------------------|-----------------------------------------------|-----------------------------------------------|
| T1               | 5.3b\(^b\) | 155.1b | 16.2b | 222.3b | 501e | 160d |
| T2               | 5.6b | 165.4b | 16.4b | 245.0b | 785c | 219bc |
| T3               | 5.5b | 156.0b | 17.2b | 228.6b | 638d | 184cd |
| T4               | 5.7ab | 173.2ab | 17.6b | 259.9ab | 926b | 287b |
| T5               | 7.0a | 201.6a | 21.7a | 287.5a | 1041a | 380a |
| T6               | 7.4a | 215.9a | 22.9a | 311.6a | 1113a | 433a |

\(^a\)Refer Table 1 for treatment description.

\(^b\)Means followed by similar lowercase letters within a column are not significantly different (p = 0.05).
Soil quality

All the soil parameters viz., SOC, available N, P and K were increased significantly under ZT with full residue retention (T5 and T6) than other treatments and lowest values were recorded for CT (T1 and T2) and ZT without residue (T3) (Table 6). ZT improved the SOC content by 21% irrespective of treatment combinations compared with CT after 4 years of cultivation. After 4 years, SOC content in 0–15 cm layer was increased by 5.7 (mean of T3 and T4) and 35.9% (mean of T5 and T6 compared to CT (T1), respectively (Table 6). SOC was increased by 32% and 40% in T5 and T6 where full residues were recycled compared to CT (5.3 g kg\(^{-1}\)). Significantly higher values of nutrients (N, P and K) were recorded with full residue recycling in T5 and T6 compared to rest of the combinations. Available N, P and K content in soil was ~30% and 40% higher under T5 and T6, respectively, compared to T1. Soil MBC and MBN were varied significantly under different treatments (Table 6). An increase of 108% and 138% in MBC and MBN was recorded in basmati RW treatments having ZT with crop residue (T5), however, in T6 where mungbean was integrated in to the system, it was higher by 171% and 145% compared to T1. Significantly lower values of MBC and MBN were observed in treatments T1 (501 and 160 µg g\(^{-1}\) dry soil) and T3 (638 and 184 µg g\(^{-1}\) dry soil) where residues were removed.

Discussion

Crop yields and system productivity

CA-based sustainable intensification of basmati RW system had positive impacts on crop yields and cropping system productivity as reported by Choudhary et al. (2018a) and Kumar et al. (2018) in non-basmati RW system. In RW system lower grain yields of DSR (T3-T6) compared to transplanted rice (T1 and T2) were obtained in basmati rice. Possible reasons for the lower yield under DSR in our study were lower number of grains panicle\(^{-1}\) (75 against 81 in PTR; data not shown) and lack of DSR specific varieties (Kamboj et al. 2012). In basmati RW system, CA-based management practices coupled with effective cultivars and weed control makes ZT-based RW system cost-effective, productive and sustainable (Sharma et al. 2015).

ZT in wheat in RW system facilitates residue recycling and early planting of wheat, which provides an option to integrate mungbean into the system for maximizing system productivity and protein yield, reduces production cost and increases profitability (Gathala et al. 2013). ZT with residue retention (T4 and T6) recorded the higher wheat yield compared to CT wheat (4 yrs’ mean basis; Table 2) because of improved soil physical, chemical and biological properties (Jat et al. 2017; Choudhary et al. 2018b), better crop establishment, root development, and reduced lodging (Aryal et al. 2016). On the other hand, in conventional RW system soil compaction and poor aggregation due to puddling in rice resulted in low yields of succeeding wheat over the years (Gathala et al. 2011b). On an average, CA-based basmati RW system resulted in 5% lower rice yield but 13% higher wheat yield thereby increasing system productivity compared to conventional (T1) system (Table 2). Mungbean provided approximately 800 kg ha\(^{-1}\) of valuable pulse grains and its yield was nearly similar under both conventional and relay seeded treatments (Table 2). Relay seeding of mungbean with last irrigation to wheat can be practised in CA-based basmati RW system for reducing tillage cost and early maturity avoiding chances of crop failure in case of early onset of monsoon at the time of maturity (Choudhary et al. 2018a). Higher system productivity was achieved with mungbean integration into non-basmati RW system with CA-based management practices (Kumar et al. 2018).

Irrigation water use and productivity

CT-based basmati RW-mungbean system used the maximum irrigation water in all the crops because PTR requires large input of irrigation water compared to DSR (Mahajan et al. 2011). Full
residue retention in ZT wheat reduced the irrigation water requirement by conserving soil moisture and reducing evaporation loss (Chauhan et al. 2012; Singh et al. 2014). Highest WP_I and WP_{I+R} were recorded with ZT-based treatment coupled with mungbean integration (T6) compared to CT system (T1) (Table 3). Mungbean needs less amount of irrigation water (one or two irrigations only) but produces appreciable amount of wheat equivalent yield (Sharma et al. 2015; Choudhary et al. 2018a). Our study showed beneficial effect of ZT and crop residue retention on crop yields, irrigation water saving, which ultimately resulted in higher WP_I and WP_{I+R} (T3 to T6) compared to CT system. The CA-based management options in different crops and cropping system are reported to produce higher yields with less irrigation water use and higher WP compared to flood irrigated CT (Yadvinder-Singh et al. 2014).

**Economic profitability**

Net returns of any crop and cropping system are directly related to variable cost and economic yields of crops. Erenstein and Laxmi (2008) reported that irrigation water, tillage and crop establishment largely contribute to total crop production costs. Higher net returns were recorded with ZT systems (with and without residue retention) compared to basmati PTR due to reduced cost of cultivation with DSR even though the yield was high (Singh et al. 2014). Similarly, in wheat, production cost was lower under ZT systems (T3–T6) compared to CT systems (Table 4). Low costs of production under ZT systems were mainly due to avoidance of preparatory tillage unlike in CT wheat where 5–6 preparatory tillage operations were performed before seeding (Sharma et al. 2015). ZT reduced the tillage and crop establishment costs by 79–85% compared to CT based cropping system (Gathala et al. 2011a). Net returns with ZT wheat were always higher than CT wheat because of low production cost (Singh et al. 2014) and high crop productivity (Jat et al. 2014). CT mungbean was less profitable than relay mungbean as major cost was involved in field preparation for seeding.

Higher system net returns recorded with ZT-RW and ZT-RW systems with residue retention (T4 and T6) compared to CT-RW system (Table 4) were mainly due to saving in cost of production (Saharawat et al. 2010) with additional yield of wheat under ZT-based systems (Kumar et al. 2018). Intensification of non-basmati RW system with mungbean was more profitable than RW system alone (Choudhary et al. 2018a). Additional yield of mungbean with a very low cost of cultivation increased the profitability of system by ~30%.

**Soil fertility**

Conservation agriculture-based management improved the SOC (Sharma et al. 2015), nutrient availability (Jat et al. 2017) and microbial properties (Choudhary et al. 2018b, 2018c) in cereal (rice/maize) based system of North-West India. ZT is known to reduce the rate of oxidation of carbon and thereby improves the SOC content, whereas CT practices accelerate microbial decomposition of SOC by exposing the previously protected organic matter leading to lower SOC content (Bhattacharyya et al. 2015). In CA-based system, ZT with residue recycling play an important role in the build-up of SOC through their marked effects on soil-related structural components and processes (Ranaivoson et al. 2017).

Zero-till treatments with residue retention showed relatively higher available N, P and K contents in soil compared to CT possibly due to the mobilization of these nutrients from the soil by microorganisms and plants, which transformed them into an available form (Choudhary et al. 2018b). Residue retention in these treatments creates favourable conditions for microbes resulted in higher nutrient content in soil (Jat et al. 2017). Earlier studies also showed higher N, P and K availability in the surface soil layers under ZT with residue retention compared to CT (Diaz-Zorita and Grove 2002). Pradhan et al. (2011) argued that higher Olsen P contents in ZT with residue recycling were due to the formation of stable complexes of P-fixing/immobilizing ions like Ca$^{2+}$, Fe$^{3+}$ and Al$^{3+}$ with soil organic matter. Higher MBC and MBN under zero tillage with residue
retention might be due to higher soil biological activities (Gajda et al. 2013; Choudhary et al. 2018b). Crop residue retention/incorporation increases available carbon in soil and improve physical conditions which creates a suitable environment for microbes (Ranaivoson et al. 2017). Integration of mungbean also contributes to higher MBC and MBN. Inclusion of legume in RW cropping system enhances soil biological activities (Masto et al. 2007; Choudhary et al. 2018b, 2018c) by facilitating more biological nitrogen fixation.

**Conclusion**

Intensification of CA-based basmati rice-wheat system provides an excellent opportunity of targeting the triple goals of soil health, doubling farmer’s income and sustainable intensification of Govt. of India by managing the crop residues into the system. Our study showed that CA-based basmati rice-wheat-mungbean system enhanced the system productivity by 36% and net returns by 43% while saving 33% of irrigation water compared to CT system. Recycling of crop residues under ZT conditions helped in improving the soil quality parameters. Mungbean integration in basmati RW system increased the protein yield by 23% and met the annual protein demand for additional eight adults ha\(^{-1}\) compared to no mungbean. CA-based sustainable intensification in the RW system is required for effective resource use, soil conservation, crop productivity and profitability in NW India.

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**Disclosure statement**

No potential conflict of interest was reported by the authors.

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**References**

APEDA. 2014. [accessed 2015 May 12] http://apeda.gov.in/apedawebsite/trade_promotion/BSK-2014/Report-Volume-VI.pdf.

Aryal JP, Sapkota TB, Stirling CM, Jat ML, Jat HS, Rai M, Mittal S, Sutaliya JM. 2016. Conservation agriculture-based wheat production better copes with extreme climate events than conventional tillage-based systems: a case of untimely excess rainfall in Haryana, India. Agric Ecosyst Environ. 233:325–335.

Bender DA. 2006. Benders’ dictionary of nutrition and food technology. 8th ed. Cambridge (UK): Woodhead, Publishing Limited.

Bhattacharyya R, Das TK, Sudhishri S, Dudwal B, Sharma AR, Bhatia A, Singh G. 2015. Conservation agriculture effects on soil organic carbon accumulation and crop productivity under a rice–wheat cropping system in the western Indo-Gangetic Plains. European J Agron. 78:11–21.

Bijay-Singh, Sharma RK, Jaspreet-Kaur, Jat ML, Martin KL, Varinderpal-Singh, Yadvinder-Singh, Chandna P, Choudhary OP, Gupta RK, et al. 2011. Assessment of the nitrogen management strategy using an optical sensor for irrigated wheat. Agron Sustain Dev. 31:589–603.
Bijay-Singh, Varinderpal-Singh, Purba J, Sharma RK, Jat ML, Yadavinder-Singh, Thind HS, Gupta RK, Chaudhary OP, Chandra P, et al. 2015. Site-specific fertilizer nitrogen management in irrigated transplanted rice (Oryza sativa) using optical sensor. Precis Agr. 16:455–475.

Chauhan BS, Mahajan G, Sardana V, Timsina J, Jat ML. 2012. Productivity and sustainability of the rice-wheat cropping system in the Indo-Gangetic Plains of the Indian subcontinent: problems, opportunities, and strategies. Adv Agron. 117:315–369.

Choudhary KM, Jat HS, Nandal DP, Bishnoi DK, Sutaliya JM, Choudhary M, Yadavinder-Singh, Sharma PC, Jat ML. 2018a. Evaluating alternatives to rice-wheat system in western Indo-Gangetic Plains: crop yields, water productivity and economic profitability. Field Crops Res. 218:1–10.

Choudhary M, Datta A, Jat HS, Yadav AK, Gathala MK, Sapkota TB, Das AK, Sharma PC, Jat ML, Singh R, et al. 2018b. Changes in soil biology under conservation agriculture based sustainable intensification of cereal systems in Indo-Gangetic Plains. Geoderma. 313:193–204.

Choudhary M, Jat HS, Datta A, Yadav AK, Sapkota TB, Mondal S, Meena RP, Sharma PC, Jat ML. 2018c. Sustainable intensification influences soil quality, biota, and productivity in cereal-based agroecosystems. Appl Soil Ecol. 126:189–198.

Diaz-Zorita M, Grove JH. 2002. Duration of tillage management affects carbon and phosphorus stratification in phosphatic paleuudalfs. Soil Tillage Res. 66:165–174.

Erenstein O, Laxmi V. 2008. Zero tillage impacts in India's rice–wheat systems: a review. Soil Tillage Res. 100:1–14.

Gajda AM, Przewloka B, Gawryjolek K. 2013. Changes in soil quality associated with tillage system applied. Int Agrophys. 27:133–141.

Gathala MK, Kumar V, Sharma PC, Saharawat YS, Jat HS, Singh M, Kumar A, Jat ML, Humphreys E, Sharma DK, et al. 2013. Optimizing intensive cereal-based cropping systems addressing current and future drivers of agricultural change in the North-Western Indo-Gangetic Plains of India. Agric Ecosyst Environ. 177:85–97.

Gathala MK, Ladha JK, Kumar V, Saharawat YS, Kumar V, Sharma PK, Sharma S, Pathak H. 2011a. Tillage and crop establishment affects sustainability of south Asian rice–wheat system. Agron J. 103:961–971.

Gathala MK, Ladha JK, Saharawat YS, Kumar V, Kumar V, Sharma PK. 2011b. Effect of tillage and crop establishment methods on physical properties of a medium-textured soil under a seven-year rice–wheat rotation. Soil Sci Soc Am J. 75:1851–1862.

Gomez AK, Gomez AA. 1984. Statistical procedures for agricultural research. 2nd ed. New York (NY): John Wiley & Sons. Humphreys E, Kulak SS, Christen EW, Hira GS, Balwinder S, Yadav S, Sharma RK. 2010. Halting the groundwater decline in North-West India- which crop technologies will be winners? Adv Agron. 109:155–217.

ICMR. 2009. Nutrient requirements and recommended dietary allowances for Indians. A Report of the Expert Group. p. 334.

Jackson NL. 1973. Soil chemical analysis. 2nd ed. New Delhi: Prentice Hall of India Pvt. Ltd.; p. 498.

Jat HS, Datta A, Sharma PC, Kumar V, Yadav AK, Choudhary M, Choudhary V, Gathala MK, Sharma DK, Jat ML, et al. 2017. Assessing soil properties and nutrient availability under conservation agriculturepractices in a reclaimed sodic soil in cereal-based systems of North-West India. Arch Agron Soil Sci. 64:531–545.

Jat RK, Sapkota TB, Singh RG, Jat ML, Kumar M, Gupta RK. 2014. Seven years of conservation agriculture in a rice–wheat rotation of Eastern Gangetic Plains of South Asia: yield trends and economic profitability. Field Crops Res. 164:199–210.

Kamboj BR, Kumar A, Bishnoi DK, Singla K, Kumar V, Jat ML, Chaudhary N, Jat HS, Gosain DK, Khippal A, et al. 2012. Direct seeded rice technology in Western indo-gangetic plains of India: CSISA experiences. CSISA, IRRI and CIMMYT. 16.

Kienzler KM, Lamers JPA, McDonald A, Mirzabaev A, Ibragimov N, Egamberdiev O, Ruzibaev E, Akramkhonov A. 2012. Conservation agriculture in Central Asia-What do we know and where do we go from here? Field Crops Res. 132:95–105.

Knudsen D, Peterson GA, Pratt PF. 1982. Lithium, sodium and potassium. In: Page AL, Miller RH, Keeney DR, editors. Methods of soil analysis. Part 2. Chemical and microbiological properties. Agronomy monograph no. 9. 2nd ed. Madison (WI): Soil Science Society of America (SSSA); p. 115–246.

Kumar V, Jat HS, Sharma PC, Gathala MK, Malik RK, Kamboj BR, Yadav AK, Ladha JK, Raman A, Sharma DK, et al. 2018. Can productivity and profitability be enhanced in intensively managed cereal systems while reducing the environmental footprint of production? Assessing sustainable intensification options in the breadbasket of India. Agric Ecosyst Environ. 252:132–147.

Lohan SK, Jat HS, Yadav AK, Sidhu HS, Jat ML, Choudhary M, Peter JK, Sharma PC. 2018. Burning issues of paddy residue management in north-west states of India. Renew Sust Energy Rev. 81:693–706.

Mahajan G, Timsina J, Kuldeep-Singh. 2011. Performance and water-use efficiency of rice relative to establishment methods in North-Western Indo-Gangetic Plains. J Crop Improv. 25:597–617.

Masto RE, Chhonkar PK, Singh D, Patra AK. 2007. Soil quality response to long term nutrient and crop management on a semi-arid inceptisol. Agr Ecosyst Environ. 118:130–142.

Olsen S, Cole CV, Walanafle FS, Dean LA. 1954. Estimation of available phosphorus in soil extraction with sodium bicarbonate. Washington (DC): USDA circular No. 939
Pradhan PR, Pandey RN, Behera UK, Swarup A, Datta SC, Dwivedi BS. 2011. Tillage and crop residue management practices on crop productivity, phosphorus uptake and forms in wheat (Triticum aestivum)-based cropping systems. Indian J Agric Sci. 81:1168–1173.

Prasad R, editor. 2012. Textbook of field crops production: food grain crops. Vol. 110. Pusa (New Delhi): Directorate of knowledge management in agriculture, KAB-II; p. 012.

Ranaivoson L, Naudin K, Ripoche A, Affholder F, Rabeharisoa L, Corbeels M. 2017. Agro-ecological functions of crop residues under conservation agriculture. A review. Agron Sustain Dev. 37(4):26.

Richards LA. 1954. Diagnosis and improvement in saline, alkali soils. Handbook No. 60. Washington (DC): USDA.

Saharawat YS, Singh B, Malik RK, Ladha JK, Gathala M, Jat ML, Kumar V. 2010. Evaluation of alternative tillage and crop establishment methods in a rice–wheat rotation in North Western IGP. Field Crops Res. 116:260–267.

SAS Institute. 2001. SAS/STAT user’s guide. Version 8-1. Cary (NC): SAS Inst.

Sharma PC, Jat HS, Kumar V, Gathala MK, Datta A, Yaduvanshi NPS, Choudhary M, Sharma S, Singh LK, Saharawat Y, et al. 2015. Sustainable intensification opportunities under current and future cereal systems of North-West India. Karnal: ICAR-Central Soil Salinity Research Institute. p. 46. Technical Bulletin: CSSRI/Karnal/2015/4. doi:10.13140/RG.2.2.16550.83521.

Sidhu HS, Singh M, Singh Y, Blackwell J, Lohan SK, Humphreys E, Jat ML, Singh V, Singh S. 2015. Development and evaluation of the Turbo Happy Seeder for sowing wheat into heavy rice residues in NW India. Field Crops Res. 184:201–212.

Singh SS, Singh AK, Sundaram PK. 2014. Agrotechnological options for upscaling agricultural productivity in eastern Indo-Gangetic plains under impending climate change situations: a review. J Agrisearch. 1:55–65.

Subbiah BV, Asija GL. 1956. A rapid procedure for the estimation of available nitrogen in soils. Curr Sci India. 25:259–260.

Vance F, Brookes P, Jenkinson D. 1987. Microbial biomass measurements in forest soil: the use of the chloroform fumigation incubation method in strongly acid soils. Soil Biol Biochem. 19:697–702.

Walkley A, Black CA. 1934. An examination of the method for determination of soil organic matter and proposed medication at the chromic acid titration method. Soil Sci. 37:29–38.

Yadvinder-Singh KSS, Jat ML, Sidhu HS. 2014. Improving water productivity of wheat-based cropping systems in South Asia for sustained productivity. Adv Agron. 127:157–258.

Yadvinder-Singh, Manpreet-Singh M, Sidhu HS, Humphreys E, Thind HS, Jat ML, Blackwell J, Singh V. 2015. Nitrogen management for zero till wheat with surface retention of rice residues in north-west India. Field Crops Res. 184:183–191.