Agricultural and Biological Sciences Journal
Vol. 7, No. 1, 2021, pp. 7-13
http://www.aiscience.org/journal/absj
ISSN: 2381-7178 (Print); ISSN: 2381-7186 (Online)

Conservation Agriculture: A Profitable and Sustainable Technology for Rice-Wheat System in Eastern Gangetic Plains of Nepal

Bedanand Chaudhary[1, *], Prakash Paneru[2], Dil Raj Yadav[3], Biswash Raj Bastola[4], Dev Kumar Saphi[4], Ram Babu Das[4], Renuka Shrestha[5], Mahesh Kumar Gathala[6], Thakur Prasad Tiwari[6], Ujjawal Kumar Singh Kushwaha[7]

[1]Retired from Nepal Agricultural Research Council, Lalitpur, Nepal
[2]Nepal Agricultural Research Council, Lalitpur, Nepal
[3]Agriculture Research Station, Dhanusha, Nepal
[4]National Rice Research Program, Dhanusha, Nepal
[5]Agronomy Division, Lalitpur, Nepal
[6]CIMMYT, Dhaka, Bangladesh
[7]National Plant Breeding and Genetics Research Center, Nepal Agricultural Research Council, Lalitpur, Nepal

Abstract

On-farm trials were conducted at five locations in Dhanusha, Nepal during 2015-2016 to evaluate performance of tillage and crop establishment methods on yield and economics in rice-wheat system. Four tillage and crop establishment methods; conventional tilled transplanted rice followed by conventional tilled wheat (CTPTR-CTW), conventional tilled transplanted rice followed by zero tilled wheat (CTPTR-ZTW), un-puddled transplanted rice followed by zero tilled wheat (UPTR-ZTW), zero tilled direct seeded rice followed by zero tilled wheat (ZTDSR-ZTW) were evaluated. Tillage and crop establishment methods significantly influenced days to heading, days to maturity and number of effective tillers per m^2 in rice and wheat. However, the tillage and crop establishment methods did not differ significantly for grain yield (t ha^{-1}) in both crops. Rice plants grown using ZTDSR matured 7-9 days earlier as compared to CTPTR allowing early planting of wheat. The highest rice yield was obtained in CTPTR-ZTW and ZTDSR-ZTW and the lowest in CTTPR-CTW. Rice yield was 14.3% higher in CTPTR-ZTW and ZTDSR-ZTW than CTTPR-CTW but wheat yield was comparable in both conventional and zero tilled plots. ZTDSR- ZTW had the highest net return of US $ 827.5 ha^{-1} and benefit cost ratio of 2.01. UPTR-ZTW also gave higher net return of US $ 579.17 ha^{-1} compared to CTPTR-CTW, which had net return of US $ 297.5 ha^{-1}. The results showed that ZTDSR-ZTW produced higher farm benefits with the lower investment without penalty in crop yield. Thus, conservation agriculture (CA) practice could be a sustainable and economic option for rice-wheat system against CTPTR-CTW. However, future works are needed to identify varietal options for sustainable CA and impellent awareness activities to promote the practice. The technology has a good prospect to improve livelihoods of the people by conserving natural resources, mitigating labor shortage issues and maintaining environment friendly.

Keywords

On-farm Trials, Rice-Wheat System, Tillage and Crop Establishments, Conservation Agriculture, Reduced Production Cost, Higher Benefits

Received: September 13, 2020 / Accepted: January 16, 2021 / Published online: February 23, 2021

* Corresponding author
E-mail address: bedanand.chy@gmail.com (B. Chaudhary)

1. Introduction

Rice-based cropping system occupies 14.43 million (M) ha in the Eastern Indo Gangetic Plains (EGP) of India, Bangladesh and Nepal [1] and contributes to employment, income and livelihoods for above 450 M people in the region, the world's highest concentration of rural poverty [2]. Rice-wheat (RW) cropping system is dominant and occupies 6.22 M ha among the rice-based systems [3]. RW rotation is nutrient exhaustive and requires large amounts of resources like water, labor, time and energy for successful cultivation of rice and wheat [4-6]. The cost of tillage and crop establishment practices accounts for 25-30% of the total production cost of a rice-wheat cropping system [7]. Crop production under conventional tillage (CT) requires 4-6 tillage operations for land preparation and planting, resulting in higher cost of production compared to conservation tillage and the benefit cost ratio is reduced [8-9]. At present the major challenge in agriculture is to produce more food with the limited resources especially land and water in a sustainable way as food production has to be doubled by 2050 in South Asia [10]. Thus, it is essential to develop an alternative system that produces a higher yield at a lower cost and improves farm profitability and sustainability [6, 11-12]. This suggests that agricultural systems need a mixture of new technologies which focus more attention on issues of sustainability, profitability and conservation agriculture in intensive production systems.

Conservation agriculture for sustainable intensification (CASI) is getting momentum in the EGP and is being adopted by farmers across the region [1, 9, 13-14] for higher productivity and profitability with mitigating global warming. However, adoption rate is not encouraging [9] though it has immense opportunity in the region. In Nepal, rice and wheat are important staple food crops and are grown in 1.49 and 0.7 M ha with production of 5.61 and 2.01 M ton, respectively [15]. RW rotation system occupies 0.56 M ha in Nepal [16] and provides food, income and employment to above 83% population in the country. However, these crops are still mainly grown under CT. The practices require large amount of resources (labor, water, energy and biocide) with low input-use efficiencies, making the practices less profitable and unsustainable. Rice is established by the conventional method of puddling and transplanting (PTR). Rice fields are kept flooded for the majority of the growing period [17]. This method provides good weed control and crop establishment, reduced percolation losses of water and increased nutrient availability [18-19]. However, PTR is highly labor, water-, and energy-intensive as large amounts of labor (for seedling uprooting and transplanting), irrigation water (for puddling and continuous flooding), and energy (for intensive tillage and in irrigation) are needed [17, 20-21]. In addition, repeated puddling destroys soil structure and creates shallow hard pan, and emits large quantity of methane (CH_4), the major greenhouse gases (GHGs) contributing to global warming [6, 22-24].

Rice cultivation in the region is rain dependent. Hence, rice transplanting is often delayed because of climate variability (uncertainty of rainfall) which leads to reduced rice yield and delayed planting of the succeeding wheat crop [25]. Moreover, the conventional rice planting system increases production costs and decreases farm profits [8, 21]. Similarly, conventional practice for wheat (CTW) also involves intensive tillage for land preparation and leads to a long turnaround period, resulting in delayed wheat planting with a loss of 20-27 kg ha^{-1} day^{-1} with every day delay in planting beyond November 15 [26-27]. Gradually, reduced or zero tilled (without tilling) (ZT) planting in wheat is gaining popularity and saving production cost [24, 28]. In addition, rising labor and water scarcity, escalating fuel prices and soil fertility issues have increased the interest in a shift from CTPTR to zero tilled dry direct-seeded rice (ZTDSR) [14, 17, 21]. To achieve the full benefits of ZT, tillage and crop establishment practices both in rice and wheat need to be improved.

Considering the need to increase crop and systems productivity, and reduce resource use, we designed and implemented farmer-participatory on-farm trials with a range of tillage practices in RW systems across 25 farmer's fields in Dhanusha, Nepal during 2015 and 2016. The objectives were to identify locally relevant CASI-based tillage options to increase cropping system productivity, reduce production costs and increase farm profits over existing CT practices without disturbing environment.

2. Materials and Methods

Site description

The experiments were carried out at five locations (Fulgama, Sinurjora, Raghunathpur, Bengadhawar and Giddha) of Dhanusha district in Nepal during 2015 and 2016 (Figure 1). The area is located in subtropical region where over 80% precipitation occurs during June to September. The area receives annual rainfall of 1200-1400 mm. The soil type in the sites ranges from sandy loam to clay loam. Majority of the farmers follow conventional practices for production of rice and wheat in the areas.

Experimental details

A total of four RW rotations referred as treatments; conventional tilled transplanted rice followed by conventional tilled wheat (CTPTR-CTW), conventional tilled transplanted rice followed by zero tilled wheat (CTPTR-ZTW), un-puddled transplanted rice followed by zero tilled wheat (UPTR-ZTW), zero tilled direct seeded rice followed by zero tilled wheat (ZTDSR-ZTW), were evaluated for system productivity, sustainability and profitability. The plot size for each treatment was 300 m^2. On-farm trials were set at five farmer's fields at each location. Each farmer's field was treated as a replication.

Cultural practices

Ramdhan, a released rice variety in Nepal, was sown in nursery for raising seedlings at seed rate of 40 kg ha^{-1} for CTPTR and UPTR in the first week of June. In CTPTR, puddling was done in submerged field with 12 cm standing water using plough before transplanting. In UPTR, water was submerged at field a day before transplanting. Manual transplanting was done using 25-30 days old seedlings. ZTDSR was sown at the rate of 30 kg ha^{-1}on the same date when nursery bed was established. Fertilizers were applied @ 100:30:30 N:P_2O_5:K_2O kg ha^{-1} in all treatments during rice season. In PTRs, half N and full dose of P_2O_5 and K_2O were applied at the time of planting, whereas in DSR one third N and full dose of P_2O_5 and K_2O were placed at a depth of 5 cm using DSR drill at the time of seeding. Remaining two third N was applied in two equal splits at 30 and 45 days after planting (DAP). In ZTDSR, existing weeds prior to the seeding of rice were killed by pre-sowing application of Glyphosate (0.6) i.e. N-(phosphonomethyl) glycine. Pre-emergence herbicide, Pendimethalin i.e. N-(1-ethyl propyl)-3, 4-dimethyl-2, 6-dinitrobenzenamine was applied within 3 DAP in DSR. Nominee gold (Bispyribac Sodium) @ 200 ml ha^{-1} was sprayed when the weeds were at 2 leaf stage and it was assured that field had sufficient moisture with 2-5 cm water level.

Bijay, a popular variety of wheat in Nepal, was used at the rate of 120 kg ha^{-1} for both CT and ZT practices. Fertilizers of 100:30:30 N:P_2O_5:K_2O kg ha^{-1}were applied in all treatments during wheat season. In CT, the plots were plowed twice (two passes each time) with a tractor-drawn 9-tine tiller, about 20 cm deep, followed by wooden planking. Basal fertilizers were separately broadcasted on the tilled soil surface followed by shallow (7-10 cm) seeding by seed drill machine and wooden planking. In ZT, the seed and basal fertilizers were drilled with the zero-till seed-cum fertilizer drill machine, drawn with a tractor. In a pass, the drill machine planted seed in 9 rows, 20cm apart and 5 cm deep. Half N and full dose of P_2O_5 and K_2O were applied as basal. Remaining P_2O_5 and K_2O were applied at two equal splits on 29 and 58 DAP in both practices. Weed management was done in ZT as adopted in ZTDSR method. Instead of Nominee gold, 2, 4-D (2, 4-Dichlorophenoxyacetic acid) herbicide was applied @ 1.5 L ha^{-1} on 35 DAP.

Data collection and analysis

Data on yield and yield attributes were recorded. Three randomly selected 3 x 3 m^2quadrates per plot were harvested manually 15-20 cm above the ground and averaged to compute yield per plot. Grain moisture was adjusted 14% for rice and 13% for wheat. Straw yield was recorded after sun drying for 3-4 days. All yield data were converted per ha basis and subjected to statistical analysis using single site and combined analyses model of Crop Stat V7.2 [29]. Comparisons among treatments, with significant differences, were based on DMRT at $P \leq 0.05$.

For economic analysis, total input costs of RW production were compared among four tillage practices. In order to obtain total cost of production, the amount of various inputs applied was multiplied by prevalent market prices. Cost of equipment used under each tillage system was calculated based on existing rental value of the equipment. Therefore, initial investment, depreciation, and insurance were not separately included in the analysis. Total grain and straw productions of rice and wheat were multiplied by the respective market price in order to calculate gross return. Net returns were calculated by deducting total costs from gross returns. Cost benefit (B:C) analysis was calculated for RW rotation for 2 years under both ZT and CT. For this, gross returns (i.e., total value of main product and the by-product) of rice-wheat production were divided by the total cost of production under the four tillage practices [24].

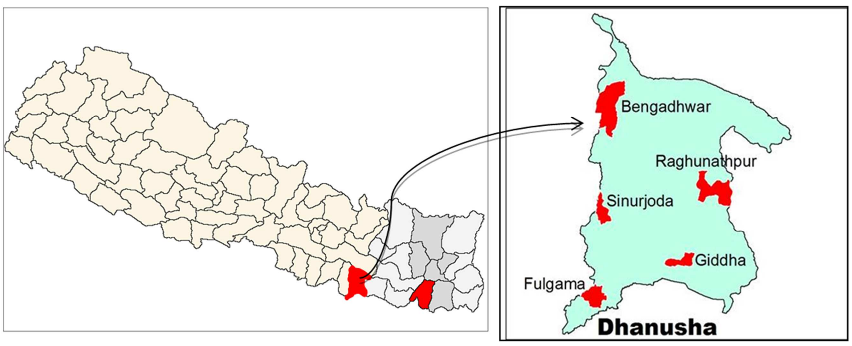

Figure 1. Map of Nepal showing experimental sites (red highlighted area) in Dhanusha district of Nepal.

3. Results

Crop establishment methods and tillage practices differed significantly for yield attributes in rice and wheat crops (Table 1 & 2). In rice, the practices of RW rotation varied for days to heading, days to maturity, number of effective tillers m^{-2} and number of grains per panicle (Table 1). In ZTDSR-ZTW rotation, rice matured early by 7-9 days, and produced the highest number of effective tillers m^{-2} and number of grains per panicle in both years. On contrary, rice in CTPTR-CTW rotation was late in maturity with the lowest number of panicles m^{-2} and reduced number of grains per panicle. In UPTR-ZTW, rice was earlier in maturity than that in CTPTR-CTW/ZTW with higher number of grains per panicle. The results indicated that change in tillage and crop establishment practice for rice improved the performance of crop. On an average, performance of wheat also varied significantly among the RW rotation practices for days to heading, days to maturity and number of grains per spike (Table 2). In ZTDSR-ZTW, wheat matured earlier than that in CTPTR-CTW with a greater number of grains per spike. However, grain and straw yields of both crops did not differ statistically among RW rotation practices in both years although rice yield was numerically higher by 14.3% in ZT practice than in CT practice (Table 1). Similar results of no yield difference were observed between DSR and PTR in the past [30-31]. However, analysis showed gradual increase in grain yield in rice and wheat crop in 2016 compared to 2015 while applying CASI options in RW systems over 2 years of experiments.

Economic analysis showed that higher net income of US $ 827.50 ha^{-1} and benefit cost ratio of 2.01 were obtained through ZTDSR-ZTW rotation among the four practices (Table 3). B:C ratio of 2.01 meant that additional economic gain was US $ 1.01 with expense of each US $. UPTR-ZTW ranked second with net income of US $ 579.17 ha^{-1} and B:C ratio of 1.55 followed by CTPTR-ZTW with net income of US $ 546.25 $ha^{-1}$and B:C ratio of 1.49. CT in RW rotation produced the lowest net income of US $ 297.50 ha^{-1} and B:C ratio of 1.24. The full CASI practice required 33% less production cost compared to CT practice (Table 3). Similarly, CTPTR-ZTW and UPTR-ZTW had lower production costs by 10 and 14%, respectively than that in CT practice. This clearly indicated that reduced or zero tillage practices in RW rotation conserved resources and increased resources productivity. Thus, less dependency on labor, less expenses on fossils energy for tillage and irrigation reduced production cost and improved farm income.

4. Discussion

Results of on-farm trials, conducted during 2015 and 2016, did not show grain and straw yield differences between CASI technologies and conventional practices (Tables 1 & 2). Similar findings were reported in the past [31]. Positive impact of zero or reduced tillage on yield in RW cropping system was realized after 2-3 years [32]. Gathala et al. [20] and Kumar et al. [33] observed that ZTDSR had similar or higher yields than those of CTPTR in the first three years The benefits of no-tillage and retention of crop residue became clear from the second year and kept increasing over time [32]. In CTPTR, repeated wet tillage operations are not only resource intensive but also destroy soil quality and lead to 8-10% yield reduction in wheat yield compared to wheat grown after DSR [17]. Amount of water consumption was reduced by 33-50% in CA practices than that in CT practices. Though the ground water management holds the key to the future sustainability of RW system in the region, the water table is being depleted at nearly 1 m yr^{-1} [34]. Currently, freshwater scarcity has become a major concern as a global systemic risk. About 4.0 billion people live under severe water scarcity at least 1 month of the year while half a billion people in the world face severe water scarcity all year round [35].

The present study showed that rice planted under ZTDSR matured 7-9 days earlier compared to conventional practice and allowed timely seeding of wheat. This allowed early and timely planting of wheat otherwise CT would have caused delay in wheat planting and the crop suffers from terminal high temperature. Planting beyond November 15 may cause yield reduction in wheat by 20-27 kg ha^{-1} day^{-1} with every day delay in planting [16, 27]. CT practices not only disturb soil environment but also lead to atmospheric pollution by releasing 26 kg Co2 to the atmosphere for each L of diesel fuel consumed for pumping irrigation water and tillage operation [36].

The study evaluated CA technologies and resources such as labor, water and energy for tillage and irrigation were saved compared to CT practices, resulting in reduced production cost (Table 3). The results clearly indicated that full or partial CASI practices consumed less investment and provided higher profit. Similar results of producing more grain with less environmental impact have been demonstrated for well managed maize production systems in the United States [37] and intensive cereal systems in China [38-39]. Crops grown in RW rotation responded better to CA practices in South Asia [1, 9-10, 14] and ZTDSR practice performed better in terms of resource productivity and sustainability compared to PTR in Nepal [21]. CASI practices in RW rotation prevented burning of rice and wheat straw, and added organic matter for upcoming crops. In addition, the practices also saved at least one week of turn around period for wheat planting. Most importantly, the practices also kept the environment clean.

Though yield advantage was not observed in the present study, a significant gain in input use efficiency and economics was reflected with benefit cost ratio of 2.01 under full CASI practices (Table 3). The net benefit was 64% higher in full CASI over CT practices. Past studies [10, 17, 21, 40] also demonstrated that yield advantages were not always achieved with CASI alone over the short period while inputs use efficiency and economic benefits were attainable.

The CA practices in RW saved resources significantly and contributed to higher profits without penalty in crop yields and soil ecology. Thus, it has a bright prospect for its dissemination in Nepal terai where 0.46 M ha is planted with wheat after rice [15]. However, knowledge and skills regarding weed management and residue retention under CA practices are crucial for the successful adoption of the technology in the area. So, training programs along with awareness campaign and sensitization (leaflet, pamphlet, radio jingle, miking etc.) are needed for promotion the technologies to wider areas in the region. It is also necessary to strengthen capacity and capability of service providers for operation, repair and maintenance of machinery to make the practices sustainable and profitable.

5. Conclusion

The present study presented that CA based practices in RW rotation reduced drudgery and production cost, and conserved natural resources i.e. soil, water and environment. The practice produced positive impact on resource productivity and contributed to higher farm benefits of US \$ 827.5 ha^{-1} compared to US \$ 297.5 ha^{-1} in CT practice. Thus, this practice could be disseminated to whole terai of Nepal with organizing certain awareness and training programs in the region to capture its benefits in national level.

Table 1. Effect of tillage and crop establishment methods on yield and yield attributes of rice during 2015 and 2016 evaluated at farmer's field in Dhanusha, Nepal.

Treatments	Plant height (cm)			Days to heading			Days to maturity			No. of effective tillers m^{-2}		
	2015	2016	Mean	2015	2016	Mean	2015	2016	Mean	2015	2016	Mean
CTPTR-CTW	108.5^{a}	103.4^{a}	105.9^{a}	107^{a}	109^{a}	108^{a}	136^{a}	139^{a}	137^{a}	351^{b}	362^{b}	357^{b}
CTPTR-ZTW	107.9^{a}	103.3^{a}	105.6^{a}	108^{a}	109^{a}	109^{a}	137^{a}	138^{a}	138^{a}	350^{b}	360^{b}	355^{b}
UPTR-ZTW	107.5^{a}	105.0^{a}	106.3^{a}	107^{a}	107^{a}	107^{a}	137^{a}	135^{b}	136^{b}	344^{b}	366^{b}	355^{b}
ZTDSR-ZTW	108.3^{a}	102.1^{a}	105.2^{a}	98^{b}	101^{a}	99^{b}	128^{b}	130^{c}	129^{c}	376^{a}	390^{a}	383^{a}

Table 1. Continue.

Treatments	No. of grains/panicle			1000-grains weight (g)			Grain yield (t ha^{-1})			Straw yield (t ha^{-1})		
	2015	2016	Mean	2015	2016	Mean	2015	2016	Mean	2015	2016	Mean
CTPTR-CTW	126^{c}	142^{c}	134^{c}	23.3^{a}	24.9^{a}	24.1^{a}	3.5^{a}	3.7^{a}	3.6^{a}	4.8^{a}	6.2^{a}	5.5^{a}
CTPTR-ZTW	138^{b}	138^{c}	138^{c}	23.6^{a}	24.7^{a}	24.1^{a}	4.2^{a}	4.3^{a}	4.2^{a}	4.9^{a}	6.1^{a}	5.5^{a}
UPTR-ZTW	136^{b}	149^{b}	143^{b}	22.5^{a}	25.0^{a}	23.8^{a}	3.8^{a}	4.3^{a}	4.1^{a}	5.0^{a}	6.0^{a}	5.5^{a}
ZTDSR-ZTW	147^{a}	152^{a}	149^{a}	22.2^{a}	24.6^{a}	23.4^{a}	4.0^{a}	4.4^{a}	4.2^{a}	5.1^{a}	6.3^{a}	5.7^{a}

Values in a column followed by different alphabetic superscript(s) are significantly different at 5% level of significance by Duncan's Multiple Range Test (DMRT)

Table 2. Effect of tillage and crop establishment methods on yield and yield attributes of wheat during 2015 and 2016 evaluated at farmer's field in Dhanusha, Nepal.

Treatments	Plant height (cm)			Days to heading			Days to maturity			No. of effective tillers m^{-2}		
	2015	2016	Mean	2015	2016	Mean	2015	2016	Mean	2015	2016	Mean
CTPTR-CTW	76.3^{a}	80.9^{a}	78.6^{a}	74^{a}	75^{a}	75^{a}	117^{a}	118^{a}	117^{a}	210^{b}	337^{b}	273^{a}
CTPTR-ZTW	76.9^{a}	80.8^{a}	78.8^{a}	71^{b}	74^{a}	73^{b}	113^{b}	116^{a}	115^{b}	207^{b}	350^{a}	278^{a}
UPTR-ZTW	75.8^{a}	80.4^{a}	78.1^{a}	71^{b}	74^{a}	72^{b}	113^{b}	116^{a}	115^{b}	212^{b}	352^{a}	282^{a}
ZTDSR-ZTW	76.4^{a}	80.6^{a}	78.5^{a}	71^{b}	74^{a}	72^{b}	113^{b}	116^{a}	115^{b}	215^{b}	349^{a}	282^{a}

Table 2. Continue.

Treatments	No. of grains/spike			1000-kernels weight (g)			Grain yield (t ha^{-1})			Straw yield (t ha^{-1})		
	2015	2016	Mean	2015	2016	Mean	2015	2016	Mean	2015	2016	Mean
CTPTR-CTW	39^{b}	38^{b}	39^{b}	45.3^{a}	34.5^{b}	39.9^{a}	2.7^{a}	3.1^{a}	2.9^{a}	4.2^{a}	5.4^{a}	4.8^{a}
CTPTR-ZTW	42^{a}	39^{b}	41^{a}	46.2^{a}	34.6^{b}	40.4^{a}	2.7^{a}	3.2^{a}	3.0^{a}	4.4^{a}	5.1^{a}	4.7^{a}
UPTR-ZTW	42^{a}	41^{a}	41^{a}	45.3^{a}	34.2^{b}	39.8^{a}	2.8^{a}	3.3^{a}	3.0^{a}	4.3^{a}	5.1^{a}	4.7^{a}
ZTDSR-ZTW	43^{a}	41^{a}	42^{a}	46.0^{a}	36.5^{b}	41.2^{a}	2.7^{a}	3.3^{a}	3.0^{a}	3.9^{a}	5.0^{a}	4.5^{a}

Values in a column followed by different alphabetic superscript(s) are significantly different at 5% level of significance by Duncan's Multiple Range Test (DMRT)

Table 3. Economics of tillage and crop establishment methods in rice-wheat system at farmer's fields of Dhanusha, Nepal during 2015and 2016.

RW Practices	Total Cost (US $*)	Gross Income (US $)	Net Return (US $)	B:C Ratio
CTTPR-CTW	1224.17	1521.67	297.50	1.24
CTTPR-ZTW	1103.75	1650.00	546.25	1.49
UTPR-ZTW	1052.50	1631.67	579.17	1.55
ZTDSR-ZTW	822.50	1650.00	827.50	2.01

*US $ was calculated @ NPR 120

Acknowledgements

The authors would like to acknowledge CIMMYT and the Australian Center for International Agriculture Research for providing financial support to conduct this study as a part of sustainable and resilient farming systems intensification project (SRFSI) in Nepal. We appreciate the support and help rendered by CIMMYT, NARC scientific and technical staff and farmers as well.

References

[1] Islam, S., Gathala, M. K., Tiwari, T. P., Timsina, J., Laing, A. M., Maharjan, S., Chowdhury, A. K., Bhattacharya, P. M., Dhar, T., Mitra, B., Kumar, S., Srivastava, P. K., Dutta, S. K., Ahrestha, R., Manandhar, S., Shrestha, S. R., Paneru, P., Alam, N. E., Hossain, S. A., Islam, R., Ghosh, A. K., Rahman, M. A., Kumar, U., Rao, K. K., and Gerard, B. 2019. Conservation agriculture for sustainable intensification: an opportunity to increase crop, system yields and water productivity for smallholders of the Eastern Gangetic Plain. *Field Crop. Res.* 238, 1-17. https://doi.org/10.1016/j.fcr.2019.04.005.

[2] Ericksen, P., Thornton, P., Notenbaert, A., Cramer, L., Jones, P., and Herrero, M. 2011. Mapping Hotspots of Climate Change and Food Insecurity in the Global Tropics. CCAFS Report no. 5. Available online at *CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)*, Copenhagen, Denmark. www.ccafs.cgiar.org.

[3] Tiwari, T. P., Gathala, M. K., and Maharjan, S., 2017. Informing Policies for Removing Barriers to Scaling Conservation Agriculture Based Sustainable Intensification in the Eastern Gangetic Plains. CIMMYT, Dhaka, Bangladesh. Report submitted to ACIAR, Canberra, Australia.

[4] Bhushan, L., Ladha, J. K., Gupta, R. K., Singh, S., Tirol-Padre, A., Saharawat, Y. S., Gathala, M., and Pathak, H. 2007. Saving of water and labor in rice-wheat systems with no-tillage and direct seeding technologies. *Agron. J.* 99, 1288–1296.

[5] Gathala, M. K., Kumar, V., Sharma, P. C., Saharawat, Y. S., Jat, H. S., Singh, M., Kumar, A., Jat, M. L., Humphreys, E., Sharma, D. K., Sharma, S., and Ladha, J. K. 2014. Reprint of "optimizing intensive cereal-based cropping systems addressing current and future drivers of agricultural change in the northwestern Indo-Gangetic Plains of India". Agric. Ecosyst. Environ. 177, 33–46. https://doi.org/10.1016/j.agee.2013.06.002.

[6] Gathala, M. K., Laing A. M., Tiwari, T. P., Timsina, J., Islam, S., Bhattacharya, P. M., Dhar, T., Ghosh, A., Sinha, A. K., Chowdhury, A. K., Hossain, S., Hossain, I., Molla, S., Mamunur, R., Kumar, S., Kumar, R., Dutta, S. K., Srivastava, P. K., Chaudhary, B., Jha, S. K., Ghimire, P., Bastola, B., Chaubey, R. K., Kumar, U., and Gerard, B. 2019. Energy-efficient, sustainable crop production practices benefit smallholder farmers and the environment across three countries in the Eastern Gangetic Plains, South Asia. *Journal of Cleaner Production,* 246, doi link https://doi.org/10.1016/j.jclepro.2019.118982.

[7] Saharawat, Y. S., Singh, B., Malik, R. K., Ladha, J. K., Gathala, M., Jat, M. L., and Kumar, V. 2010. Evaluation of alternative tillage and crop establishment methods in a rice-wheat rotation in north-western IGP. *Field Crops Res.* 116, 260–267.

[8] Gathal, M. K., Timsina, J., Islam, T. S, Krupnik, J., Bose, T. R., Islam, N., Rahman, M., Hossain, I., Rashid, H. A., Ghosh, A. K., Hasan, M. K., Khayer, A., Islam, Z., Tiwari, T. P., McDonald, A., 2016. Productivity, profitability, and energetics: a multi-criteria and multi-location assessment of farmers' tillage and crop establishment options in intensively cultivated environments of South Asia. *Field Crop. Res.* 186, 32-46. https://doi.org/10.1016/j.fcr.2015.11.008.

[9] Devkota, M., Devkota, K. P., Acharya, S., and McDonald, A. J. 2019. Increasing profitability, yields, yield stability through sustainable crop establishment practices in the rice-wheat systems of Nepal. *Agricultural Systems* 173, 414-423. https://doi.org/10.1016/j.agsy.2019.03.022.

[10] Ladha, J. K., Rao, A. N., Raman, A. K., Padre, A. T. R., Dobermann, A., Gathala, M., Kumar, V., Saharawat, Y., Sharma, S., Piepho, H. P., Alam, M., Liak, R., Rajendran, R., Reddy, C. K., Prasad, R., Sharma, P. C., Singh S. S., Saha, A., Noor, S., 2015. Agronomic improvements can make future cereal systems in South Asia far more productive and result in a lower environmental footprint. Glob. *Chang. Biol.* 01-21 https://doi.org/10.1111/gcb.13143, 1354-1013.

[11] Gupta, R., and Seth, A. 2007. A review of resource conserving technologies for sustainable management of the rice–wheat cropping systems of the Indo-Gangetic Plains (IGP). *Crop Prot.* 26, 436–447.

[12] Jat, M. L., Saharawat, Y. S., and Gupta, R. 2011. Conservation agriculture in cereal systems of South Asia: Nutrient management perspectives. *Karnataka Journal of Agricultural Sciences* 24, 100-105.

[13] Kumar, V., Jat, H. S., Sharma, P. C., Singh, B., Gathala, M. K., Malik, R. K., Kamboj, B. R., Yadav, A. K., Ladha, J. K., Raman, A., Sharma, D. K., and McDonald, A. 2018. Can productivity and profitability be enhanced in intensively managed cereal systems while reducing the environmental footprint of production? Assessing sustainable intensification options in the breadbasket of India. *Agriculture, Ecosystems and. Environment.* 252, 132-147. https://doi.org/10.1016/j.agee.2017.10.006.

[14] Pokharel, D., Jha, R. K., Tiwari, T. P., Gathala, M. K., Shrestha, H. K., and Panday, D. 2018. Is conservation agriculture a potential option for cereal-based sustainable farming system in the Eastern Indo-Gangetic Plains of Nepal. Cogent Food & Agriculture 4: 1557882. https://doi.org/10.1080/23311932.2018.1557582.

[15] ABPSD, 2018. Statistical information on Nepalese agriculture 2017/18. *Agri-business Promotion and Statistical Division*, MoAD, Singh Durbar, Kathmandu, Nepal.

[16] Tripathi, J., Bhandari D., Justice S., Shakya N. K., Kharel T. P., and Sishodia R. 2002. Resource Conservation Technologies for Wheat Production in Rice-Wheat System, Proceedings of Wheat Research Papers presented at *25th National Winter Crops Workshop*.

[17] Kumar, V., Ladha, J. K. 2011. Direct seeding of rice: recent developments and future research needs. *Advances in Agronomy*, 111, 297–413.

[18] Sharma, P. K., Ladha, J. K., and Bhushan, L. 2003. Soil physical effects of puddling in rice-wheat cropping systems. In: Ladha, J. K., Hill, J. E., Duxbury, J. M., Gupta, R. K., B, R. J. (Eds.), *Improving the Productivity and Sustainability of Rice-Wheat Systems: Issues and Impacts*, pp. 97–113 Madison, WI: ASA Special Publication 65.

[19] Johnson, D. E. and Mortimer, A. M., 2005. Issues for weed management in direct-seeded rice and the development of decision-support frameworks. *Workshop on Direct seeded Rice in the Rice-Wheat system of the Indo-Gangetic Plains*. 1-2 February 2005. G. B. Pant University of Agriculture & Technology, Pantnagar, Uttaranchal. India. pp 1-8.

[20] Gathala, M. K., Kumar, V., Sharma, P. C., Saharawat, Y. S., Jat, H. S., Singh, M., Kumar, A., Jat, M. L., Humphreys, E., Sharma, D. K., Sharma, S., and Ladha, J. K. 2013. Optimizing intensive cereal-based cropping systems addressing current and future drivers of agricultural change in the north-western Indo-Gangetic Plains of India. *Agric. Ecosyst. Environ.* 177, 85-97. https://doi.org/10.1016/j.agee.2013.06.002

[21] Chaudhary, B., Manandhar, S., and Yadav D. R. 2018. Cost effective crop establishment method for increased and sustainable rice production in eastern Gangetic plains of Nepal. *AGRICA* 7, 37-42.

[22] Hobbs, P. R. and Moris, M. L., 1996. Meeting South Asia's future food requirement from rice-wheat cropping system: priority issues facing researchers in the post green revolution era. NRG paper 96-01. CIMMYT, Mexico. 46p.

[23] Reiner, W., and Milkha, S. A. 2000. The role of rice plants in regulating mechanisms of methane emissions. *Biol. Fertil. Soils* 31, 20–29.

[24] Aryal, J. P., Sapkota, T. K., Jat, M. L., and Bishnoi, D. K. 2015. On-farm economic and environmental impact of zero-tillage wheat: a case of north-west India. *Exp. Agric.* 51, 1–16.

[25] Cornish, P. S., Karmakar, D., Kumar, A., Das, S., and Croke, B. 2015. Improving crop production for food security and improved livelihoods on the East India plateau. I. Rainfall-related risks with rice and opportunities for improved cropping systems. *Agric. Syst.* 137, 166–179. https://doi.org/10.1016/j.agsy.2015.01.008.

[26] Tripathi, S. C., Mongia, A. D., Sharma, R. K., Kharub, A. S., and Chhokar, R. S. 2005. Wheat productivity at different sowing time in various agro-climatic zones of India. *SAARC J. Agric.* 3, 191–201.

[27] CSISA, 2019. Cereal Systems Initiative for South Asia (CSISA): *Agronomy and seed systems scaling*. Final Report (2014-2019). International Maize and Wheat Improvement Center (CIMMYT), Kathmandu, Nepal. 19p.http://csisa.org/annual-reports/.

[28] Keil, A., D'Souza, A., and McDonald, A. 2015. Zero-tillage as a pathway for sustainable wheat intensification in the Eastern Indo-Gangetic Plains: does it work in farmers' fields? *Food Secur.* 7, 983-1001.

[29] IRRI, 2009. CropStat 7.2 for Windows Tutorial Manual. Crop Research Informatics Laboratory. International Rice Research Institute. 379p.

[30] Humphreys, E., Kukal, S. S., Christen, E. W., Hira, G. S., Singh, B., Yadav, S., and Sharma, R. K. 2010. Halting the ground water decline in north-west India: which crop technologies will be winners? *Adv. Agron.* 109, 155–217.

[31] Liu, H., Hussain, S., Zheng, M., Peng, S., Huang, J., Cui, K., and Nie, L. 2015. Dry direct seeded rice as an alternative to transplanted-flooded rice in Central China. *Agron. Sustain. Dev.* 35, 285–294. https://doi.org/10.1007/s13593-014-0239-0.

[32] Jat, R. K., Sapkota, T. B., Singh, R. G., Jat, M. L., Kumar, M., Gupta, R. K., 2014. Seven years of conservation agriculture in a rice–wheat rotation of Eastern Gangetic Plains of South Asia: yield trends and economic profitability. *Field Crops Res.* 164, 199–210.

[33] Kumar, V., Jat, H. S., Sharma, P. C., Balwinder-Singh, Gathala, M. K., Malik, R. K., Kamboj, B. R., Yadav, A. K., Ladha, J. K., Raman, A., Sharma, D. K., and McDonald, A. 2018. Can productivity and profitability be enhanced in intensively managed cereal systems while reducing the environmental footprint of production? Assessing sustainable intensification options in the breadbasket of India. *Agric. Ecosyst. Environ.* 252, 132–147. https://doi.org/10.1016/j.agee.2017.10.006.

[34] Kumar, R., Gopal, R., Jat, M. L., and Gupta, R. K. 2010. Conservation Agriculture Based Strategies for Sustainable Weed Management in Maize (Zea mays). *Training Manual, Maize for Freshers*. New Delhi, India: Directorate of Maize Research.

[35] Mekonnen, M. M. and Hoekstra, A. Y. 2016. Four billion people facing severe water scarcity. Science Advances. http://advances.sciencemag.org/

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

[37] Grassini P., and Cassman K. G. 2012. High-yield maize with large net energy yield and small global warming intensity. *Proceedings of the National Academy of Science,* 109, 1074–1079.

[38] Shen, J., Cui, Z., Miao, Y., Mi, G., Zhang, H., Fan, M., Zhang, C., Jiang R., Zhang, W., Li, H., Chen, X., Li, X., and Zhang, F. 2013. Transforming agriculture in China: from solely high yield to both high yield and high resource use efficiency. *Global Food Security*, 2, 1–8.

[39] Chen, X., Cui, Z., Fan, M., Vitousek, P., Zhao, M., Ma, W., Wang, Z., Zhang, W, Yan, X., Yang, J., Deng, X., Gao, Q., Zhang, Q., Guo, S., Ren, J., Li, S., Ye, Y., Wang, Z., Huang, J., Tang, Q., Sun, Y., Peng, X., Zhang, J., He, M., ZhJ., Wag, G., Wu, L., An, N., Wu, L., Ma, L., Zhang, W., and Zhang, F., 2014. Producing more grain with lower environmental costs. *Nature*, 514, 486–489.

[40] Ladha, J. K., Hill, J. E., Duxbury, J. D., Gupta, R. K., and Buresh, R. J. 2003. Improving the Productivity and Sustainability of Rice–Wheat Systems: Issues and Impact. *American Society of Agronomy Spec. Publ.* 65, ASA, CSSA, SSSA, Madison, WI, USA.