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Shikha Thapa Magar
Agricultural University Of Hebei

Jagadish Timsina
University of Melbourne

K.P. Devkota
Mohammed VI Polytechnic University

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Conservation agriculture for increasing productivity, profitability and water productivity in rice-wheat system of the Eastern Gangetic Plain

Shikha Thapa Magar[a,b,*], Jagadish Timsina[c,d], Krishna Prasad Devkota[e], Liang Weili[a,b,*], Neeranjan Rajbhandari[f]

[a] Department of Crop Production, Faculty of Agronomy, Hebei Agricultural University, Baoding, Hebei 071001, China
[b] Hebei Provincial Key Laboratory for Crop Growth Regulation, China
[c] Global Evergreening Alliance, Melbourne, Australia
[d] Institute for Study and Development Worldwide, Sydney, 8/45 Henley Road, Homebush West, NSW 2134, Australia
[e] African Sustainable Agriculture Research Institute (ASARI), Mohammed VI Polytechnic University (UM6P), Laayoune, Morocco
[f] NIRAS, Bakhundole, Sanepa 3, . GPO Box 8975, EPC No 525 Lalitpur, Nepal

A R T I C L E I N F O

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A B S T R A C T

There are increasing concerns about the negative effects of conventional tillage (CT), extreme climate events, increased weed incidence, and reduced availability of farm inputs on crop yield and yield stability, profitability, and water productivity in rice-wheat (R–W) systems of the Eastern Gangetic Plains (EGP) in South Asia. Conservation agriculture (CA)-based tillage practices have been proposed in the region to address these concerns. We analysed 84 on-farm trials' data comparing CA-based practices with farmers' CT practices in R–W systems of eastern Terai region of Nepal in the EGP. The objectives were to investigate crop and cropping systems productivity, profitability, yield stability, irrigation (WP_i) and total water productivity ($WP_{(r+i)}$), and fertilizer-use efficiencies of three CA- and one CT-based practices in R–W systems. Treatments included: (i) CT-based: puddled transplanted rice - conventional tillage wheat (PTR–CTW); (ii) CA-based: PTR – zero tillage wheat (PTR–ZTW); (iii) CA-based: direct-seeded rice – ZTW (DSR–ZTW); and (iv) CA-based: un-puddled transplanted rice – ZTW (UPTR–ZTW). Results showed that although there were no significant differences in yield of either rice or wheat or R–W system between CA-based and CT treatments, there was a significant reduction in production cost (by 245–369 USD ha^{-1}) mainly due to reduced labor use and increased net gain (188–223 USD ha^{-1}) in all CA-based R–W system. DSR–ZTW showed the highest yield stability and net profit, demonstrating its adaptability in the region. Among the irrigation applicators (35%) in rice, DSR used 107 mm (67 mm higher than PTR) irrigation water with WP_i of 70% and 96% of PTR and UPTR, respectively due to the need of additional irrigation for crop establishment. In contrast, among the irrigation applicators (75%) in wheat, due to earlier sowing of ZTW, it required 18% less irrigation water resulting in 9% higher WP_i compared to CTW. However, a follow-up study two years after completion of field trials revealed that no local farmers had continued CA-based practices mainly due to high weed pressure, lack of land leveling, inaccessibility of zero-till (ZT) drill machines, and lack of ZT service providers. Effective support systems incentivizing in land leveling, ZT machines, technical knowledge dissemination, and the development of integrated weed management practices for scaling-out strategies are essential to adopt CA-based practices. As the results have great implications to reduce production costs and increase farm profits, save energy and water, increase land and labor productivity, and improve food security of millions of smallholder farmers in the EGP, strong policy support to incentivize farmers to avoid the adoption barriers of CA-based practices is required.

1. Introduction

Conservation Agriculture (CA) – by maintaining permanent soil cover with residue retention, minimum soil disturbance through reduced tillage, and crop diversification - has become a new paradigm for sustainable intensification of farming systems in the 21st century as it has the potential to improve crop productivity with increased water-, energy-, and nutrient-use efficiencies, and economic returns (FAO 2014, Kassam et al., 2018, Reicosky, 2007). However, the definition and principles of CA are ambiguously used in global literature. In on-farm implementations of CA in the Indo-Gangetic Plains (IGP) of South Asia, researchers often consider the practice as CA even only when zero or

* Corresponding authors. Hebei Agricultural University, Baoding, Hebei 071001, China.
E-mail addresses: shikha.thapa@hebau.edu.cn (S.T. Magar), lwl@hebau.edu.cn (L. Weili).

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reduced tillage is practiced, without considering the other two CA principles. Therefore, the definitional ambiguity and implementation variations of CA can vary the estimates of CA adoption in different sub- or eco-regions in the IGP (Brown et al., 2018).

The CA-based practices, mostly with zero tillage (ZT), have been adopted in about 180 million ha (12.5%) of global cropland, mostly in developed countries. In case of small and subsistence farmers in Asia and Africa, CA has been adopted on only about 13.9 million ha and 1.5 million ha, corresponding close to 8% and 1% of the total cropland, respectively (Connor et al., 2011). In the IGP, promotion of CA-based practices, mainly ZT for wheat in rice-wheat (R–W) cropping system, was started in the early 1990s (Connor et al., 2011, Dixon et al., 2020, Hobbs et al., 2019) and this has been successfully extended from wheat to rice benefiting both crops of R-W system (Aryal et al., 2015, Erenstein and Laxmi, 2008). Adoption of CA practices occurred initially in the northwest IGP with large farm size, favorable environment, and adequate infrastructures. It has now gradually been extended to the Eastern Gangetic Plains (EGP) though with much less adoption due to small farm size, inadequate infrastructure, and unfavorable environment such as rainfall extremes and variability (Bhatt et al., 2021, Erenstein, 2009). At the early stage of adoption of CA, affordability, accessibility, and operation of ZT machines have been particular issues in the IGP, and rapid diffusion of ZT in the western IGP was mainly driven by locally fabricated ZT machines and service providers (Hobbs et al., 2019). Thus, the adoption of ZT has been increased at high rates among large and wealthy farmers of India and Pakistan in the northwestern IGP (Chauhan et al., 2012), but not many among small and subsistence farmers of the EGP.

The eastern Nepal Terai, country's breadbasket region, located in the EGP, produces over 18% of the nation's rice and wheat (Statistical Information 2015). Rice-wheat is the dominant cropping system (85% of arable area) in the Terai of Nepal (Dixon et al., 2020, Islam et al., 2019, Timsina et al., 2010). Widely practiced conventional tillage (CT) is threatening the sustainability of this system in the IGP (Bhatt et al., 2021, Chauhan et al., 2012, Timsina et al., 2010, Timsina and Connor, 2001) mainly due to decreasing labor availability, increasing production costs, increased weed incidence, extreme climatic events, and the lack of appropriate machinery service provision for crop production. In the conventional R–W system, rice is transplanted in puddled soils and grown under ponded condition, while wheat is grown after rice harvest in well-drained dry soil after repeated tillage. Repeated tillage for crop establishment prolongs turnaround period, delays wheat sowing by 10–15 days, and consequently leads to yield decline by coinciding wheat grain filling period with westerly hot dry air after mid-February (Timsina et al., 2010, Timsina and Connor, 2001, Devkota et al., 2019). Repeated multiple tillage destroys soil structure, diminishes nutrient availability (Timsina et al., 2010, Timsina and Connor, 2001), and increases the cost of irrigation, labor, and fuel (Islam et al., 2019, Jat et al., 2009). With such adverse effects of CT, the R–W system needs alternative options that demand less water, energy, and labor (Connor et al., 2011, Bhatt et al., 2021, Timsina et al., 2010, Timsina and Connor, 2001). To meet this demand, alternative tillage and crop establishment practices, such as dry-direct seeded rice (DSR), unpuddled transplanted rice (UPTR), and ZT wheat (ZTW) have been developed and evaluated across the IGP, but with limited farmer adoption, particularly in the Terai region of Nepal in the EGP (Aryal et al., 2015, Farooq et al., 2011, Haque et al., 2016).

On-farm trials comparing CA with CT practices in the R–W system were conducted by CIMMYT (International Wheat and Maize Improvement Center) and partners during 2014 to 2017 by the Sustainable and Resilient Farming System Intensification (SRFSI) project in the eight districts of the EGP, including two districts (Dhanusha and Sunsari) in the eastern Terai of Nepal. The agronomic and economic performance indicators of the CA practices vary according to the location with soil and climatic conditions, crop management practices and technical know-how of the farmers, and availability of herbicides and machinery service providers. Such indicators have been compared among DSR, puddled transplanted rice (PTR) and unpuddled machine transplanted rice (MTR) in Odisha, eastern India by Devkota et al., 2020. However, systematic comparison of such CA-based practices in R–W system to assess their potential to improve the economic and environmental indicators in the IGP, and particularly in the EGP, is lacking. Systematic comparison of such performance indicators in R–W system would help to improve the sustainability of the R–W cropping systems in the region. Further, in the IGP, there has been many research on the technology development for the adoption of CA-based practices in R–W system especially in India and Pakistan (Hobbs et al., 2019, Jat et al., 2009, Saharawat et al., 2010, Jat et al., 2014, Choudhary et al., 2018), but there has been limited research decomposing the reasons for adoption and non-adoption of those practices including in the Terai region of Nepal. Thus, the objectives of this study were to compare crop and cropping system yields and stability, profitability, and water productivity between CA and CT practices, to understand reasons behind the adoption or non-adoption of CA practices, and to identify trade-offs among various performance indicators in R–W system of the eastern Terai region of Nepal in the EGP.

2. Materials and methods

2.1. Site, climate, and soil

This study analysed the data obtained from the on-farm experiments conducted by CIMMYT and partners for three years (2014–2016) in two eastern Terai districts (Sunsari, 26º 38´29.76″ N lat. and 87º 07´44.76″ E long.; Dhanusha, 26º 30´31.56″ N lat. and 86º 02´09.60″ E long.) of Nepal. Sunsari is 95 m and Dhanusha is 102 m above mean sea level (Figure S1). Data were retrieved from the CIMMYT's publicly available data repository network Dataverse. The experimental sites are characterized by sub-tropical climate with the monsoon, Kharif (June-October) and winter, Rabi (November- March/April) seasons. The mean monthly minimum temperatures during Rabi were lower in Sunsari (13 °C) than in Dhanusha (14 °C). Similarly, the mean monthly minimum and maximum temperatures during Kharif were lower in Sunsari (25 °C and 30.5 °C) than in Dhanusha (26 °C and 31.5 °C), respectively (Figure S2). The 2012–2020 long-term climate data from NASA Power (NASA POWER 2020) showed average annual rainfall higher in Sunsari (1341 mm; coefficient of variation 19%) than in Dhanusha (1195 mm; coefficient of variation 22%). The experimental sites in Sunsari had sandy loam to silty clay loam while in Dhanusha they had clay loam to silty clay loam soils (Sinha et al., 2019) (Table S1). Soils were analysed for pH, total organic carbon (SOC), total N, Olsen available P, and exchangeable K using various methods mentioned on Table S1 (Page et al., 1982, Brenner and Mulvaney, 1982, Olsen and Sommers, 1982, Knudsen et al., 1982, UC Davis Analytical Laboratory 2022). The detectable limits for SOC, total N, available P, and exchangeable K based on UC Davis lab methods were 0.02% C, 0.001% N, 1.0 ppm, and 1.0 ppm respectively (https://anlab.ucdavis.edu/analysis/Soils/410). Soils were acidic to neutral in both districts. Soils in Sunsari had higher (0.34 –2.31%) soil organic carbon than in Dhanusha (0.25–1.77%). The difference in SOC between the two districts was particularly due to difference in soil parent materials. Parent materials in soils of Sunsari were alluvial and limestone derived (Dijkshoorn and Huting, 2009), and informal interviews with the participating farmers revealed that the farmers added more crop residues and other organic materials in their fields compared to those in Dhanusha, contributing to build up of organic carbon in Sunsari soils. Total nitrogen (N) was higher in Dhanusha than in Sunsari but reverse was the case for available phosphorus (P) and exchangeable potassium (K) (Table S1). Both districts have poorly buffered soils prone to leaching of nutrients.

2.2. Farmer's selection and engagement

All the on-farm experiments were managed by farmers under close supervision and support from researchers of the National Rice Research Program in both study districts. At the beginning of the trials implementation, farmers were motivated by explaining the purpose and outcome of the experiments, and provided training on crop establishment (seeding depth, row distance, calibration of the seed and fertilizer rates in the seed drill machine, mat nursery preparation for the UPTR), fertilizer and herbicide management, and best agronomic management practices especially focusing on the CA-based practices. Also, farmers were invited and involved in the joint field visits during the trial implementations. Seed, fertilizers, and herbicides for all on-farm trials were supplied by the project. Also, each village was provided with one ZT machine and one rice transplanting machine for UPTR.

2.3. On-farm experiments and treatment description

On-farm experiments were conducted in nine villages, five in Dhanusha and four in Sunsari, the Eastern Terai region of Nepal. The two districts are far apart by more than 100 km and the villages within each district are far apart by 5–10 km (Fig. S1). These two districts were particularly selected as because R-W cropping system is practiced by >80% farmers in each of those districts with the proximity of rice and wheat research centers to monitor and facilitate the experiments. There were three crop establishment treatments in rice, i.e., PTR representing CT, and DSR and machine transplanted UPTR representing CA-based practices, and two establishment methods in wheat, i.e., ZTW seeded using zero-till seed-cum-fertilizer drill representing CA and conventional tillage wheat (CTW) representing CT. Thus, the four establishment methods compared in R−W system were: (i) CT-based: PTR−CTW, (ii) CA-based: PTR−ZTW, (iii) CA-based DSR−ZTW, and (iv) CA-based: UPTR−ZTW (Table S2). Over the three-years period, a total of 84 on-farm experiments (i.e., 84 replications), each farm with four treatments, were conducted in the two districts using a randomly complete block design (RCBD). All experiments were implemented by the farmers with the researcher's supervision and monitoring and using the concept of participatory research (Norman et al., 1995).

Two dry-tillage using a harrow connected to a 35-hp tractor was used in all rice establishment methods. In the PTR, on the transplanting day, the field was repeatedly puddled and leveled using a wooden plank connected at the end of the harrow. In contrast, in the UPTR, one dry-tillage using the same harrow connecting the wooden plank at the end was used for leveling followed by one irrigation, and then seedlings transplanted using a transplanting machine. In the PTR, seedlings were transplanted manually in a random geometry. In both PTR and UPTR, 21–40 days old seedlings were transplanted. In DSR, one day before seeding, one dry-tillage connecting the wooden plank for leveling was used and seeds were seeded in a row using a 11-row zero-till-seed-cum-fertilizer-drill. In CTW, as in rice, two tillage with leveling (using a wooden leveler connected with the harrow) were used one day before seeding; then seeding was done manually (broadcasting) followed by planking. In ZTW, after rice harvesting, round-up was applied once followed by a pre-sowing irrigation and wheat was seeded using the same machine (as used for DSR) 4–7 days after round-up application (Islam et al., 2019).

2.4. Crop management practices

Nitrogen (N), phosphorus (P), and potassium (K) fertilizers were used at rates of 114–175, 50–107 kg ha^{-1} and 35–50 kg ha^{-1} in rice, and 175–185, 87–106, and 50 kg ha^{-1} in wheat, respectively in all establishment methods. In DSR and ZTW, P fertilizer was applied at the time of seeding through the seed drill machine while in PTR, UPTR and CTW, it was hand broadcast during the final land preparation. In DSR and ZTW, K fertilizer was hand broadcast before seeding and together with P fertilizer in PTR, UPTR and CTW. In all establishment methods, one-third of N was applied basally and the remaining two-thirds were top-dressed in two splits, the first after three weeks of seeding (wheat) or seeding or transplanting (rice) and the second at three weeks after the first application. Fertilizers used were urea, diammonium phosphate and muriate of potash for N, P and K respectively. A pre-sowing irrigation was provided to DSR as the seeds were sown before the start of pre-monsoonal rainfall. All rice treatments were grown under rainfed condition with some supplemental irrigation, with number ranging from 1 to 4 with averaged depth of water per irrigation of 70 mm (Islam et al., 2019); irrigation was applied mainly before topdressing of N fertilizer. In wheat, four irrigations were applied in all fields at tillering, panicle initiation, flowering, and grain filling stages in Sunsari but was rarely irrigated in Dhanusha. Weeds in rice were controlled with application of the pre-sowing glyphosate (1000 g a.i. ha^{-1}) in all CA treatments, while a pre-emergence herbicide (Pendimethaline) within 72 hour of seeding and a post-emergence herbicide Byspiribac sodium (Nominee Gold) were applied at two or three weed-leaf stage during 20–30 days after seeding in DSR, or at transplanting in PTR and UPTR. In ZTW, weeds were controlled with the pre-seeding herbicide glyphosate followed by one post-emergence herbicide Sulfosulfuran (Leader). In addition, one or two manual weeding was done when weeds persisted.

2.5. Data collection

Data used in this study were obtained from CIMMYT's publicly available data repository network Dataverse (https://data.cimmyt.org/dataverse/srfsidvn/?q=Nepal). Data were used from only those farmers who had completed all four treatments for all three years. In both districts, in both crops and all treatments the grain and straw yields were determined from a 30 m^2 sampling area by sub-sampling five 6 m^2 quadrates within a field by avoiding border effects. Samples were collected when grains were ripe and ready for harvesting. After harvest samples were fully sun/air-dried to bring to 14% grain moisture for each crop, and grain yields were recorded on a stable air-dry weight basis (Islam et al., 2019).

2.5.1. Stability analysis

Agriculture sustainability depends on the stability of crop yield (Liu et al., 2019). The constancy of yield in the agriculture system over a long period or across various spatial environments (treatments) is defined as yield stability (Urruty et al., 2016). Crop yield stability can be categorized into static and dynamic stability (Becker and Léon, 1988, Piepho, 1998). Static stability is assessed using the coefficient of variance (CV) while dynamic stability using the regression coefficient or slope (b_i) obtained from the linear regression (Liu et al., 2019, Piepho, 1998, Finlay and Wilkinson, 1963). In this study, we used both types of stability analysis (for yield) under different crop establishment treatments in the R−W system across six environment-site combinations (2 districts × 3 years).

*Static stability***:** It was estimated using the CV, with its lower value indicating higher stability across multiple environments.

$$\text{Coefficient of variation (CV)} = \frac{\text{Standard deviation}}{\text{Mean}} \text{ X } 100\% \quad (1)$$

*Dynamic stability***:** The slope or the environment index (bi) was estimated as the average yield of all treatments at each environment-site combination. The treatment with bi close to or equal to 1 indicates that a treatment adapts to all environments. A b_i <1 indicates that the treatment has above-average stability and adapts to low-yielding environments (specifically adapted to the unfavorable environment), while a b_i>1 indicates below-average stability and is suitable to high-yielding environments (specifically adapted to the favorable environment).

2.5.2. Irrigation and total water productivity

Irrigation (WP_i) and total water productivity ($WP_{(r+i)}$) expressed in kg grain mm^{-1}ha^{-1} irrigation and rainfall plus irrigation water, as shown in Eqs. 2 and 3, were calculated following Connor et al. (Connor et al., 2011).

$$\text{Irrigation water productivity}\ \left(\text{Wpi kg grain mm}^{-1}\text{irrigation water}\right) = \frac{\text{Grain yield}\ \left(\text{kg ha}^{-1}\right)}{\text{Depth of water applied (mm)}} \quad (2)$$

$$\text{Total water productivity}\ \left(\text{WP (r + i) kg grain mm}^{-1}\ \text{water}\right) = \frac{\text{Grain yield}\ \left(\text{kg ha}^{-1}\right)}{\text{Depth of water applied (mm)}} \quad (3)$$

Where 'r' represents rainfall amount (mm) from NASA Power (NASA POWER 2020) for Jun-Sept (4 months) for rice and Nov-Mar (5 months) for wheat and 'i' represents applied irrigation amount (mm).

2.5.3. Economic analysis

Economic analysis (Errington, 1984, Mendiburu and Yaseen, 2020) was used to compare the performance of CA against CT practices. All calculations were carried out on a per hectare basis and monitory values were expressed in USD (Table S3). Labor use (in labor days) was calculated by summing up labor days for all production-related activities based on 8 daily working hours per person. Net profit was computed for each treatment in rice, wheat, and R–W system across 3 years and 2 districts. The unit costs of inputs (seed, fertilizer, herbicide), labor, and machinery hire for tillage and seeding were collected from the local market (Table S3). As the unit prices variations across years and locations were low, we used the same unit prices for all locations and years. The amounts of inputs applied, labor used (for seeding/transplanting, weeding, irrigation and fertilizer application, harvesting, threshing, and cleaning and drying) and the machinery (tractor) time used for ploughing were recorded for the entire experimental period. Both grain and straw prices collected from the local market were considered while computing profitability.

$$\text{Input cost} = \text{Quantity of inputs applied x unit price of inputs} \quad (4)$$

$$\text{Value of production (Vp)} = \text{Yield x price of grain}\ \left(\text{USD, kg ha}^{-1}\right) \quad (5)$$

$$\text{Reduced or added cost} = \text{Input cost for CT practice} - \text{input cost for CA practice.} \quad (6)$$

$$\text{Additional or reduced benefit} = \text{Vp for CT practice} - \text{Vp for CA practice} \quad (7)$$

$$\text{Sum of increased benefit} = \text{Reduced cost} + \text{Additional benefit} \quad (8)$$

$$\text{Sum of decreased benefit} = \text{Added cost} + \text{Reduced benefit} \quad (9)$$

$$\text{Net gain} = \text{Sum of increased benefit} - \text{Sum of decreased benefit} \quad (10)$$

$$\text{Profitability} = \text{Vp} -- \text{Total cost of production} \quad (11)$$

2.6. Economic and environmental performance indicators

Further, to analyze the trade-offs among sustainability indicators and compare different establishment methods across crops and locations (districts), we computed labor productivity as kg grain labor day^{-1} (excluding family labor) and N-, P-, and K-use efficiencies (NUE, PUE and KUE, respectively) as kg grain obtained kg^{-1} elemental nutrient (N, P, and K). In the trade-offs analysis, we expressed herbicide amount as herbicide intensity (L or kg herbicide ha^{-1}).

2.7. Farmers' feedback on adoption of CA practices

Thirty farmers from each district (each district with two villages and 15 farmers from each village) who participated in the implantation of on-farm trials plus two local researchers from each of those four villages who assisted in implementing the project activities were interviewed in December 2019, i.e., two years after the completion of the project. We selected only those farmers who actively participated in on-farm trials in all years and both crops. They were interviewed using semi-structured close ended type of questionnaires to understand the reasons for adoption or non-adoption of the CA-based practices tested and promoted by the project. Jointly, 11 reasons for non-adoption and 6 reasons for adoption were identified and farmers were asked to either agree or disagree with those reasons.

2.8. Statistical analysis

Combined analysis of variance (ANOVA) for district (location), year and establishment method were conducted using 'agricolae' package of R Version 4.0.4 (Mendiburu and Yaseen, 2020) for yield, net profit, and irrigation and total water productivity (WP_i and WP_{r+i}). Before conducting the ANOVA, the normality of the data distribution for each crop and cropping system in different years was examined for yield and net profit using Shapiro-Wilk test. Conformity of the homogeneity of variance was also performed using Bartlet''s test (Snedecor and Cochran, 2021). The normality and homogeneity assumptions of ANOVA were met with non-significant p-values so there was no need for data transformation. While conducting ANOVA (crop-wise and system-level) of RCBD, individual farmers were considered as replication, and the establishment method as treatment. The treatment mean differences were analysed using the least significant difference (LSD) at 5% and 1% of the level of significance. Trade-offs among eight performance indicators (yield, net profit, labor productivity, water productivity, herbicide intensity, NUE, PUE, and KUE) were analysed using the normalized (0–1) scale spider/radar graphs and different establishment methods compared across locations (districts), crops and the R–W system.

3. Results

3.1. Rainfall during the crop growing season

During the rice growing Kharif season (June-September), the total rainfall was 1051 mm in Sunsari and 968 mm in Dhanusha, while during the wheat growing Rabi season (Nov-Mar/April), it was almost similar (55 mm Sunsari and 49 mm Dhanusha). During the Kharif season, Sunsari received higher rainfall by 40–162 mm (highest in 3rd year) than Dhanusha. During the Rabi season in 2nd year, Sunsari received 14 mm higher rainfall than Dhanusha (Fig. 1).

3.2. Crops and cropping systems yields

The combined ANOVA for district, year and establishment method showed a non-significant interaction between district-and-establishment method and year-and-establishment method; however, the district, year, and district x year effects were significant for yield and net profit.

The combined ANOVA showed no significant differences ($p>0.05$) in grain yields of rice, wheat, and R–W system among the three CA-based and one CT-based establishment methods (Table 1). District x year interaction effect was however significant for rice, wheat, and R–W system yields. There was no significant yearly variability in rice yield; in contrast, wheat yield varied ($p<0.05$) across years, with highest yield in 2nd year followed by 3rd year. Rice yield was significantly higher in Sunsari by 0.97 t ha^{-1} (21%) than in Dhanusha (yield= 4.55 t ha^{-1}), while wheat yield was significantly higher in Dhanusha by 0.31 t ha^{-1} (9%) than in Sunsari (yield= 2.99 t ha^{-1}).

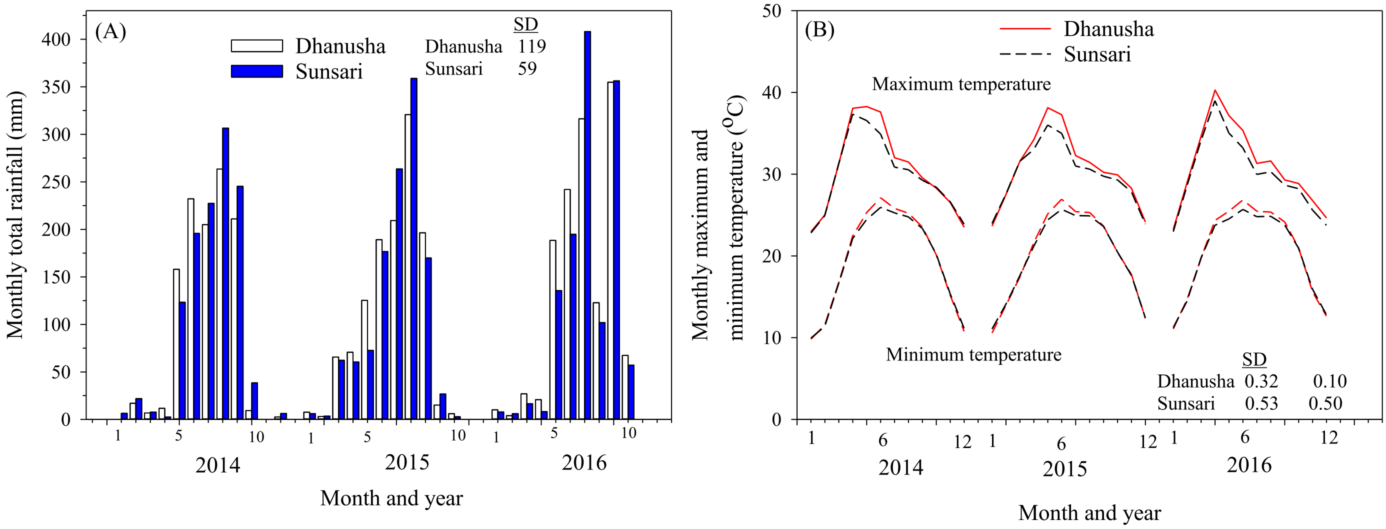

Fig. 1. . Monthly total rainfall (mm) and monthly maximum and minimum temperatures (°C) in Dhanusha and Sunsari districts during 2014 to 2016. SD= Standard deviation (SD) of rainfall and temperatures during the experimental years. Data source: NASA POWER (2020).

Table 1
Combined analysis of grain yield (t ha^{-1}) and net profit (USD ha^{-1}) as affected by different establishment methods over two districts and three years in rice, wheat, and rice-wheat system, 2014–2016.

District, year and establishment method	Rice		Wheat		Rice-wheat system	
	Grain yield	Net profit	Grain yield	Net profit	Grain yield	Net profit
District						
Dhanusha	4.55b	217b	3.30a	458a	7.85b	672b
Sunsari	5.52a	637a	2.99b	264b	8.19a	865a
Year						
2014	5.55	436a	2.95c	430a	8.50	866a
2015	4.53	265c	3.42a	391ab	7.96	659c
2016	4.76	364b	3.17b	382b	7.72	726b
Establishment method (EM)						
PTR–CTW	4.84	300c	3.12	282b	7.96	584c
PTR–ZTW	4.89	276c	3.23	432a	8.06	703b
DSR–ZTW	4.86	455a	3.24	439a	7.91	873a
UPTR–ZTW	4.83	364b	3.21	426a	7.91	777b
Grand mean	4.85	348	3.20	395	7.96	734
ANOVA						
District	***	***	***	***	***	***
Year	ns	ns	***	***	ns	*
EM	ns	***	ns	***	ns	***
District x Year	**	**	***	ns	***	***
District x EM	ns	***	ns	ns	ns	***
Year x EM	ns	ns	ns	ns	ns	ns

Means followed by the same letter (a, b) in each column for different districts, years, and establishment methods in rice, wheat, and rice-wheat system do not differ by the LSD test at $p<0.05$. The values are significantly different when the difference (between districts, years, and establishment methods) is less than the LSD value at $p<0.05$. ns: nonsignificant ($p>0.05$); * significant at $p<0.05$; ** significant at $p<0.01$; and *** significant at $p<0.001$. DSR=direct seeded rice; PTR=puddled transplanted rice; UPTR=unpuddled transplanted rice; ZTW=zero tilled wheat; CTW=conventional tilled wheat.

In Dhanusha, rice yield in DSR−ZTW treatment in 2015 was higher by 0.37 t ha^{-1} (by 10%; $p<0.05$) than in PTR−CTW (yield = 3.99 t ha^{-1}) (Table 2). Likewise, wheat yields in PTR−ZTW and DSR−ZTW in 2014 were statistically non-significant, but they were significantly higher than in PTR−CTW and UPTR−ZTW. In Sunsari, rice yields were non-significant in all years. Wheat yields in 2014 however were significantly different among four establishment methods, where mean yield in ZTW (grown after PTR, or DSR, or UPTR) was higher by 0.43 t ha^{-1} (15%) than of PTR-CTW (yield = 2.85 t ha^{-1}).

3.3. Crops and cropping systems profitability

The net profit differed significantly across districts, years (except rice), establishment methods, and district x establishment method (for rice only) (Table 3). Combined over districts and years, the comparison of net profit from wheat in three CA-based alternative establishment methods showed significantly higher profit from ZTW established after DSR by 162 USD ha^{-1} (62%) and after UPTR by 143 USD ha^{-1} (55%) than after PTR (259 USD ha^{-1}). In rice, net profit from DSR was significantly higher than other two methods in all three years in Dhanusha but the trend was not consistent for Sunsari (Table 3). In wheat grown after PTR, the net profit was significantly ($p<0.05$) higher by 144 USD ha^{-1} (51%) in PTR-ZTW than in PTR-CTW (profit= 282 USD ha^{-1}). Comparing between the two districts, the net profit in rice was higher in Sunsari by 420 USD ha^{-1} than in Dhanusha (profit = 217 USD ha^{-1}), whereas the net profit in wheat was higher in Dhanusha by 194 USD ha^{-1} than Sunsari (profit = 264 USD ha^{-1}). When net profits in rice across treatments and districts were combined, the profit was highest in 2014 (436

Table 2
Grain yield (t ha^{-1}) of rice, wheat and rice-wheat (R-W) systems as affected by different establishment methods in on-farm trials across three years in two districts of Nepal.

Year	Establishment method	Dhanusha			Sunsari		
		Rice	Wheat	R-W	Rice	Wheat	R-W
2014	PTR–CTW	6.02	2.74ab	8.76	5.51	2.85b	8.36
	PTR–ZTW	5.52	2.84a	8.35	5.52	3.28a	8.8
	DSR–ZTW	5.65	2.84a	8.49	5.27	3.28a	8.55
	UPTR–ZTW	5.41	2.68b	8.09	5.41	3.28a	8.69
	LSD at p=0.05	ns	*	ns	ns	**	ns
2015	PTR–CTW	3.99b	3.54	7.53	6.16	2.59	8.75
	PTR–ZTW	4.23ab	3.53	7.76	6.16	3.18	9.34
	DSR–ZTW	4.36a	3.53	7.89	6.18	3.18	9.36
	UPTR–ZTW	4.16ab	3.48	7.65	6.62	2.84	9.46
	LSD at p=0.05	*	ns	ns	ns	ns	ns
2016	PTR–CTW	4.41	3.25	7.65	5.29	2.84	8.13
	PTR–ZTW	4.50	3.31	7.81	5.46	2.93	8.39
	DSR–ZTW	4.46	3.34	7.80	5.21	2.93	8.14
	UPTR–ZTW	4.42	3.36	7.78	5.35	2.97	8.32
	LSD at p=0.05	ns	ns	ns	ns	ns	ns

Means followed by the same letter (a, b) in each column for different districts, years, and establishment methods in rice, wheat, and R-W system do not differ by the LSD test at $p<0.05$. The values are significantly different when the difference (between districts, years, and establishment methods) is less than the LSD value at $p<0.05$. ns: nonsignificant ($p>0.05$); * significant at $p<0.05$; and ** significant at $p<0.01$. For treatment description see Table 1.

Table 3
Net profit (USD ha^{-1}) as affected by different establishment methods in on-farm trials across three years in two districts of Nepal.

Year	Establishment method	Dhanusha			Sunsari		
		Rice	Wheat	R-W	Rice	Wheat	R-W
2014	PTR–CTW	261b	364b	626c	710a	204b	914
	PTR–ZTW	250b	544a	794b	489c	355a	844
	DSR–ZTW	449a	588a	1037a	539bc	353a	892
	UPTR–ZTW	340ab	575a	916ab	577b	353a	929
	LSD at p=0.05	*	***	***	***	***	ns
2015	PTR–CTW	2d	345	358c	942	159b	1034
	PTR–ZTW	117c	434	555b	685	362a	1073
	DSR–ZTW	316a	445	748a	834	360a	1230
	UPTR–ZTW	181b	433	601ab	827	281ab	1243
	LSD at p=0.05	***	ns	***	ns	*	ns
2016	PTR–CTW	81d	309b	390c	722a	173b	909
	PTR–ZTW	174c	534a	708b	481c	250a	670
	DSR–ZTW	403a	533a	935a	632ab	245a	734
	UPTR–ZTW	264b	513a	749b	599bc	254a	767
	LSD at p=0.05	***	***	***	*	***	ns

Means followed by the same letter (a,b) in each column for different districts, years, and establishment methods in rice, wheat, and R-W system do not differ by the LSD test at $p<0.05$. The values are significantly different when the difference (between districts, years, and establishment methods) is less than the LSD value at $p<0.05$. ns: nonsignificant ($p>0.05$); * significant at $p<0.05$; and *** significant at $p<0.001$. For treatment description see Table 1.

USD ha^{-1}) while it was lowest in 2015 (265 USD ha^{-1}) i.e., 39% reduction in yield than 2014 (Table 1**).** There was high occurrence of weeds in rice in 2015 (Islam et al., 2019), which resulted in lower yield and lower profit than in 2014. On the other hand, in wheat, the net profit was highest in 2015 (391 USD ha^{-1}) and lowest in 2014 (430 USD ha^{-1}), due to higher rainfall contributing to higher yield in 2015 compared to other years (Fig. 1**;** Table 1**).**

CA-based treatments had a higher net gain over CT, mainly resulting from reduced labor cost by 44–60 USD ha^{-1} (Table 4). In rice, DSR and UPTR respectively had 56 USD ha^{-1} and 40 USD ha^{-1} higher net gains than PTR. The reduced production cost in DSR was due to cost avoidance for raising seedlings in and uprooting from the nursery bed, and land preparation and transplanting seedlings in main field, all of which are required for PTR. Similarly, the higher economic return from UPTR over PTR mainly resulted from the reduced cost for tillage and labor cost for transplanting. However, due to the need for one to two extra irrigation and increased herbicide cost, the benefits were reduced from DSR and UPTR compared to PTR. In wheat, ZTW had a 106 USD ha^{-1} (9%) higher net gain over CTW mainly because of decreased labor and tillage costs. DSR–ZTW had highest net gain (223 USD ha^{-1}, 9%), followed by UPTR–ZTW (188 USD ha^{-1}, 7%) and PTR–ZTW (143 USD ha^{-1}, 6%) over PTR–CTW. A large part of the increased cost in DSR–ZTW was from the increased herbicide and irrigation applications.

Fig. 2 shows the yield relationships between CA-based and CT practices for rice, wheat, and R–W system. The results show that in all production environments, yield trends for CA-based practices under both poor (low yielding environment) and good (high yielding environment) follow the CT practice in rice, wheat, and R–W system. The net profit relationships between the CA-based and CT practices shown in Fig. 3 indicate that the profits from DSR (455 USD ha^{-1}) and PTR (276 USD ha^{-1}) were significant, though there was higher variability in the profitability of DSR compared to PTR (Table 1**).** Also, the profitability of UPTR (364 USD ha^{-1}) was significantly higher compared to PTR. Similarly, the profitability of ZTW (432 USD ha^{-1}) was significantly higher than of CTW (282 USD ha^{-1}). For the R–W system, the profitability of PTR–CTW (584 USD ha^{-1}) was significantly lower than PTR–ZTW (703 USD ha^{-1}) and DSR–ZTW (873 USD ha^{-1}). The variability in the profitability of PTR–ZTW was higher than PTR–CTW, while higher profit variability was observed for both DSR–ZTW and PTR–ZTW. The profitability from DSR–ZTW was significantly higher than PTR–CTW, and higher variability observed for the profitability of PTR–CTW than DSR–ZTW.

3.4. *Crop and cropping systems yield stability*

Fig. 4 shows static and dynamic yield stability for the four establishment methods. Rice yield varied the lowest in the PTR–CTW treatment, as indicated by the smallest CV of 40%. In dynamic stability, for overall site-years, rice yield in the PTR–ZTW and DSR–ZTW treatments showed below-average stability, indicating their suitability in the high-yielding environment. On the other hand, rice yield had above-average stability in UPTR–ZTW, indicating its suitability in the low-yielding environment. Furthermore, rice yield was the most stable and well-adapted to all study environments in PTR–CTW, indicating that the CT practice in rice is more adaptable across environments.

Similarly, wheat yield varied the least in PTR–ZTW in overall six environment-sites combinations as indicated by the smallest CV of 20% (Fig. 4). In contrast, it varied most with a CV of 24% in PTR–CTW. In dynamic stability analysis, wheat yield in UPTR–ZTW had below-average stability and thus was suitable for high-yielding environments. The regression coefficient of wheat yield was lower than 1 in PTR–ZTW and PTR–CTW showing above-average stability and its suitability in the low-yielding environments. Moreover, wheat yield in DSR–ZTW was the most stable and thus was well-adapted to all study environments, indicating the suitability of CA-based (ZT) practice for wheat.

The R–W system yield in PTR–CTW varied the least (CV = 25%) while in UPTR–ZTW it varied the most (CV = 26%) among overall site-years combinations (Fig. 4). In dynamic stability, the PTR–ZTW, DSR–ZTW, and UPTR–ZTW treatments had regression coefficients higher than 1, indicating below-average stability, and their suitability in high-yielding environments. But, PTR–CTW had the smallest regression coefficient indicating its suitability in the low-yielding environments. Analysis of yield stability of farmer-participatory on-farm trials in the R–W system in the Terai of Nepal thus provides evidence that the CA-based practices such as PTR, ZTW, and DSR–ZTW were the most stable practices respectively for rice, wheat, and the R–W system, and were suitable for all study environments.

Table 4
Inputs costs and increased benefit (USD ha^{-1}) for rice, wheat, and rice-wheat system in different establishment methods in on-farm trials in two districts of Nepal (average of 84 farms from two districts and three years).

Items	Rice (1)		Wheat (1)	Rice-wheat system (1)		
	DSR	UPTR	ZTW	PTR-ZTW	DSR-ZTW	UPTR-ZTW
Reduced cost						
Labor	1.7	23.5	19.4	22.9	44.2	59.9
Tillage	127.3	50.6	105.8	104.3	231.5	154.8
Nursery/seeding (2)	7.5	-	-	-	7.5	-
Uprooting (3)	7.4	-	-	-	7.4	-
Transplanting (4)	65.4	15.4		-	65.4	15.4
Seed	-	-	1.2	1.2	1.3	1.2
Equipment	-	3.2	-	4.9	4.6	7.3
Fertilizer	4.5	0.2	0.7	1.8	7	1.1
Irrigation	-	-	7.7	9.3	-	5.1
Pesticide	-	-	-	15.9	-	-
Increased Benefit						
Yield	-	-	26.9	21.4	-	-
Sum of increased benefit	213.8	92.9	161.7	181.7	368.9	244.8
Increased cost						
Seeding (Zero tillage)	35.1	-	38.9	38.9	72.9	37.8
Nursery/seeding	-	2.7	-	-	-	2.7
Seed	1.4	-	-	-	-	-
Equipment	0.4	-	9.3	-	-	-
Irrigation	28.8	2.9	-	-	20.6	-
Pesticide	64.3	27.9	7.3	-	48.4	12
Reduced Benefit						
Yield	28.1	19.2	-	-	4	4
Sum of reduced benefit	158.1	52.7	55.5	38.9	145.9	56.5
Net gain	55.7	40.2	106.2	142.8	223	188.3

Notes: (1) DSR−ZTW and UPTR−ZTW were compared with PTR−ZTW for rice, and PTR−ZTW was compared with PTR−CTW for wheat, while three CA treatments were compared with PTR−CTW for the R-W system. Results of DSR−ZTW and UPTR−ZTW in the rice-wheat system are not sum of the listed data of DSR and ZTW or UPTR and ZTW.
(2) Labor used for nursery preparation and seeding in PTR and UPTR were 2.4 and 3.4 labor days ha^{-1}, respectively.
(3) Labor used for uprooting in PTR and UPTR was 2.6 labor days ha^{-1}.
(4) Labor used for transplanting in PTR and UPTR were 23.2 and 17.9 labor days ha^{-1}, respectively.

Table 5
Irrigation water use (mm ha^{-1}), irrigation water productivity (WPi, kg mm^{-1} ha^{-1}), and total water productivity with rainfall and irrigation (WP; r+i), kg mm^{-1} ha^{-1}) for rice, wheat and rice-wheat system in different establishment methods in on-farm trials in two districts of Nepal.

District	Establishment method	Rice			Wheat			Rice-wheat system		
		Irrigation water use	WP (i)	WP (r+i)	Irrigation water use	WP (i)	WP (r+i)	Irrigation water use	WP (i)	WP (r+i)
Sunsari	PTR−CTW	-	-	5.39	136a	24.3b	18.6b	137a	73.0b	7.69
	PTR−ZTW	-	-	5.51	103b	33.1a	24.4a	103b	93.6a	7.90
	DSR−ZTW	112	42.7	5.22	108b	31.9a	23.9a	127ab	73.3b	7.14
	UPTR−ZTW	-	-	5.54	106b	33.0a	24.1a	106b	93.7a	7.72
	LSD at p=0.05	-	-	ns	**	*	**	***	**	ns
Dhanusha	PTR−CTW	99b	48.5a	4.53	103a	34.0b	25.6	145b	62.6a	7.43
	PTR−ZTW	95b	50.6a	4.57	88b	40.2a	27.9	130b	76.2a	7.50
	DSR−ZTW	163a	35.1b	4.33	90b	38.7a	27.6	200a	51.5b	7.15
	UPTR−ZTW	103b	48.7a	4.46	92b	37.6a	27.3	143b	63.6a	7.32
	LSD at p=0.05	*	*	ns	*	*	ns	**	**	ns

Means followed by the same letter (a,b) in each column for different districts, years, and establishment methods in rice, wheat, and rice-wheat system do not differ by the LSD test at $p<0.05$. The values are significantly different when the difference (between districts, years, and establishment methods) is less than the LSD value at $p<0.05$. $WP_{(r+i)}$=total water productivity with rainfall and irrigation water; WP_i= irrigation water productivity. ns: nonsignificant ($p> 0.05$); * significant at $p<0.05$; ** significant at $p< 0.01$; and *** significant at $p< 0.001$. For treatment description see Table 1

3.5. Irrigation water use, and irrigation and total water productivity

In Sunsari, only the DSR in the DSR-ZTW system required one extra irrigation during establishment and resulted in non-significant $WP_{(r+i)}$ among treatments. In wheat, however, when established after PTR in two R−W systems, ZTW used only 63% irrigation water as used by CTW and resulted in higher WP_i and $WP_{(r+i)}$ by 24% over CTW. Also, in Dhanusha, though DSR required one extra irrigation, it showed much higher irrigation water use, lower WP_i, and non-significant $WP_{(r+i)}$, with a WP_i of 96% and 70% of UPTR and PTR. In wheat after PTR under two R−W systems, ZTW used only 82% irrigation water as used by CTW and had a WP_i and $WP_{(r+i)}$ of 9% higher compared to CTW. These differences were significant at 1% statistical level (Table 5).

3.6. Trade-offs among economic and environmental performance indicators

In rice, Dhanusha had lower yield, net profit, labor productivity, water productivity, NUE and KUE than Sunsari (Fig. 5). In contrast, in wheat, it had higher yield, net profit, water productivity, NUE, PUE and KUE in trade-off with higher herbicide use. In Sunsari, however, labor productivity was consistently highest under CT (PTR−CTW) in both crops and the R−W system. Pesticide use was lower in both crops in Dhanusha than in Sunsari.

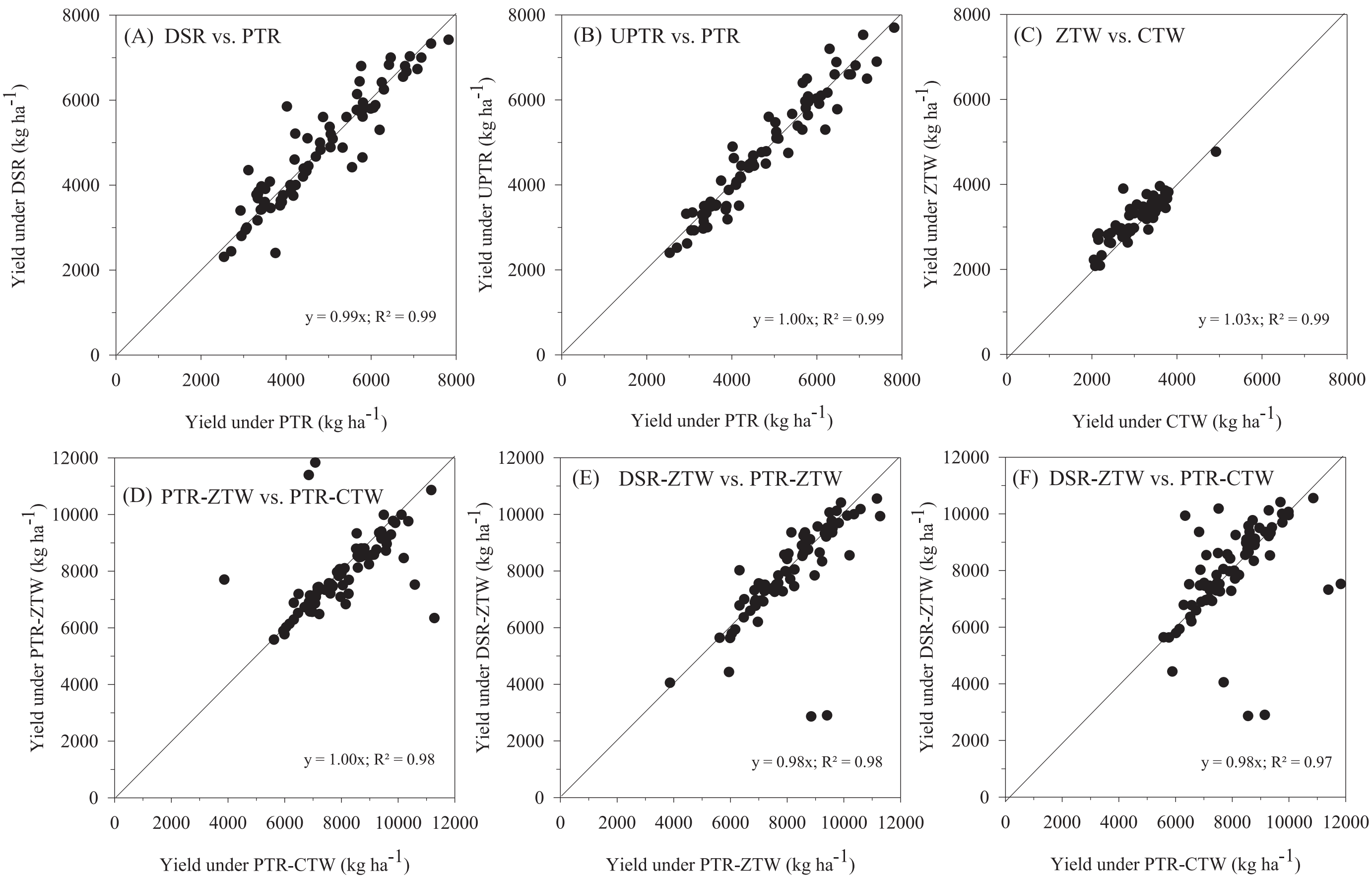

Fig. 2. Grain yield relationship between CA and CT method of establishment in rice, i.e., DSR vs. PTR (A) and UPTR vs. PTR (B); wheat, ZTW vs. CTW (C); and in three rice-wheat systems, i.e., PTR–ZTW vs. PTR–CTW (D), DSR–ZTW vs. PTR–ZTW (E), and DSR–ZTW vs. PTR–CTW (F) for grain yield. For treatment description see Table 1.

3.7. Farmers' feedback on adoption of CA practices

The interviewed farmers from two villages in Dhanusha reported that none of them continued CA-based practices two years after the completion of the field trials. The major limitations for the adoption of DSR were increased weed pressure, unavailability of laser land leveling machine, lack of skilled service providers to operate the machine, and poor technical know-how (Fig. 6). Similarly, the major reasons for the non-adoption of ZTW were increased weed pressure, non-availability of ZT drill machine, laser land leveling machine and skilled service providers to operate those machines, and poor technical know-how. For both CA-based and CT practices, farmers reported non-availability of improved variety was not a big issue. A disadvantage of CA-based practices in the monsoon season was that the early planting under such system resulted in rice harvest that coincided with terminal rains (15th September to 15th October). Herbicide application in DSR was often delayed due to heavy rainfall in the monsoon season, and absorption and translocation of herbicides were less effective due to low soil moisture in the dry season. There were no local ZT machine service providers in both districts, and incentives for CA practices were yet to be put in place by policymakers. However, still some farmers believed that those alternative CA-based establishment methods can give equal or better yield and higher profits, reduce drudgery, require less labor, reduce overall production cost, and allow for the timely crop establishment compared to CT-based practices in both crops (Fig. 6).

4. Discussion

4.1. Crop and cropping systems yields

The results of this study showed that DSR yields in both districts were slightly lower but not significantly different to those from PTR or machine transplanted UPTR. Previous studies also showed a 6–8% lower (but non-significant) grain yield of dry DSR compared to PTR (Saharawat et al., 2010, Gathala et al., 2015). In a long-term experiment on a R–W system in Bihar in northeast India too, DSR yield was lower than PTR in the first three years, similar in the next two years, and higher in the sixth year (Jat et al., 2014). Lower DSR yields in the first few years were also reported for the rice-based cropping systems in northwest India (Gathala et al., 2013, Kumar et al., 2018). In those studies, soil type caused yield variability in different sites as the DSR yield did not decrease for seven consecutive years on a clay loam soil but decreased on a sandy loam soil. Soil chemical properties and texture classes across our trial sites in Dhanusha and Sunsari were similar to those in Bihar (Sinha et al., 2019). Lower DSR yields obtained in our study are also consistent with that of Jat et al. (Jat et al., 2014). In contrast to our findings, however, in the western Terai Region of Nepal, DSR had higher yield than PTR in the first year but no significant yield differences in the next two years. In our study, early sowing of DSR before the initiation of monsoon and lack of irrigation water might have affected germination of rice seeds and reduction in grain yield (Devkota et al., 2019). It has also been reported that weak plant stands and weed infes-

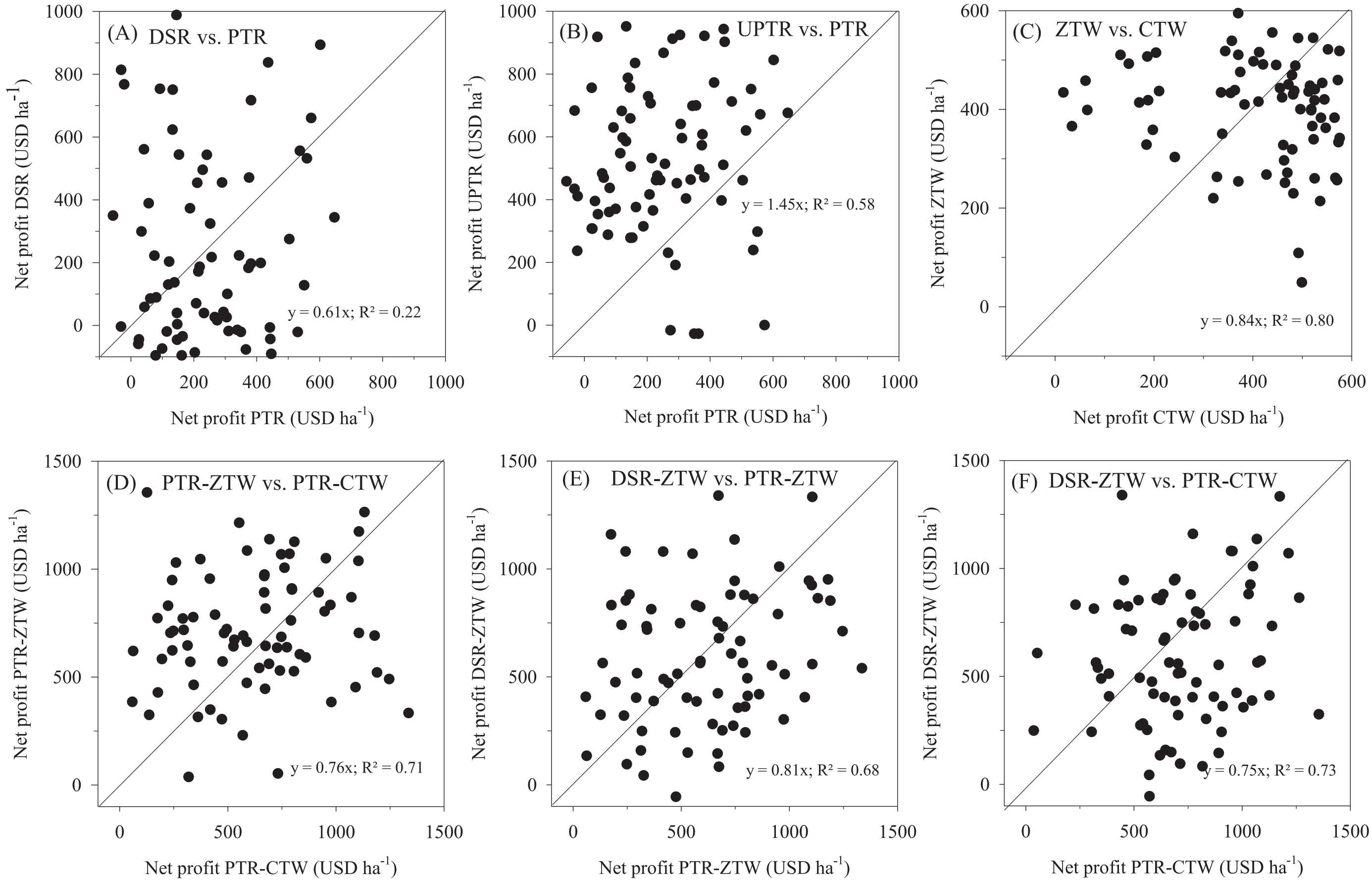

Fig. 3. Net profit relationship between CA and CT method of establishment in rice, i.e., DSR vs. PTR (A) and UPTR vs. PTR (B); wheat, ZTW vs. CTW (C); and in three rice-wheat systems, i.e., PTR−ZTW vs. PTR−CTW (D), DSR−ZTW vs. PTR−ZTW (E), and DSR−ZTW vs. PTR−CTW (F) for net profit. Exchange rate; 1 USD = 110 NPR. CA= conservation agriculture, CT=conventional tillage. For treatment description see Table 1.

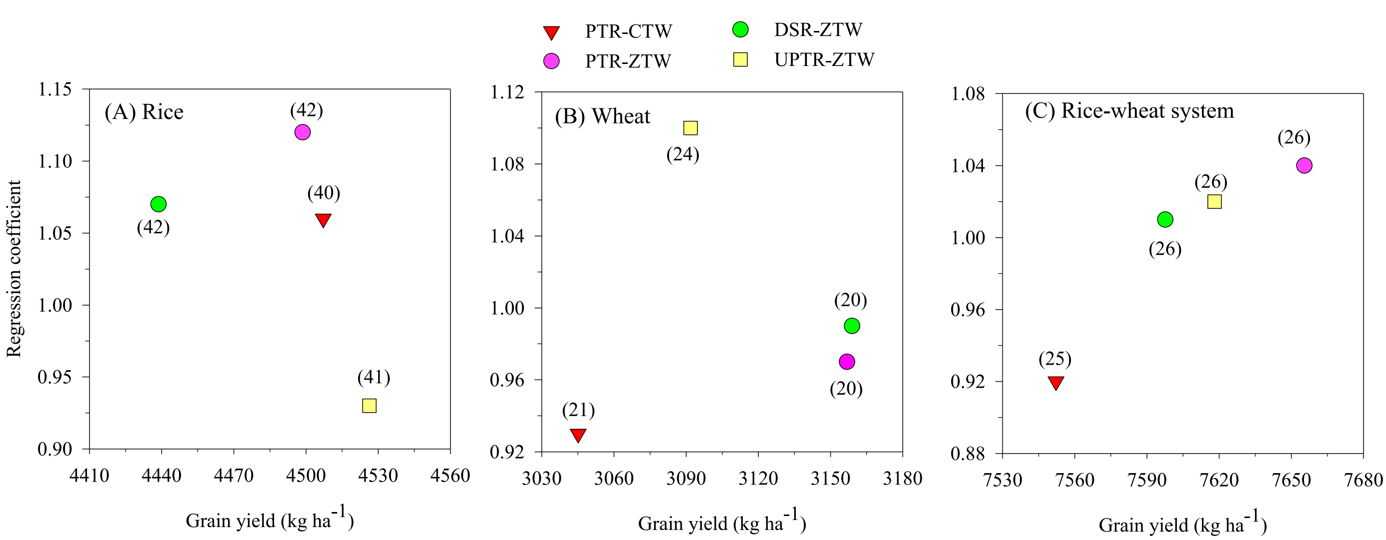

Fig. 4. Yield stability of rice (A), wheat (B) and rice-wheat system (C) as affected by different establishment methods. Data averaged across two districts for three years. Figures in parentheses coefficient of variation (CV, %). For treatment description see Table 1.

tations in DSR are the primary reasons for its low yield (Devkota et al., 2019, Farooq et al., 2011, Liu et al., 2014), where weeds could cause up to 68–100% yield loss (Kumar and Ladha, 2011, Rao et al., 2007). These findings suggest that the DSR performance is related to soil condition and rainfall pattern and weed control, and these conditions need to be fine-tuned for the DSR to be better adapted to the Terai plain of Nepal.

In the subsequent season, wheat yield under ZT was higher than under CT, though the difference was not statistically significant. In contrast to our findings, Devkota et al. (Devkota et al., 2019) reported sig-

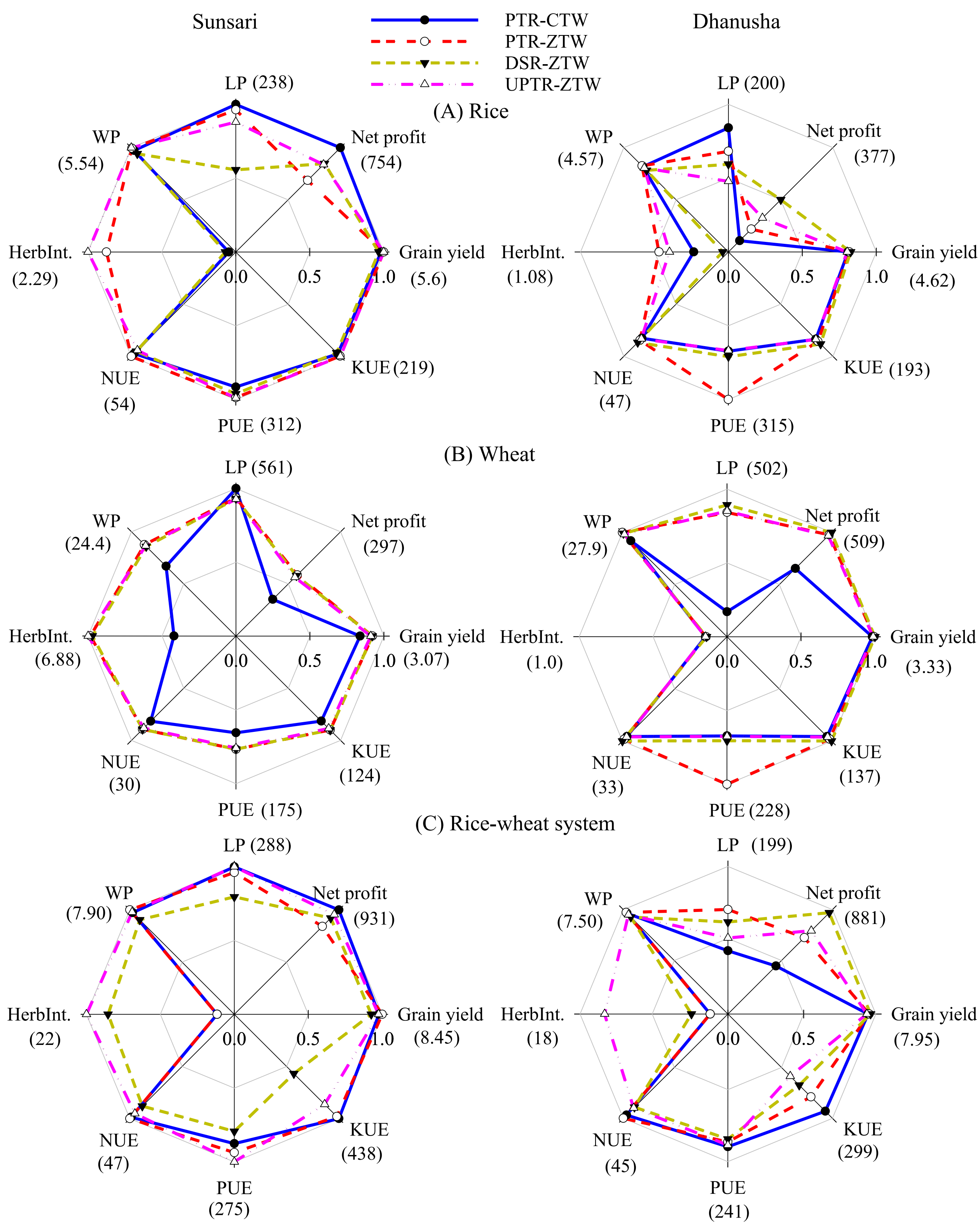

Fig. 5. Trade-offs among different indicators of economics and environment as affected by establishment methods in rice (A), wheat (B) and rice-wheat systems (C) in irrigated (Sunsari) and rainfed (Dhanusha) districts. Grain yield = grain yield (kg ha^{-1}); LP=labor productivity (kg grain labor d^{-1}); WP=water productivity (kg grain mm^{-1} rainfall and irrigation water); HerbInt. = herbicide intensity (L herbicide ha^{-1}); NUE=N-use efficiency (kg grain kg^{-1} N); PUE=P-use efficiency (kg grain kg^{-1} P); and KUE=K-use efficiency (kg grain kg^{-1} K). Values in parentheses are the maximum value. For treatment description, see Table 1.

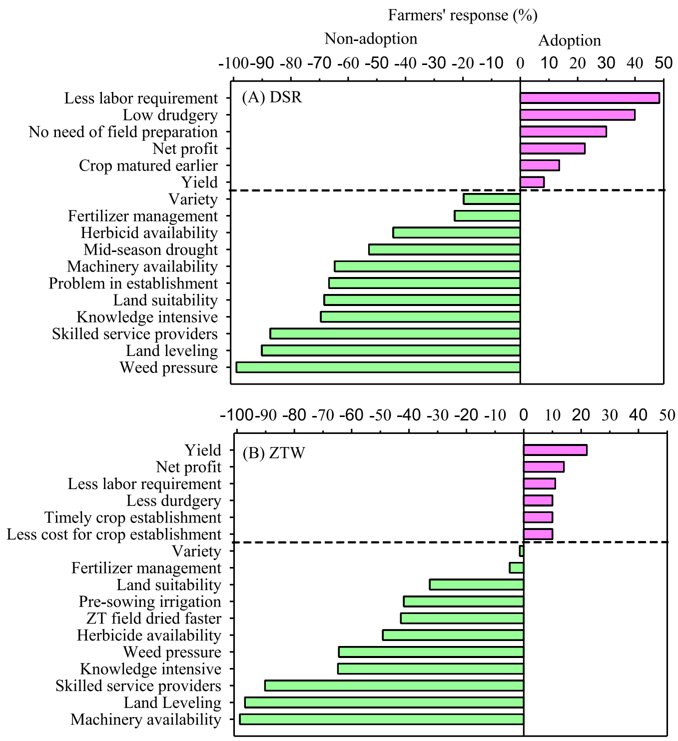

Fig. 6. Farmers' responses (%) to the major constraints and reasons for adoption and non-adoption of DSR (A) and ZTW (B) in two Terai districts of Nepal.

nificantly higher wheat yield under ZT compared to CT in the western Terai region of Nepal. Kumar et al. (Kumar et al., 2018), Jat et al. (Jat et al., 2014), and Saharawat et al. (Saharawat et al., 2010) also reported higher wheat yield under ZT, particularly when grown in rotation after DSR or UPTR. Higher wheat yield under ZT in all these studies were attributed to earlier sowing of wheat due to avoidance of tillage and reduced turnaround period, which avoided terminal heat stress.

Rainfall variability is one of the main reasons for low crop yield and yield variability in Nepal. The Terai region is prone to both drought and flood. The spatial-temporal variation of the computed daily precipitation extremes from 76 stations during 1970–2012 showed prolonged dry periods and decreased post-monsoon precipitation across the whole country (Krupnik et al., 2020). A dry wind from the west interrupts grain filling by shortening crop season, and pre-monsoon storm triggers farmers to advance the wheat harvest resulting in low yield (Annual Report 2016). A severe drought in 2006 also resulted in a 13% reduction in the rice area planted and decreased rice and wheat production by 2.0% and 3.3%, respectively (Gumma et al., 2011). In extreme climates, CA-based practices such as zero or no-tillage has shown yield increase under favorable climate and enhanced agroecosystem resilience and yield stability, emphasizing the requirement of CA as climate change resilient technology (Nouri et al., 2021). In the IGP, the adverse effect of climate change on agricultural production is becoming a growing threat for the food security and poverty as many studies have predicted significant impact of change in temperatures and precipitations on agriculture especially on rice, wheat and maize yields (Parry et al., 2004, Aggarwal and Rani, 2009, Aggarwal et al., 2019). With extreme rise in temperature, increased water scarcity, frequent floods and droughts and declining soil carbon content, the conditions could be worsened (Singh and Pathak, 2014). Conventional agriculture with intensive tillage is not only prone to climate change but it also emits large amount of greenhouse gas (GHGs) contributing to climate change (Sapkota et al., 2015). Hence, there is much need of adaptation of CA practices in R-W system of the EGP under the prevailing climate change conditions.

4.2. Crop and cropping systems yield stability

In intensive R-W system, in addition to need for the seasonal yield enhancements of component crops, the enhanced systems yield stability is crucial under extreme climate events. The static and dynamic stability assessment to understand the adaptation of CA practices under R–W cropping system at farm level with extreme climate conditions such as drought and high rainfall variability however becomes uncertain due to complexity of the interactions. This study assessed the effect of different CA-based practices on the productivity, stability, and economic and environmental performance indicators of R–W cropping system. The results revealed the least yield variation in DSR–ZTW system across the environments and highly adaptive high yielding sites (Fig. 4). DSR–ZTW also showed higher profitability (Table 4) and water productivity (Table 5) compared to CT practice. As yield stability determines the capacity of crops to produce constantly under changing environment, the analysis of the yield stability was aimed to determine the yield sensitivity across changing environment (establishment methods) (Brenner and Mulvaney, 1982, Olsen and Sommers, 1982). There have been several studies determining the adoption of CA in the IGP, while stability analysis has been limited to determine the adaptability of CA in Nepal and largely in the EGP. This research showed better adaptability of the CA-based DSR–ZTW system in Nepal Terai; however, another milestone needs to be crossed for the adoption of this system (reasons are explained in the next section).

4.3. Water use, and irrigation and total water productivity

Irrigation water productivity (WP_i) and total water productivity ($W_{(r+i)}$) of DSR was lower than PTR and UPTR due to higher water application through one extra irrigation during establishment. This finding disagrees with those reported by Saharawat et al. (Saharawat et al., 2010) and Gathala et al. (Gathala et al., 2015); both studies reported 10–30% water saving in DSR compared to PTR. On the other hand, our results are consistent with those of Sudhir-Yadav et al. (Sudhir et al., 2014) who reported that irrigation water use in DSR was similar to or higher than in PTR, depending on soil drainage and irrigation schedule. Alam et al. (Alam et al., 2018) also demonstrated that soil cracking before irrigation and deep drainage resulted in higher water use by DSR compared to PTR. Avoidance of puddling increases infiltration rate in DSR fields, especially in soils with lower bulk density. However, if the timing of DSR sowing could be planned in such a way that if one irrigation during establishment could be avoided then WP_i of DSR would be similar to or higher than PTR and UPTR. Our results of higher WP_i in ZTW than CTW are, however, in agreement with previous findings (Erenstein and Laxmi, 2008, Erenstein, 2009, Chauhan et al., 2012). Matching of crop water demand with rainfall pattern as affected by sowing/planting and harvesting dates, and soil and other factors can affect crop yield, irrigation needs, and WP_i. Further research comparing DSR with UPTR and PTR with timely sown DSR and accurate measurements of irrigation water would be required for robust assessment of water productivity of rice and R–W system in Nepal and the EGP.

4.4. Economics of production

In the IGP, the contribution of irrigation and tillage costs to total production cost in the R–W system is substantial (Erenstein and Laxmi, 2008). Although, there were variations in net profit from rice, wheat and R-W systems across years due to the variable yields, our findings of reduced costs in all CA-based treatments in the R–W system have demonstrated a window of opportunity for their adoption in Nepal. A number of studies across the IGP have also shown reduced production cost and higher economic returns from DSR (Chakraborty et al., 2017) and ZTW (Erenstein, 2009, Gathala et al., 2015, Thind et al., 2019) compared to PTR and CTW, respectively. Similarly, in the western IGP, DSR–ZTW showed 84% increase in net return compared to PTR–CTW

(Choudhary et al., 2018). Two years' experimental trials across eight districts of three countries in the EGP also showed a substantial reduction in production cost and increase in gross margin from CA-based practices than the CT practices (Gathala et al., 2021). Despite the higher net profit from DSR than PTR, the higher profit variability in DSR indicates uncertainties in profits from DSR. We suggest for more robust economic analysis to compare the profitability and its variability in DSR compared to PTR and UPTR for the R−W system of Nepal and he EGP.

4.5. Adoption of CA-based practices: Factors affecting and requirements for success

Weeds are one of the important constraints in adopting CA-based practices by smallholder farmers as such practices result in increased weed incidence requiring effective weed control with the application of appropriate pre- and post-emergence herbicides (Erenstein, 2009, Matloob et al., 2015, Raj and Syriac, 2017, Ramesh, 2015, Sudhir et al., 2011). The current study shows that the higher weed occurrence in CA is the technical limitation for its adoption in Nepal. The need for increasing amount and intensity of herbicide application for CA practices prohibits smallholder farmers from their adoption due to increasing herbicide costs and lack of skills for herbicide application and use of herbicide sprayer; over or misuse of herbicides can also cause environmental problem (Fig. 5). Such issues have also been addressed by several researchers in other parts of IGP (Raj and Syriac, 2017, Ramesh, 2015, Sudhir et al., 2011). During our field visit to Dhanusha in December 2019, farmers complained about the high incidence of weeds in DSR compared to PTR and UPTR (Fig. 6). Further, many farmers could not apply herbicides due to their unavailability at right time and those who used, their effectivity and efficiency were reduced due to heavy rainfall after application.

Adoption of ZTW in western IGP in India was determined by the wealth of farm households, reflecting farmers' capacity of risk-bearing and innovation, and their ability to evaluate the benefit in their fields (Hobbs et al., 2019, Erenstein, 2012, Farooq et al., 2007). Our field visit to Dhanusha revealed that some villages had no irrigation facility during the winter season due to inaccessibility of groundwater. Farmers' ownership of shallow tube well was higher in Sunsari (50.7%) compared to Dhanusha (22%), presumably due to large farm size in Sunsari (mean, 1.13 ha) and small farm size (mean, 0.8 ha) and fragmented land in Dhanusha. Also, the groundwater table was highly variable between seasons, with deep groundwater (low water table) during pre-monsoon and shallow (high water table) during post-monsoon season in Dhanusha (Okwany et al., 2015). The adoption of CA practices by small farmers of Nepal and largely in the EGP would only be possible when technical issues (Fig. 6) could be addressed better and scaling out strategies such as the timely supply of appropriate CA equipment and herbicides, and farmer's training on CA practices was put in place. Also, scaling out strategies such as access to credit or loan to farmers for purchase of ZT machines, enabling policy to encourage the local ZT machine service providers, and farmers training on CA must be put in place for their adoption (M.K. Gathala et al., 2020a and M.K. Gathala et al., 2020b).

The SRFSI project can be perceived of designing and implementing researcher-designed/managed and farmer-implemented participatory on-farm trials (Dijkshoorn and Huting, 2009) to test the performance of the CA-based alternative establishment methods against CT practices. Higher crop and labor productivity and higher profitability with improved environmental indicators (increased water productivity, NUE, PUE, and KUE, and reduced pesticide use) are important metrics in developing new farming practices to achieve sustainability and the sustainable development goals (SDGs, https://sdgs.un.org/goals), especially SDG 1 (No poverty) and 2 (Zero hunger). CA has been promoted for agricultural sustainability due to its potential for resource conservation and meticulous use of agricultural inputs while achieving higher yield and stability. However, the adoption of CA worldwide is poor due to high initial cost of machinery, inability of ZT machines to handle loose straw left on the surface after combine harvesting of previous crop and lack of scale-appropriate and locally adapted machinery in many locations (Brown et al., 2018). Apart from technical elements of new cultivars, adjusted dates of seeding and harvesting, more efficient weed, water and soil nutrient management, livelihoods of farming households, natural resources use and management, and impacts on environment should also be taken into consideration. Intensification of CA in technology dimension needs further refinements and adapted to local conditions, with the continuing need for systematic, multi-scale, and interdisciplinary work. Complete basic data on soil properties, weather data, and local socioeconomic conditions should be collected for system design and analysis to achieve this purpose. Therefore, to avoid adoption barriers, future investments in effective support systems would require: (a) incentivizing use of equipment such as precision land leveler, zero-tillage seed drills, and rice transplanting machines; (b) technical knowledge dissemination and farmers empowerment; (c) development of site-specific integrated CA-based crop, nutrient and weed management practices; (d) innovative scaling-out strategies reaching millions in short time; and (e) service provisioning and entrepreneurship. As the small-holder farmers in the EGP lack most of those resources and might not be able to afford individually, once the advantage of the CA-based practices is internalized, resources can be arranged by mobilizing rural co-operative funding, agriculture banking, crop-insurance, and development of local youth entrepreneur machine service providers.

5. Conclusions

The analysis of data from 3 years of on-farm experiments comparing CA-based and CT practices in the R−W system in 84 farmers' fields in two Terai districts of Nepal showed no significant yield differences between CA-based and CT practices in rice, wheat, or R−W system. However, the DSR−ZTW system showed higher yield stability than other systems, demonstrating its better adaptability in the studied environments. Irrigation water use was higher and WP_i and $WP_{(r+i)}$ lower for DSR than PTR and UPTR, while irrigation water use was significantly lower and WP_i and $WP_{(r+i)}$ higher for ZTW than CTW. CA-based practices substantially reduced production costs and resulted in higher profitability over CT in rice, wheat, and R−W system.

We conclude that despite inconsistent benefits in yield and water requirements and weed problems, DSR is attractive to farmers of Nepal due to its reduced labor demand, low production cost, and higher profits. Likewise, ZTW is more profitable than CTW due to reduced labor and tillage costs. Overall, among the CA-based systems evaluated, the R−W system with DSR followed by ZTW is the most promising system in terms of productivity, profitability, stability, and WP_i. However, for the farmer adoption of CA, scale-appropriate CA-based machines and machinery service providers, and appropriate herbicides need to be timely provided to the farmers. These results have wider applications not only for R-W system in Nepal, but also for the entire EGP where other cropping systems such as cotton-wheat system which is practiced widely (4.5 M ha in the South Asia and 2.6 M ha in India) and is vital for the food security of millions of smallholder farmers in the region.

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Declaration of Competing Interest

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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Supplementary materials

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