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Conservation Agriculture in Intensive Rice-Wheat Rotation of Western Indo-Gangetic Plains: Effect on Crop Physiology, Yield, Water Productivity and Economic Profitability

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Abstract

In the intensive rice-wheat system (RWS) of the western India, direct dry seeding of rice, zero tillage in both rice and wheat, and residue recycling from rice can greatly reduce water and labour input, eliminate residue burning, and potentially conserve natural resources. The objectives of this 2-year field study conducted at the Project Directorate for Cropping Systems research Modipuram, India in 2005 to 2007 were to determine the effects of tillage, crop establishment methods and residue on crop growth, physiology, grain yield, water productivity, and economic profitability in RWS. The treatments included six combinations of rice establishment and tillage in rice with and without *Sesbania* co-culture. In the following season wheat was raised as zero-till (ZTW) in all the treatments and the residue from previous rice was either removed or retained on the soil surface without incorporation. Compared to conventional till puddled transplanted rice (CT-PTR), rice yields in dry direct-seeded rice (DSR) averaged 9.9 % lower with zero till (ZT) and 7.3% lower with CT. Rice yields were similar from CT-DSR and ZT-DSR. The *Sesbania* co-culture in rice increased mean grain yield by 5% compared to no *Sesbania*. DSR under CT and ZT was characterized by more panicle number per m^2 but less grain number per panicle, and lower harvest index compared with CT-PTR. Mean wheat grain yield was significantly higher from crop planted after ZT-DSR (5.03Mg ha^{-1}) compared to sown after CT-PTR (4.74t ha^{-1}), and CT-DSR (4.86tha^{-1}). Higher leaf water potential and increased photosynthesis rates were recorded in wheat under residue mulch compared to no mulch. Canopy temperature in wheat during the grain filling stage was 0.6-1.5°C lower under residue retention compared to residue removal. The normalized vegetative index (NDVI) adequately described the effect of residue mulch on the growth of both rice and wheat crops. Residue retention increased mean grain yield of wheat by 9.9% compared to removal of residue. On an average, DSR used 7-13.9% less water compared to CT-PTR. Water productivity of wheat was highest (0.91kg grain m^{-3} water) in ZT-DSR/ZTW+R and lowest (~0.77kg grain m^{-3} water) in CT-PTR/ZTW and CT-DSR/ZTW. Overall, DSR/ZTW+R had higher water productivity and net returns than CT-PTR/ZTW in the RWS. Our study showed that conservation agriculture-based crop management practices (ZT-DSR/ZTW+R) could provide a better alternative to the conventional RWS to sustain high productivity while significant savings in water, labour and production costs under changing climate.

Keywords: Conventional tillage; Direct-seeded rice; Economics; Rice-wheat system; Residue mulch; Water productivity; Zero tillage

Abbrevations: RWS: Rice-Wheat System; IGP: Indo-Gangetic Plains; DSR: Dry Seeded Rice; NR: Net Returns; NRr: Net Return of Rice; NRw: Net Return of Wheat; GR: Gross Returns; GLM: General Linear Model

Introduction

Rice-wheat is the most important cropping system (RWS) for food self-security of South Asia occupying 13.5 million hectares in the Indo-Gangetic Plains (IGP) [1]. Conventional tillage and traditional crop establishment methods for the RWS require a large amount of labor, energy and water, resulting in high cost of cultivation thus making it unsustainable [2,3]. In the irrigated RWS, conventional tillage practice in rice paddies referred to as puddling requires large input of irrigation water, it is laborious and time consuming. The puddling process leads to sub-soil compaction and destroys the soil structure, resulting in restricted root penetration and low productivity of the succeeding wheat crop [4,5]. Water and labor scarcity are becoming major concerns for the productivity and sustainability of the RWS in South Asia. There has been a steady rate of decline in the depth to the groundwater in much of the RW area of north-west India [6,7]. More efficient alternatives for tillage and crop establishment methods are urgently needed to save labor and irrigation water and increase profits in RWS. The potential solutions include a shift from intensive tillage to no or reduced tillage and/or from transplanting to direct-seeding of rice.

Direct dry seeded rice (DSR) is an emerging agronomical production system that consumes less water, faster and easier to plant while being less labor intensive and provides higher economic returns than conventional flooded rice [8-12]. Experiments in different countries of South Asia showed 20-57% water savings in DSR compared to conventional till puddled transplanted rice (CT-PTR) mainly due the elimination of puddling and the alternate wetting and drying irrigation method used instead of continuous flooding [13-16].

In an exhaustive review, Kumar & Ladha [16] showed that yields of DSR were lower by 9.2–-10.3% and 12.7- 21.0% than CT-PTR in India and Pakistan, respectively. The yield gap between aerobic and flooded rice appears to depend on climate and soil physical properties, becoming greater under hotter and drier conditions [10,15,17,18]. In studies in where good crop establishment and good weed control and proper water and nutrient management practices have been followed, equivalent or higher yields are often reported under DSR than in CT-PTR [9,19,20]. As a result of savings in irrigation water in DSR, its water use productivity (grain yield per liter of water applied) was either similar when yields were lower or higher when yields were similar to that of CT-PTR [8,16,17,21,22].

Studies conducted in the United States [23,24] and in the Philippines [25] showed similar yields of DSR in some seasons but not in others between reduced/zero and conventional tillage. There are a few reports on the performance of DSR under ZT conditions in RW system in the IGP of South Asia. Intensive irrigated RW systems of South Asia are generating large quantities of crop residues as a result of increased crop production. In RW systems in the IGP, because of a limited time (1-3 weeks) between the rice and wheat crops and a lack of alternative uses for crop residues, farmers often burn residue of the rice crop in the open field instead of returning residue to the soil. One of the major problems of open-field straw burning is atmospheric pollution [26,27]. This problem is particularly serious in NW India and China, which represent major irrigated rice ecosystems in Asia. Recycling of crop residues has been suggested to improve overall soil quality through replenishing soil organic matter and to support sustainable crop production [28,29]. Establishment of the wheat crop by zero tillage with retention of crop residues on the soil surface potentially offers a labor-saving alternative to the burning of rice residues that pollutes the environment. The development of the Turbo Happy Seeder- an innovative seed-cum-fertilizer drill for direct drilling through the residue [27,30] facilitates planting through the residue (loose as well as anchored stubbles) in combine harvested fields and eliminates burning in addition to other potential benefits of the mulching. The retention of the rice residue as well as changes in tillage might reduce evapotranspiration losses, which could reduce irrigation water use in wheat [31] in addition to buffering soil moisture, soil temperature, and canopy temperature [12,32] which in turn offers yield enhancing effects. Grain yields of wheat planted into the rice stubble residue were 5-10% more compared to CT [15,33,34].

In the RWS of NW India, wheat straw is generally collected from the fields and used as animal fodder but about 20-25% remains in the field after its retrieval using a straw combine. Alternatively, therefore, green manure legumes such as *Sesbania* could be used as mulch in rice. In DSR, *Sesbania* seed can be broadcast-sown or line-sown at the time of rice and knock down by spraying of herbicide 30-40 days after seeding, creating surface mulch. Previous studies showed that intercropping of *Sesbania* with DSR increased the grain yield and N uptake of rice [12,35,36] compared to sole crop. However, no information is available in the literature on the effect of green manure crops (particularly co-culture) on water use efficiency in rice. Moreover, in most studies, the effect of different tillage, crop establishment and residue management (mulch) are reported on crop yields only. Crop yields are measured at the end of the season as a static result of seasonal crop performance, but these results do not reflect the fluctuations of the crop's performance throughout the season. In order to finetune resource management, insight in crop performance (crop physiology) over time is crucial. Several physiological parameters reflect the crop performance during different growth stages of the crop to provide precise information on the effect of management practices on physiological processes at different crop developmental stages which in turn reflects in yield. The normalized difference vegetative index (NDVI) is successful in predicting photosynthetic activity, because this vegetation index includes both near infrared and red light. The NDVI was shown to be strongly correlated to biomass accumulation and final yield [37,38], and crop water stress [39]. Recently, Verhulst et al. [40] successfully used NDVI-based crop growth and development curves to characterize the effect of tillage, rotation and residue management on the crop performance of maize and wheat. In addition, canopy temperature, photosynthetic rate, leaf water potential at critical potential at critical stages provides precise information on in-season crop performance in relation to final out-put as affected by different management practices.

Although alternative tillage and crop establishment options have previously been evaluated in RWS in the IGP, their responses in terms of yield and water productivity are often variable and are affected by many factors such as climate, soil type and hydrological conditions. Few studies have examined the combined effects of crop establishment, tillage and straw mulch, on plant growth, crop physiology, grain yield and economics of RWS. Therefore, the study was aimed at

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a) Determining the effects of crop establishment, tillage and residue mulch on crop yields, growth and yield components, water use efficiency and economics of RWS, and

b) Crop physiological parameters under conservation agriculture-based management systems.

Materials and Methods

Experimental site

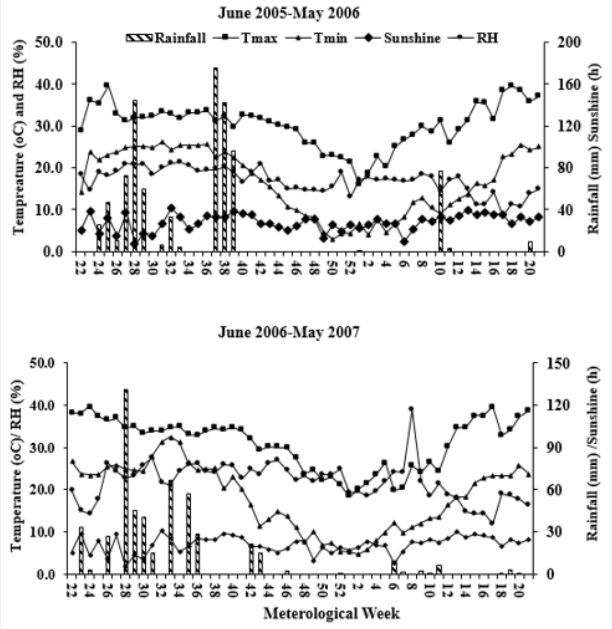

Figure 1: Weekly maximum and minimum temperature, sunshine hours, relative humidity, and rainfall at the experimental site.

A 2-year field experiment was established in the wet season of 2005 at the research farm (29° 4' N and 77° 46' E; 237m above mean sea level) of the Project Directorate for Cropping Systems research (PDCSR) Modipuram, India. The climate of the area is semi-arid subtropical, characterized by very hot summers and cold winters. The hottest months are May and June when maximum temperature reaches 45-46°C, whereas, during December and January, the coldest months of the year, temperature often goes below 5°C. The average annual rainfall is 863mm, 75-80% of which is received through the northwest monsoon during July-September. The weather pattern during the study period is given in Figure 1. There was no large variation in weather parameters during the two years of the study, except rainfall during the rice season in 2005 was higher (815mm) than in 2006 (449mm).

Samples from the 0-15cm soil layer were collected at the start of the field experiment, air-dried, crushed to pass through a 2-mm sieve, and stored in plastic jars for analysis. The soil was sandy loam in texture (International Soil Science Society) with clay, silt, and sand at 165, 205, and 62 g kg^{-1} soil, respectively; pH (1:2, soil: water) 8.1; electrical conductivity (EC) 0.4dS m^{-1}; exchangeable sodium percentage (ESP) 13.5g kg^{-1}; organic C (Walkley and Black), 8.3g kg^{-1}; total N (Kjeldahl digestion) 0.88g kg^{-1}; Olsen P (0.5M NaHCO$_3$ extractable) 25mg kg^{-1}; and 1M NH$_4$OAc extractable K 121mg kg^{-1} using standard analytical procedures [41]. The soil retained 18 and 7% water (mass basis) at −30 and −1500kPa water potentials, respectively determined on disturbed soil samples using a pressure-plate apparatus [42].

Experimental details and management

Table 1: Description of treatments included in the study.

Treatment No.	Treatment Details		Treatment Code
	Rice	Wheat	
T1	Conventional till puddled transplanted rice + Sesbania mulch (CT-PTR+S)	Zero-till wheat + rice residue mulch (ZTW+R)	CT-PTR + S/ZTW + R
T2	Conventional till puddled transplanted rice (no sesbania mulch) (CT-PTR)	Zero-till wheat (rice residue removed) (ZTW)	CT-PTR /ZTW
T3	Zero-till direct-seeded rice + Sesbania intercrop as mulch (ZT-DSR + S)	Zero-till wheat + rice straw mulch (ZTW+R)	ZT-DSR+S/ ZTW+R
T4	Zero-till direct-seeded rice (no Sesbania intercropping) (ZT-DSR)	Zero-till wheat (rice straw removed) (ZTW)	ZT-DSR/ZTW

T5	Conventional-till direct-seeded rice + Sesbania intercrop as mulch (CT-DSR+S)	Zero-till wheat + rice straw mulch (ZTW+R)	CT-DSR+S/ZTW +R
T6	Conventional-till direct-seeded rice (no Sesbania intercropping) (CT-DSR)	Zero-till wheat (rice straw removed) (ZTW)	CT-DSR/ZTW

The field was leveled using a laser equipped drag scrapper (Trimble™, USA) with an automatic hydraulic system attached to a 60HP tractor. After leveling, the land was tilled using a sub-soiler (chiseler) up to a 50cm soil depth followed by ploughing and pulverization with a harrow/cultivator to remove the soil compaction variability on account of past management practices. Wheat was then raised as a general crop before the execution of the experimental treatments in rice in June 2005. Six treatments (T1-T6) involving two rice establishment methods (conventional till puddled transplanted rice (CT-PTR) and direct dry seeded rice (DSR) and two tillage methods in DSR (conventional till and zero-till) with and without *Sesbania* co-culture were evaluated for rice (Table 1). In the succeeding winter season zero tillage with and without rice residue retention was evaluated in wheat under a rice–wheat rotation. The treatments were replicated thrice in a factorial randomized complete block design and the plot size was 20.0m by 6m (120m^2).

Tillage and crop establishment

Seed bed preparation for conventional till puddled transplanted rice (T1 and T2) included 2 dry-harrowings + 2 wet cultivations (puddling) + 1 planking. The anchored wheat crop stubbles were incorporated at field preparation. Twenty-one days old rice seedlings were transplanted manually (2-3 seedlings hill^{-1}) at 20cm by 15cm spacing. In T3 and T4, direct dry-seeded rice (DSR) was sown using zero-till seed- cum-fertilizer drill under zero-tillage at 20cm row spacing in 15cm anchored wheat crop stubbles. In conventional-till direct-seeded rice (T5 and T6), after conventional dry tillage (2-discing harrowings + 2-cultivators + 1 planking) direct seeding of rice was done using same seed- cum-fertilizer drill (same as for T3 and T4) at 20cm row spacing. In all the plots, zero-till wheat was seeded at 20-cm row spacing with turbo happy seeder (zero-tillage seed cum fertilizer drill). In residue mulch plots (T1, T3 and T5) 30-cm anchored rice stubbles and partially loose rice residue were retained at the surface (see details under residue management).

Sesbania aculeata and crop residue management

In T1 *Sesbania aculeata* (6Mg ha^{-1}, fresh biomass) raised in the adjoining field was manually placed as mulch on the soil surface between the two rows at10-12 d after transplanting. *Sesbania* added 1.1Mg ha^{-1} of dry matter and 23kg N ha^{-1}. In T3 and T5 treatments, *Sesbania* seeds were broadcasted on the same day of sowing of direct-seeded rice. *Sesbania* plants were knocked down by spraying 2, 4-D herbicide at 30 days after sowing, which added about 1Mg ha^{-1} dry biomass.

Rice was harvested manually after leaving 30-cm anchored crop stubbles in residue retained plots and after threshing partially loose residue uniformly spread back before wheat seeding in treatments T1, T3 and T5. Rice residue amounted to about 8Mg ha^{-1} (dry weight basis, averaged across all treatments) at harvest. On other hand, in the rice residue removal plots (T2, T4 and T6) crop was harvested from the ground level.

The wheat crop was harvested at 15-cm height in residue retention plots (T1, T3 and T5) adding about 1.0Mg ha^{-1} of stubbles. While wheat stubbles were retained in ZT plots (T3), these were incorporated into the soil in the CT-PTR (T1) and CT-DSR (T5) plots. In residue removal plots (T2, T4 and T6), wheat crop was harvested at ground level.

Seeding and seed rate

Transplanting of rice seedlings (rice hybrid PHB 71) was done manually in the last week of June. In T3-T6, rice was direct drill-seeded in the first week of June, using a zero-till seed cum fertilizer drill with the cupping seed-metering system, and on the same day nursery was raised for transplanted rice to maintain the same date of seeding in all treatments. The seeding rate for drill-seeded rice was 25kg ha^{-1} and for raising nursery for CT-PTR seed rate used was 15kg ha^{-1}. Wheat (PBW 343) was sown in the first week of November in all the treatments using a seed rate of 100kg ha^{-1}.

Irrigation water management in rice and wheat

In puddled transplanted rice (T1 and T2), plots were flooded (75-mm irrigation water) initially for 2 weeks to establish seedlings, and the subsequent irrigations (75mm of irrigation water) were applied when the soil matric potential (using tensiometer) decreased to about -20kPa in the 10-15cm soil layer. To the direct-seeded rice (T2-T6), light irrigations (50mm irrigation water) were given at a day after seeding and then 4 to 5d intervals for 3 weeks after germination, followed by subsequent irrigations (75mm of irrigation water) when the soil matric potential decreased to about -20kPa in the 10-15cm soil layer.

To wheat, five irrigations (50mm each) were applied at crown root initiation (21 days after seeding, DAS), maximum tillering (35-50 DAS), flowering (50-70 DAS), dough (85-100 DAS), and late dough (115-125 DAS) stages.

Fertilizer application

In rice, all plots received 150kg N as urea and diammonium phosphate, 26kg P as diammonium phosphate, 50kg K as muriate of potash, and 8.75kg Zn ha^{-1} as zinc sulphate. A full rate of P and K and a one-fourth N rate were applied using a zero-till seed-cum-fertilizer drill at the time of seeding in DSR and these were broadcast manually at the time of transplanting in CT-PTR. The remaining N was applied in three equal splits at 35 to 40, 45 to 50, and 60 to 70 DAS, respectively. Zinc was broadcast at seed-

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ing in DSR and at transplanting in CT-PTR plots. In wheat, all treatments received 120kg N, 26kg P and 50kg K, and full rates of P and K, and one-half N rate were applied using a zero-till seed-cum-fertilizer drill at sowing. The remaining N was applied in two equal splits at just before first irrigation (CRI) and second irrigation (tillering), respectively.

Weed management

Weeds in zero-tillage plots before the seeding of rice and wheat were killed by a pre-plant spray of glyphosate at 900g a.i. ha^{-1}. In DSR plots, pendimethalin 1000g a.i. ha^{-1} was applied at 2 DAS in moist soil, followed by one post emergence spray of 2,4-D ester 500g a.i. ha^{-1} at 30 DAS to knock down *Sesbania* and broadleaf weeds. In transplanted rice, butachlor 1000g a.i. ha^{-1} was applied 2 days after transplanting. One hand weeding was also done in transplanted and DSR to keep the plots weed-free. For wheat, grassy and broad leaf weeds were controlled by spraying sulfosulfuron + metsulfuron methyl at 35g a.i. + 4g a.i. ha^{-1} at 25 to 30 DAS.

Water application and measurements

Irrigation water was applied using polyvinyl chloride pipes of 10-cm diameter and the amount applied to each plot was measured using a water meter (Dasmesh Mechanical Works, India). The quantity of water applied, and the duration of irrigation were computed using the following equations:

Quantity of water applied (l) = Depth of irrigation (m) × plot area (m^2) × 1000 ----- (1)

Duration of irrigation per plot (min) = Quantity of water to be applied (l) × flow rate (l min^{-1}) ----- (2)

Rainfall data were recorded using a rain gauge. The total amount of water applied (input water) was computed as the sum of water applied through irrigations and rainfall. The input water productivity (WP_{I+R}) was computed as follows [10]:

WP_{I+R} (kg grain m^{-3} of water) = grain yield (kg ha^{-1})/ total input water (m^3) ------ (3)

Yield and yield parameters measurements

At maturity, rice and wheat growth and yield parameters that is, plant height, total number of effective panicles/tillers, panicle or ear length, number of grains panicle^{-1} or number of grains ear head^{-1}, and 1000-grain weight were measured. Total number of panicles was recorded using 1m^2 quadrate at two places in each plot. Simultaneously 10 plants were randomly selected from each quadrate for measurements of yield parameters. Grain and straw yields were determined from an area of 15by 4m (60m^2) in all plots. The rice grains were threshed manually, and wheat grains were threshed using a plot thresher; dried in a batch grain dryer and weighed. Grain moisture was determined immediately after weighing. Grain yields of rice and wheat were reported at 140 and 120g kg^{-1} water content, respectively. Straw weight was determined after oven-drying at 70°C to constant weight and expressed on an oven dry-weight basis.

In-season optical sensor measurements

Spectral reflectance readings were taken periodically across the growing seasons of rice and wheat. Spectral reflectance expressed as normalized difference vegetative index (NDVI) was measured using a handheld GreenSeeker™ optical sensor unit (NTech Industries Incorporation, Ukiah, CA, USA). The unit senses a 0.6 x 0.1m^2 area when held at a distance of approximately 0.6–1.0 m from the illuminated surface. The sensed dimensions remain approximately constant over the height range of the sensor. The sensor unit has self-contained illumination in both the red ([656nm with ~25nm full width half magnitude (FWHM) and NIR (774 with ~25nm FWHM) bands http://www.ntechindustries.com/datasheets.php, confirmed on 09 April 2012).

The sensor outputs NDVI at a rate of ten readings per second. The sensor was passed over the crop at a height of approximately 0.9m above the crop canopy and oriented so that the 0.6m sensed width was perpendicular to the row and centered over the row (Bijay-Singh et al. 2011). With advancing stage of growth, sensor height above the ground increased proportionally. Travel velocities were at a slow walking speed of approximately 0.5ms^{-1} resulting in NDVI readings averaged over distances of 0.05m.

Crop physiological parameters

Plant canopy temperature was regularly monitored at 1600h using an infrared canopy thermometer from flowering initiation through maturity during the wheat growing season in 2005-06 and 2006-07. Leaf water potential and photosynthesis rates were also measured at three times during flowering initiation at 3- day interval. The leaf water potential was measured before stomata opening in between 0400 to 0600h by selecting the fully expanded 2nd top most leaf from three randomly selected wheat plants within each plot with the help of a portable plant water status console (Model 3115, Soil Moisture Equipment Corp). Similarly, the photosynthesis rate of fully expanded 2nd top most leaf from three wheat plants in each plot was measured using an infra-red gas analyzer (IRGA), (Model 6400). Data for the both leaf water potential and photosynthesis rate collected at three times were averaged.

Gross margin analysis

All input costs including of tractor use, seed, fertilizer, fuel, biocides, irrigation, and labor and returns for outputs were used for gross margin analysis in respective years in the study [10,15]. These data were obtained from current market price paid for inputs [43,44]. The cost of human labor used for tillage, seeding, irrigation, fertilizer and pesticide application, weeding, and harvesting of rice and wheat crops was based on person-day ha^{-1} [45]. Time (h) required to complete a particular field operation in a given treatment was recorded and expressed as person-day ha^{-1}, considering 8h to be equivalent to 1 person-day. Similarly, time (h) required by a tractor-drawn machine to complete a field operation includes tillage, seeding, fertilizer application and har-

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vesting was recorded, and expressed as h ha^{-1}. Time (h) required to irrigate a particular plot and consumption of electricity (l h^{-1}) by the pump was also recorded. Cost of irrigation was calculated by multiplying time (h) required to irrigate a particular plot, consumption of electricity units by the pump (1h^{-1}) and cost of electricity per unit. The cost of cultivation and gross returns were calculated as described by Gathala et al. [10]. Straw values of rice and wheat were calculated using current market rates. Net returns (NR) were calculated as the difference between gross returns and total cost of cultivation. System productivity was calculated by adding the grain yield of rice and wheat in each year, and the system net returns (SNR) were calculated by adding the net return of rice (NRr) and wheat (NRw) for the individual year. The benefit/cost ratio computed by dividing the gross returns (GR) by the total cost of cultivation.

Data analysis

The data were subjected to ANOVA and analyzed using the general linear model (GLM) procedures of the statistical analysis system [46]. Treatment means were compared by Tukey's honest significant difference (HSD) test. Unless stated otherwise, differences were considered significant only when $P < 0.05$.

Results

Growth and yield parameters of rice and wheat

Table 2: Effect of tillage, crop establishment and residue on crop growth and yield parameters (averaged over 2yrs) of rice and wheat in the rice-wheat system.

Treatment	Effective Tiller/ Panicle (m^{-2})		Plant Height (cm)		Ear/Panicle Length (cm)		Grains (Ear Panicle^{-1})		1000 Grain Weight (g)		Biomass (Mg ha^{-1})		Harvest Index	
Rice														
*T1	265	c	122	a	28.98	a	185	a	22.25	a	16.81	a	0.45	a
T2	267	c	122	a	28.22	ab	174	ab	21.85	a	16.61	a	0.45	a
T3	284	ab	105	b	27.67	abc	171	ab	21.22	a	16.63	a	0.42	b
T4	289	a	103	b	26.48	c	140	c	21.2	a	16.26	a	0.42	b
T5	261	c	103	b	26.96	bc	137	c	20.44	a	16.49	a	0.44	ab
T6	274	bc	109	b	28.05	abc	156	bc	21.28	a	17.04	a	0.42	b
Residue														
Residue	270	b	110	a	27.87	a	164	a	21.3	a	16.64	a	0.44	a
No residue	277	a	112	a	27.58	a	157	a	21.44	a	16.64	a	0.43	a
Wheat														
*T1	356	ab	95	a	8.72	a	40.57	ab	42.5	a	12.12	ab	0.41	a
T2	334	b	91	b	8.84	a	40.76	ab	42.48	a	10.64	d	0.42	a
T3	377	a	95	a	8.74	a	41.61	ab	42.12	a	12.5	a	0.42	a
T4	358	ab	91	b	8.62	a	39.13	b	42.08	a	11.16	cd	0.43	a
T5	349	ab	96	a	9.45	a	42.2	a	41.72	a	11.65	bc	0.44	a
T6	336	b	92	b	8.88	a	41.33	ab	42.56	a	10.89	cd	0.42	a
Residue														
Residue	361	a	95	a	8.97	a	41.46	a	42.11	a	12.09	a	0.42	a
No residue	343	b	91	b	8.78	a	40.41	b	42.37	a	10.9	b	0.43	a
Source	**Analysis of Variance (ANOVA)**													
Rice														
Replication	0.412		0.181		0.018		0.365		0.252		0.351		0.402	
Treatment (T)	<0.001		<0.001		0.005		<0.001		0.112		0.532		0.008	

Residue (R)	0.014	0.322	0.354	0.078	0.744	0.926	0.275
R x T	<0.001	<0.001	0.003	<0.001	0.074	0.413	0.005
Wheat							
Replication	0.145	0.083	0.549	0.11	0.89	0.154	0.165
Treatment (T)	0.01	0.04	0.145	0.035	0.613	<0.001	0.126
Residue (R)	0.008	0.002	0.277	0.043	0.428	<0.001	0.542
R x T	0.028	0.917	0.127	0.053	0.58	0.011	0.089

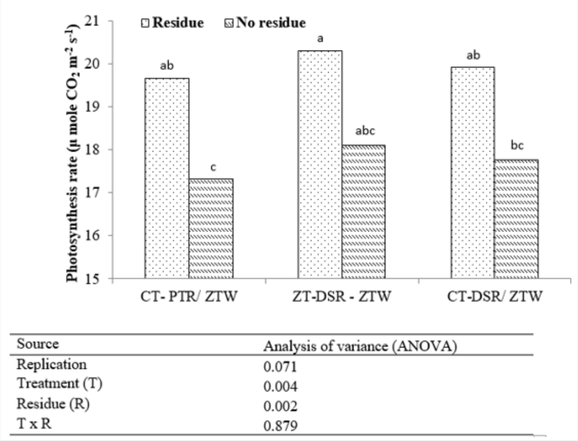
*For treatment descriptions refer to table 1. Treatment means within a column followed by the same letter were not statistically different according to LSD (0.05).

A combined ANOVA over the two years showed a significant effect of treatments and treatment × year interaction on rice in 2006-07 and wheat growth and yield attributes (Table 2). Crop growth parameters and yield attributes of rice, except 1000- grain weight and biomass yield were significantly affected by tillage, residue and crop establishment (CE) methods (Table 2). CT-PTR with and without residue (T1 and T2) did not differ in any of the growth and yield attribute parameters. Rice plants were taller in CT-PTR with residue (T1) than in DSR irrespective of tillage (T3-T6). The number of panicles was higher (284 and 289m^{-2}) in ZT-DSR (T3 and T4) compared to all other treatments (265–274m^{-2}), except CT-DSR with no residue (T5). CT-PTR rice with residue (T1) had longer panicle length than in T4 and T5 and more number of grains per panicle than in T4-T6. Panicle length in T1-T3 and T6 was similar.

Plant height was significantly higher in treatments with rice residue, irrespective of tillage and CE methods (Table 2). Grain number per spike was significantly higher in T5 (ZTW +R-CTDSR) than in T4 (ZTW-R-ZT-DSR) but was on a par with all other treatments. The total biomass was maximum in ZTW+R after ZT-DSR (T3) and minimum in ZTW-R after CT-PTR (T2). On an average, it was 10.9% higher in residue mulch treatments compared to no residue. Interestingly, mean biomass in wheat was higher by 1.19Mg ha^{-1} (10.9%) in residue retention compared to no residue plots. Ear length, 1000-grain weight and harvest index were not affected by tillage, residue and CE methods in wheat (Table 2). Effective tiller density of wheat was significantly higher (5.2%) in residue treatments compared to no residue. Effective tiller density was higher in ZTW with residue planted after ZTR (T3) compared to ZTW with no residue planted after CT-PTR (T2) and after

Grain yiel

Table 3: Pe



Source	Analysis of variance (ANOVA)
Replication	0.071
Treatment (T)	0.004
Residue (R)	0.002
T x R	0.879

Figure 3: Effect of different tillage options and crop residue mulch on photosynthesis rates (two years mean) at the flowering stage of wheat in the rice-wheat system. CT-Conventional till, PTR-Puddled transplanted rice, ZT- Zero till, DSR- Direct dry seeded rice, ZTW-Zero till wheat.

Treatme												
*T1												
T2												
T3												
T4												
T5												
T6												
Residue	7.33	a	4.43	a	11.76	a	7.14	a	5.78	a	12.92	a
No residue	7.51	a	3.86	b	11.36	b	6.8	b	5.43	b	12.24	b
Source	**Analysis of Variance (ANOVA)**											
Replication	0.744		0.424		0.573		0.751		0.968		0.916	
Treatment (T)	0.144		<0.001		0.105		<0.001		0.001		0.001	
Residue (R)	0.159		<0.001		0.014		<0.001		0.001		<0.001	
R x T	0.158		0.001		0.5		<0.001		0.019		0.058	

*For treatment descriptions refer to table 1. Treatment means within a column followed by the same letter were not statistically different according to LSD (0.05).

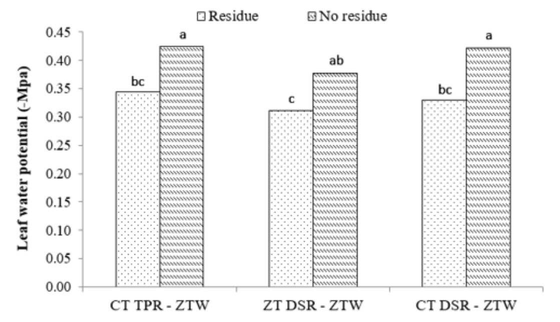
Rice yield was not influenced by tillage, crop establishment (CE) and *Sesbania* co-culture/mulch in the first year (2005-06) of the study (Table 3). A combined ANOVA over the years showed a significant effect of treatments and treatment × year interaction on rice in 2006-07 (Table 3). CT-PTR with residue retention (T1) produced 9.8-18.2% higher yields than DSR (T3-T6). Despite higher number of panicles m^{-2}, lower yield in DSR (T3-T6) compared with CT-PTR (T1) in 2006-07 suggests that higher panicle number could not compensate the losses caused by lower number of grains $panicle^{-1}$. In 2006-07, yield of CT-PTR with residue retention (T1) was significantly higher compared to all other treatments and was lowest in ZT-DSR with no residue (T4). Rice yields in T2, T3, T5 and T6 were similar. ZT-DSR with residue retention (T3) yielded like CT-DSR with or without residue (T5, T6). In 2006-07, *Sesbania* mulch in CT-PTR (T1 versus T2) and *Sesbania* co-culture in ZT-DSR (T3 versus T4) rice yielded significantly higher compared to no *Sesbania* (Table 3). *Sesbania* co-culture in rice increased mean grain yield of CT-PTR and ZT-DSR by about 6.6% compared to no *Sesbania* treatments. It is, however, difficult to separate out the effect of *Sesbania* co-culture and wheat straw retention in the present study.

The residual effect of tillage and crop establishment adopted during the rice phase and direct effect of residue management on yield of succeeding wheat crop were significant, and these effects started showing after one cropping cycle (Table 3). ZTW+R planted after ZT-DSR (T3) always produced the highest wheat yield, while ZTW without residue after CTDSR transplanted rice (T6) produced the lowest yield. Overall, wheat with rice residue produced significantly higher (14.8% in 2005-06 and 6.4% in 2006-07) yield than without residue.

System productivity

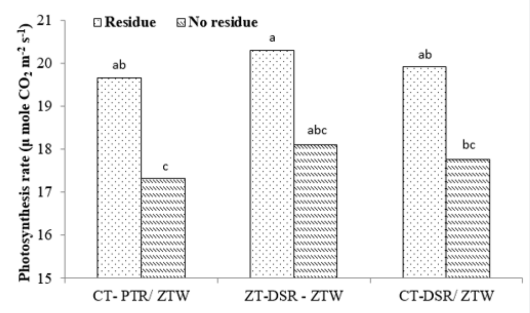
The system productivity (rice + wheat) was similar under different tillage treatments and CE methods in 2005-06 (Table 3). In 2006-07, the system productivity of T1, T2, T3, and T5 did not differ significantly, although T4 had the lowest productivity. On average, rice residue mulch in wheat had significantly higher productivity compared to no residue during both seasons.

Leaf water potential, photosynthetic rate and canopy temperature in wheat



Source	Analysis of variance (ANOVA)
Replication	0.560
Treatment (T)	0.001
Residue (R)	<0.001
T x R	0.121

Figure 2: Leaf water potential (two years mean) under different tillage options and crop residue mulch at flowering stage of wheat in the rice-wheat system. CT- Conventional till, PTR-Puddled transplanted rice, ZT- Zero till, DSR- Direct dry seeded rice, ZTW-Zero till wheat.



Source	Analysis of variance (ANOVA)
Replication	0.071
Treatment (T)	0.004
Residue (R)	0.002
T x R	0.879

Figure 3: Effect of different tillage options and crop residue mulch on photosynthesis rates (two years mean) at the flowering stage of wheat in the rice-wheat system. CT-Conventional till, PTR-Puddled transplanted rice, ZT- Zero till, DSR- Direct dry seeded rice, ZTW-Zero till wheat.

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Leaf water potential of wheat recorded during flowering initiation was significantly affected by mulching, irrespective of rice treatments (Figure 2). There was no effect of previous rice treatments on leaf water potential of wheat. On average leaf water potential was 0.9 MPa higher in the plots with mulching compared to no mulching. Photosynthesis rate in wheat measured during flowering initiation was significantly higher in ZTW + R (T1) compared to T2 (Figure 3). However, mulching showed no significant effect on photosynthesis rate in ZTW after DSR (T3-T6).

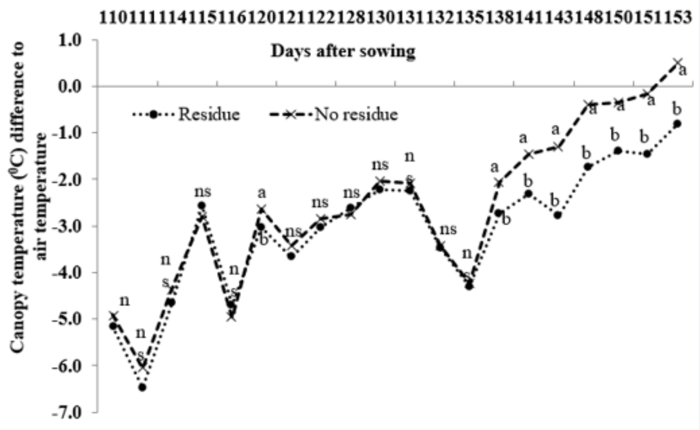

Figure 4: Effect of crop residue mulch on canopy temperature (two years mean) at the maturity stage of wheat in the rice-wheat system.

There was no effect of previous rice treatments on the canopy temperature measured during grain filling stage (110 days after sowing till maturity) of wheat, therefore data were averaged for no mulch and mulch treatments and are presented in Figure 4. Canopy temperature was significantly lower (0.6 to 1.5°C) under mulching compared to no mulching during 138 to 153 days after sowing (Figure 4).

NDVI-based crop growth

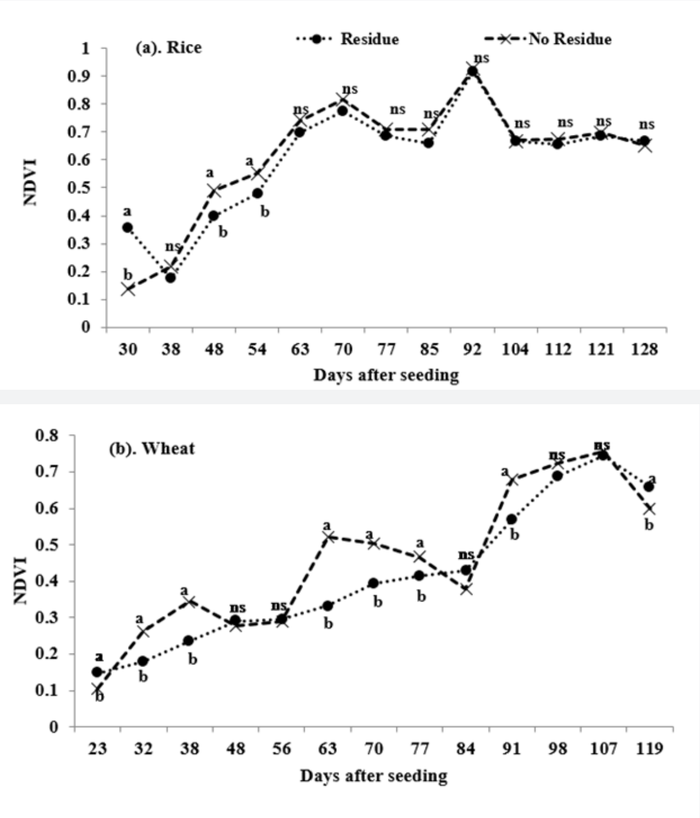

Figure 5: Green Seeker normalized difference vegetation index (NDVI) values during different growth stages of (a) rice and (b) wheat with and without residues averaged across different tillage treatments (mean of 2 years).

The average NDVI values were plotted against time for with and without residue treatments (averaged over tillage and crop establishment). For rice, NDVI values gradually increased along the growing season until a maximum was reached at 104 DAS/ planting (Figure 5a). Residue mulch along with co-culture/mulching of *Sesbania* resulted in faster rice growth at the beginning (35 days after planting/sowing) compared with no residue and then the crop in no residue treatments showed somewhat better growth until 70 days after planting. The residue retention had no effect on NDVI values recorded during the later rice season (Figure 5a). Rice grain yield was also similar under residue removal and residue retention treatments in 2005-06. In 2006-07, average rice yield was however, 5% higher in residue retention compared to residue removal treatments.

A similar form of the NDVI-based growth and development curves was seen in wheat (Figure 5b). Residue mulch in ZT wheat resulted in slower growth compared to zero tillage without residue retention at the beginning of the season until 98 days after seeding. The NDVI in wheat increased until 107 days after seeding and thereafter, wheat growth in residue mulch was like that in residue removal plots.

Water use and water productivity

Irrigation water use

In the rice season, year 2005 was relatively high-rainfall year, with seasonal rainfall of 815mm compared to 449mm in 2006 that caused much difference in irrigation water use (Table 4). Rice used more irrigation water (11.8 and 8.3%, respectively) in CT-PTR with no residue (T2) compared to ZT-DSR+R (T3) and CTDSR +R (T5) in 2005-06. On an average, DSR (after conventional/ zero tillage) (T3 -T6) had 13.9% less water use compared to CT-PTR (T1 and T2) in 2006-07. Rice residue mulch in wheat along with co-culture of *Sesbania* in rice saved 71 and 34mm of irrigation water in 2005-06 and 2006-07, respectively. The amount of irrigation used in ZT-DSR was similar to that in CT-DSR.

Table 4: Effect of tillage, crop establishment and residue options on applied irrigation water and input water productivity in the rice-wheat system.

Treatment	Irrigation Water Applied (mm ha^{-1})												Input Water Productivity (kg grain m^{-3} water)											
	2005-06						2006-07						2005-06						2006-07					
	Rice		Wheat		System		Rice		Wheat		System		Rice		Wheat		System		Rice		Wheat		System	
*T1	1820	ab	428	a	2248	a	2175	a	397	a	2573	a	0.28	a	0.87	ab	0.38	a	0.29	a	1.09	b	0.42	bc
T2	1872	a	398	a	2270	a	2129	a	390	a	2518	a	0.28	a	0.76	c	0.36	a	0.28	a	1.06	b	0.41	c
T3	1674	c	417	a	2091	b	1879	b	381	a	2260	b	0.28	a	0.91	a	0.39	a	0.3	a	1.2	a	0.45	a
T4	1755	abc	397	a	2152	ab	1839	b	379	a	2219	b	0.29	a	0.87	a	0.38	a	0.28	a	1.11	ab	0.43	abc
T5	1728	bc	435	a	2163	ab	1856	b	387	a	2243	b	0.29	a	0.85	abc	0.39	a	0.3	a	1.16	ab	0.45	a
T6	1809	abc	412	a	2221	ab	1840	b	382	a	2222	b	0.29	a	0.77	bc	0.36	a	0.3	a	1.1	ab	0.44	ab
Residue																								
Residue	1741	b	427	a	2167	a	1970	a	388	a	2358	a	0.29	a	0.87	a	0.38	a	0.3	a	1.15	a	0.44	a
No residue	1812	a	402	b	2214	a	1936	a	384	a	2320	a	0.29	a	0.8	b	0.37	b	0.29	b	1.09	b	0.43	b
Rainfall (mm)	815		82		897		449		115		564													
Source	Analysis of Variance (ANOVA)																							
Replication	0.423		0.023		0.886		0.566		0.642		0.5		0.437		0.025		0.595		0.296		0.828		0.323	
Treatment (T)	0.001		0.208		0.015		0.001		0.433		0.001		0.897		0.003		0.047		0.055		0.014		0.001	
Residue (R)	0.011		0.028		0.086		0.383		0.434		0.322		0.821		0.001		0.007		0.048		0.012		0.004	
T x R	0.012		0.697		0.014		0.001		0.381		0.001		0.823		0.015		0.281		0.09		0.036		0.002	

*For treatment descriptions refer to table 1. Treatment means within a column followed by the same letter were not statistically different according to LSD (0.05).

The irrigation water use in wheat was similar in all the treatments and ranged from 397-435mm in 2005-06 and 379 to 397mm in 2006-07 (Table 4). This was expected because tillage management in wheat for all the treatments was similar. The mean use of irrigation water was 25mm lower with residue compared to no residue in 2005-06. However, no such effect was observed in 2006-07. For the system, all treatments had the similar irrigation water use, except T3 (ZTW+R after ZT-DSR) which had significantly lower (7%) irrigation water use compared to T1 and T2 in 2005-06 (Table 4). In 2006-07, total amount of irrigation water use in the RW cultivation followed a similar trend to that of rice.

Water productivity

Water productivity (WP) in rice and RWS was not affected by tillage and CE methods in 2005-06 (Table 4). Water productivity of wheat was highest (0.91kg grain m^{-3} water) in T3 and lowest (0.76 -0.77kg grain m^{-3} water) in T2 and T6, and similar (0.85-0.91kg grain m^{-3} water) in T3 to T6. Like 2005-06, WP in 2006-07 in rice was not affected by tillage, residue and CE methods.

WP in wheat was significantly lower in T1 and T2 compared to T3, but it was similar in T1, T2, and T4 to T6. In RW system, WP was highest (0.45kg grain m^{-3}) in T3 and T5 and lowest (0.41-0.42kg grain m^{-3} water) in T1 and T2, with other treatments having values in the following order: T4 (0.43kg grain m^{-3} water) = T6 (0.44kg grain m^{-3} water). Overall, comparing treatments based on system productivity and water productivity data, T3 was the best treatment, T4 and T5 were the next best and T2 was the poorest treatment. The higher system productivity in T3 in 2006-07 was due to less amount of irrigation water used in rice and higher yield of following wheat compared with other treatments.

Gross Margin Analysis

The cost of rice cultivation was significantly affected by tillage and CE methods (Table 5). The cost of rice cultivation was highest in CT-PTR (T1 and T2), followed by CT-DSR (T5 and T6), and lowest in ZT-DSR (T3 and T4). The difference between the highest and lowest cost of cultivation was US\$137ha^{-1}. The cost of wheat cultivation was similar in all the treatments (Table 5). The total cost of RW cultivation followed a similar trend to that of rice, with the highest and lowest cultivation costs again differing by US\$137ha^{-1}. The highest net returns (US\$435-443ha^{-1}) from the rice crop were obtained with ZT-DSR (T3 and T4), followed by CTDSR (T5 and T6) (US\$ 407-413ha^{-1}) and lowest (US\$ 369-387ha^{-1}) in CT-PTR (T1 and T2). Net returns from wheat were highest in T3, followed by T1, T4, and T5, and least in T2 and T6. The difference in net returns between the highest and lowest values was US\$ 109ha^{-1}. Considering the RWS, the highest net returns were obtained with T3 and T4 (US\$1130-1185), followed by T5, T1 and T6 (US\$ 1071-1101), and lowest was with T2 (US\$ 1001). Like net returns, the benefit: cost ratio in rice was highest with ZT-DSR (1.90), followed by CTDSR (1.74), and lowest with CT-PTR (1.60). In wheat, the trend was T3 > T1 =T4=T5 > T6=T2 (Table 5). The trend in the benefit: cost ratio from the RWS was like that of rice.

Table 5: Partial budgeting (averaged over 2yrs) under different tillage, crop establishment and residue options in the rice-wheat cropping system.

Treatment	Cost of Production (US \$ ha^{-1})						Net Returns (US \$ ha^{-1})						Benefit: Cost Ratio					
	Rice		Wheat		System		Rice		Wheat		System		Rice		Wheat		System	
*T1	638	a	364	a	1002	a	387	bc	697	b	1083	b	1.61	c	2.9	b	2.08	c
T2	631	a	368	a	999	a	369	c	632	c	1001	c	1.59	c	2.69	c	1.99	c
T3	501	c	364	a	865	c	443	a	741	a	1185	a	1.9	a	3.02	a	2.36	a
T4	494	c	368	a	862	c	435	a	695	b	1130	ab	1.9	a	2.87	b	2.31	a
T5	565	b	364	a	929	b	407	abc	694	b	1101	b	1.73	b	2.89	b	2.18	b
T6	558	b	368	a	926	b	413	ab	658	c	1071	b	1.75	b	2.77	c	2.15	b
Residue																		
Residue	568	a	364	a	932	a	412	a	711	a	1123	a	1.74	a	2.94	a	2.21	a
No residue	561	a	368	a	929	a	406	a	662	b	1068	b	1.75	a	2.78	b	2.15	b
Source	**Analysis of Variance (ANOVA)**																	
Replication	0.952		0.931		0.944		0.919		0.401		0.87		0.842		0.467		0.93	
Treatment (T)	<.001		<.001		<.001		0.001		<.001		<0.001		<0.001		<0.001		<0.001	
Residue (R)	0.446		0.468		0.226		0.39		<0.001		<0.001		0.817		<0.001		0.001	
T x R	0.164		0.127		0.096		0.001		<0.001		<0.001		<0.001		<0.001		<0.001	

*For treatment descriptions refer to table 1. Treatment means within a column followed by the same letter were not statistically different according to LSD (0.05).

Discussion

Rice productivity

Earlier published research has shown higher panicles m^{-2} in DSR than in CT-PTR and higher spikelet sterility and smaller spike length in DSR than CT-PTR [9,10]. Our results show higher panicle density in DSR treatments compared with CT-PTR; however, panicle length and number of grains per panicle were lower in the DSR treatments relative to the CT-PTR treatments (Table 2). Based on many datasets, Kumar & Ladha [16] reported 10% lower yields in DSR compared to CT-PTR in India. Similarly, Farooq et al. (2011) reported that despite lower yields under DSR compared to CT-PTR, DSR has received much attention because of its low input (water, labour, cost) demand. With continued breeding, future aerobic rice (DSR) varieties should possess many spikelets and sufficient adaptation to aerobic conditions such that they will consistently achieve yields comparable to the potential yield of flooded rice [47]. Maintaining enough development of the fertilized grain is another challenge to developing high-yielding DSR. The lower harvest index of DSR compared to CT-PTR was probably due to its low remobilization ability under aerobic conditions leading to more straw yield.

Huang et al. [19] reported that yields of super hybrid rice on organic matter rich soil for ZT-DSR, CT-DSR and CT-PTR were similar under researchers managed conditions. In our study, rice yield was not affected by tillage and crop establishment methods in 2005-06; however, rice yield was higher in CT-PTR treat-

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ments relative to DSR treatments (ZT or CT) in 2006-07. A review of studies from Australia, China, Japan, the Philippines, and the USA, suggests that the yield penalty of aerobic rice is generally less in temperate climates than in the tropics [17]. For example, in a study from Japan, Kato et al. [47] reported that average yield under aerobic conditions was similar to or even higher than that achieved with flooded conditions.

In earlier studies, Singh et al. [35] and Yadav [36] have reported an increase in rice yield by 10.3 to 22% from *Sesbania* co-culture compared to no *Sesbania* in DSR due to weed suppression and atmospheric nitrogen fixation. The increase in mean rice yield with *Sesbania* co-culture in our study was 6.6% (Table 3). However, *Sesbania* co-culture may pose risks of competition with rice if 2,4-D application is ineffective or 2,4-D application is delayed due to continuous rain and could also increase the cost of production. Moreover, *Sesbania* co-culture may limit the use of herbicides as some of these herbicides may kill *Sesbania* also [16].

Liu et al. [48] from a 3-year study on RWS in Chengdu flood plain, southwest China, reported that plastic film mulching resulted in 12% higher average yield of rice while wheat straw mulching led to 14% lower average yield of rice compared with lowland rice under traditional flooding. Changes in soil temperature in relation to root growth and nutrient uptake are likely to be the major factors responsible for the changes in rice yields under non-flooded mulching cultivation.

Wheat productivity

The disposal of rice residue is a serious problem in north-west India. Many farmers burn the rice straw, leading to air pollution and a decline in soil organic matter content. In order to improve soil fertility and conserve water, local governments encourage farmers to return the straw to the field. Our results indicated that wheat yield was greater in the residue mulch treatment compared to the no mulch treatment. These results are consistent with the findings of (Chakraborty et al. 2008) [30,34] in which ZT wheat yield under rice residue mulch was significantly higher than after removal or burning of residue. In another study, zero-tilled wheat after zero-tilled rice had 19 to 25% higher yield than conventional tilled wheat after CT-PTR [10].

Bijay-Singh et al. [49] summarized 41 data sets from China and India with reduced or no-till wheat, barley, or rapeseed which revealed that mulching rice residue often increased yield. A combined analysis of the data set revealed that that mulching upland crops with rice residue leads to increased productivity. Wheat yield increased by up to 1.9Mg ha^{-1} when rice residue was retained as mulch. Possible reasons for the increase in wheat yield are that the straw mulch reduced soil temperatures, conserved more soil moisture, and reduced the canopy temperature during grain filling. The increase in wheat biomass through residue retention could have major implications to achieve high wheat yield. White & Wilson [50] reported that variation in grain yield was more strongly associated with variation in biomass (an increase of 0.78Mg ha^{-1} in grain yield per 1Mg ha^{-1} increase in biomass) than in harvest index.

The effect of mulch on crop yield depends on the extent of its influence on biophysical conditions that constrain crop growth [51]. Many studies have confirmed that straw mulch conserves soil moisture and reduces weed growth (Rahman et al. 2005) [27,30]. In contrast, other studies reported that straw mulch decreased winter wheat yield [52]. These results indicate that the effect of straw mulch on crop yield depends on crop and climate conditions [53].

Crop physiology parameters

The higher leaf water potential recorded with mulching suggests that mulch reduced soil evaporation and provided better soil moisture and temperature conditions [27]. Photosynthesis rate in wheat measured during flowering initiation was significantly higher in ZTW + R (T1) compared to T2 (Figure 3). Ehrler et al. [54] reported that drought stress significantly decreased the leaf water potential and relative water content of wheat, which had pronounced effects on photosynthetic rate. It is generally observed that the higher the leaf water potential, the higher was the photosynthetic rate [40]. Jiang et al. [55] showed that increase in grain yield of wheat cultivars have been associated with the elevation of photosynthetic rate and stomatal conductance over the past 50 years. In an earlier study, Lal et al. [56] reported an increase in leaf water potential of maize due to higher soil moisture content under ZT compared to CT but no such effect was observed in cowpea.

In an earlier study, Manpreet-Singh et al. [57] recorded 2.9^{o}C lower canopy temperature recorded between 135-142 days after wheat sowing under straw mulch as compared to straw burning. The increase in canopy temperature in no residue treatment was perhaps due to moisture stress that might have occurred due to increased respiration and decreased transpiration resulting from stomatal closure [40]. The low canopy temperature in wheat can minimize adverse impact of rising soil temperatures often observed during grain filing stage leading to substantial yield increases in the northwestern India [58].

NDVI-based crop growth

Verhulst et al. [40] and [38] reported that NDVI increased with the expansion of the crop growth, as the leaves began to fill the row, intersecting with leaves from smaller plants. The wheat residue recycled in rice amounted to 1.0 Mg ha^{-1} and a major fraction of rice residue retained in wheat most likely decomposed during the pre-rice period, leaving small effects on rice growth. Further research is needed to establish the use of NDVI-based crop growth to predict rice yield. Reports on differences in rice growth under different residue management practices are presently scarce.

Mandal et al. [59] and Scotford and Miller (2004b) found similar results for wheat. Verhulst et al. [40] reported that the NDVI should be considered as a measurement of plant growth and development reflecting various factors and the measurement is

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non-destructive, easy and fast. Sidhu et al. [30] showed that the maximum soil temperature in surface layers for irrigated wheat grown into rice residue was 2-3^{0}C lower from that for wheat grown after removal/burning of residue. This could partly be responsible for the observed growth lag in residue retention plots. Decomposition of incorporated rice residue has the potential to lower soil N availability due to its high C-to-N ratio which induces N immobilization [60]. The change in N cycling could partly explain why the NDVI-based crop growth and development curves of no residue take off more quickly in comparison with the residue retention treatments, i.e. more inorganic N is available for the growing crop [40]. Wheat under mulch remains greener over extended periods (7-10 days) and compensated for initial poor growth [27].

Water productivity

The DSR reduced water use and increased WUE relative to CT-PTR; however, rice yields were lower in the DSR treatments compared to the CT-PTR treatments (Table 4). From an earlier study, Gathala et al. [10] reported that DSR used 191mm (averaged over 7 years) of lesser irrigation water that CT-PTR. Although surface mulch is known to reduce evaporation losses in wheat, it failed to convert the benefit in reducing irrigation water requirement [27]. The water productivities of 0.8-1.0kg m^{-3} in rice were achieved in the study by Kato at al. [47], which are substantially higher than those of our study. There is thus ample scope to increase water use efficiency in DSR through selecting high yielding cultivars and following proper water management practices.

System productivity and profitability

Our study shows that ZT- based DSR followed by ZT wheat with residue mulch has potential to replace conventional practice of growing rice and wheat without a yield penalty on a system basis. The zero-tillage DSR with or without co-culture of *Sesbania* followed by ZTW with or without rice residue was the most profitable RWS due to saving labor, time, water and energy costs. There are several reports showing savings in savings in irrigation water, labour, and production costs, and higher net economic returns in DSR and ZTW compared with conventional till rice and wheat in the IGP [3,15,16]. Presently, there are a few studies on the performance of ZT-DSR/ ZTW with rice residue mulch in system perspective relative to the conventional systems in the South Asia [61-67].

Conclusion

During the past 2 decades, researchers in close association with farmers have put significant efforts to address the issues of declining farm profitability, depleting water resources and deteriorating soil health by developing and refining conservation agriculture (CA) based crop management practices for the rice-wheat system (RWS) in the IGP of South Asia. However, most CA research revolved around wheat; lacking system approach. This study on tillage, crop establishment, crop residues and inclusion of legumes (all three key elements of CA) in the RWS provides systematic information on the effect of CA based crop management on crop growth and physiology, productivity, profitability and water use in a system perspective. Although the productivity of rice under CT-PTR +R was higher than DSR, irrespective of tillage and residue retention, the highest wheat productivity (4.51-5.96Mg ha^{-1}) was obtained with ZTW+R (T3), which was followed by CT-DSR+R (T5). Due to differential yield responses of two cereals in rotation with tillage and CE methods, the average system (rice–wheat) productivity was similar with CT-PTR (T1, T2) and ZT-DSR (T5, T6). Furthermore, ZT-DSR/ZTW+R (T3) is likely to be superior in the long-run because of gradual improvement in soil quality, especially physical properties [10,16]. There is still a need to improve the productivity of direct drill-seeded rice to further increase the system productivity. In Japan, Kato et al. [30] achieved grain yield of over 10Mg ha^{-1} for the super-high-yielding variety Takanari with an ample sink capacity (grain number x grain weight) under aerobic conditions, strongly suggesting that high yields can be achieved with a high-yielding rice cultivar suitable for cultivation under aerobic conditions. Surface mulching in ZTW is a promising technology for managing rice straw and avoiding straw burning. More research is needed to evaluate ZT-DSR/ ZTW with rice residue mulch in system perspective relative to the conventional systems under different soil and climate situations in South Asia.

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