Does conservation agriculture promote sustainable intensification in the rice–wheat system of the Indo-Gangetic Plains in India? Empirical evidences from on-farm studies

Ankita Kandpal, T. M. Kiran Kumara* and Suresh Pal

ICAR-National Institute of Agricultural Economics and Policy Research, New Delhi 110 012, India

The sustainability of rice–wheat (RW) production system in the Indo-Gangetic Plains (IGP) of India is being threatened by climate change, and land and water degradation. Conservation agriculture practices provide a nature-based solution by addressing these challenges without affecting food security. In this study, a meta-analysis framework was employed to assess the on-farm economic and environmental impacts of CA in the RW system of the Indian IGP. Results show a higher on-farm yield response of CA in wheat (+5.6%) and a slight reduction in rice yield (–0.4%) compared to conventional tillage (CT). Nevertheless, the Eastern IGP witnessed a positive rice yield (+4.3%) under CA. Carbon sequestration potential of the RW system was found to be significantly higher (+22.70%) in CA. Implementation of CA practices resulted in a substantial reduction of carbon dioxide (–18.80%) and global warming potential (–23.26%). A significant amount of water was saved following CA practices on farms (+19.78%). From an economic point of view, CA practices were found to be more cost-effective with higher net returns compared to conventional tillage in the study region. Outscaling CA represents a win-win strategy for mitigating climate change without affecting food and livelihood security in the region. Providing payment for ecosystem services and developing cost-effective technologies are critical for the outscaling of CA in the IGP.

Keywords: Carbon sequestration, climate change, conservation agriculture, food security, rice–wheat system.

THE rice–wheat (RW) system is the predominant food production system of the Indo-Gangetic Plains (IGP) in the Indian subcontinent which is also pivotal for achieving food and livelihood security. Spreading over 13.5 million hectares (m ha) of arable lands, it contributes to more than 80% of the total cereal production of the IGP in India, Pakistan, Nepal and Bangladesh[1–4]. In the IGP of India, it covers the states of Punjab, Haryana, Uttar Pradesh, Bihar and West Bengal, spanning over 10.3 m ha of arable land and contributing more than 50% of the total food production[5–7].

After the Green Revolution in the IGP, food grain production increased significantly, leading to foodgrain sufficiency in India. However, post-Green Revolution, the productivity growth of the R–W system witnessed either a decline or stagnation[6,8]. A plethora of studies have highlighted the excessive use of external chemical inputs, inappropriate cultivation practices, and degradation of natural resources as the major factors[7,9–11]. Further, the heavy external input requirement of rice and wheat resulted in a higher cost of production and lower profitability[12]. Thus, the sustainability of the R–W cropping system is rigorously threatened by factors, such as declining yield and water productivity, deterioration of soil fertility, and environmental pollution caused by residue burning[13].

Climate change and fluctuations in food production pose a great threat to the sustainability of the R–W system[14]. Therefore, to address these challenges, conservation agriculture (CA) practices are being promoted in the IGP of India[15]. CA is based on three broad crop management principles, viz. (i) no/minimal soil disturbance (no-till), (ii) maintaining permanent soil organic cover (at least 30%) and (iii) crop diversification[16,17]. Simultaneous adoption of these three principles leads to an ecological base for the CA system, which has potential agronomic, environmental and economic benefits over conventional tillage (CT)[18–22].

On-farm studies of CA are crucial for identifying the impact generated in real farming situations. Numerous on-station studies have compared the various components of CA with CT in the IGP of India. However, these studies were carried out under diverse ecological and agronomic conditions, which creates ambiguity in drawing generalized conclusions about the benefits of CA. This study aims to synthesize the results of various on-farm studies of CA under the R–W system in the Indian IGP in the framework of meta-analysis assessing its impacts on multiple dimensions, viz. crop yield, carbon sequestration, greenhouse gas (GHG) emissions, water use and economic benefits.

Data and methods

An extensive literature search was performed using online search engines, viz. Google Scholar, Scopus and Science

---

*For correspondence. (e-mail: kiran.tm@icar.gov.in)

Table 1. Summary of data used in the meta-analysis

Category	Observations	Studies	No-tillage (NT)*	Conventional tillage (CT)*
Yield (Mg ha^{-1})	67	50	5.18 ± 1.81	4.98 ± 1.85
Water use (mm ha^{-1})	52	8	1184 ± 1099	1271 ± 1169
Carbon sequestration (Mg ha^{-1})	40	10	24.94 ± 11.39	20.36 ± 7.39
GHG emission (CO_2 eq. kg ha^{-1})	13	8	898 ± 1096	1289 ± 1115
Cost (US\$ ha^{-1})	21	18	334.82 ± 138.62	376.32 ± 144.7
Net returns (US\$ ha^{-1})	19	16	244.32 ± 203.64	179.85 ± 179.23

*Mean ± standard deviation.

Table 2. Effect of conservation agriculture (CA) practices on grain yield under the rice–wheat (R–W) cropping system

Particulars	Practice	Rice	Wheat	R–W system
Mean yield (Mg ha^{-1})	NT	4.97	4.52	9.61
	CT	4.99	4.28	9.45
	Difference	–0.02	0.24*	0.15
	Change (%)	–0.4	5.6	1.5
Median	NT	4.70	4.62	9.30
	CT	4.97	4.21	9.33
Standard deviation	NT	0.43	0.77	1.04
	CT	0.47	0.77	1.19
Minimum	NT	4.64	2.41	7.98
	CT	4.51	2.50	7.72
Maximum	NT	5.64	5.64	11.15
	CT	5.63	5.37	10.92
Response ratio		0.99	1.06	1.01

*indicates 1% level of significance.

Direct untill March 2020, to compile the relevant information. The keywords used were no-till, zero tillage, minimum/reduced tillage, conservation agriculture, crop yield, crop residue, rotation, greenhouse gas emission, water use, rice, wheat, IGP and/or India. The studies were screened and selected based on the criteria followed by Pittelkow *et al.*[23] and Kumara *et al.*[18,19]. Totally 212 pairwise observations from 110 studies in rice and wheat crops of the Indian IGP were selected for analysis after removing outliers (Table 1). Since on-farm research studies related to carbon sequestration and GHG emission were not available, on-station studies carried out in the IGP of India were considered.

The effect of CA practices on crop yield was examined by synthesizing the results of various on-farm studies using descriptive statistics, and a paired *t*-test was used to identify the significant difference in yield. Further, the effect size of each study was estimated as the response ratio (RR), i.e. ratio of the outcome variable of CA and CT. RR was calculated using the following equation[24]

$$\text{Effect size} = \text{Response ratio (RR)} = \left[\frac{\bar{X}_T}{\bar{X}_C}\right], \qquad (1)$$

where $\bar{X}_T$ and $\bar{X}_C$ .are the mean yield under CA and CT respectively. Since most of the studies did not report the variance of means, observations were weighted by the sample size of the study.

The amount of water utilized, carbon sequestration potential, GHG emissions and net returns were analysed using descriptive statistics. In addition, a paired *t*-test was used to evaluate the mean difference between different attributes of CA. Further, the data were converted into USD using the average exchange rate of the years when the study was carried out. Further, trade-offs among yield, water use, cost and net returns were analysed using radar charts and compared between crops in the R–W system.

Results and discussion

Yield differential

The crop-wise analysis revealed a significantly higher (+5.6%) on-farm grain yield of wheat crops under CA than CT confirmed by the RR of wheat (>1). In contrast, the on-farm grain yield of rice under CA had marginally reduced (–0.4%) (Table 2). Overall, CA had a positive response under the R–W system with a +1.5% higher grain yield. Nevertheless, the region-wise analysis reflected a positive effect (+4.3%) in rice yield in the Eastern IGP under CA (Figure 1). The increase in yield under no-till wheat was mainly attributed to early sowing due to the prevention of soil disturbing activities, decrease in terminal heat stress, increase in input use efficiency and less weed infestation[25]. Further, on-farm studies conducted have also documented similar outcomes of higher yield under no-tillage ranging from 15% to 36% in both the Northwestern and Eastern regions of the IGP. Although no-tillage positively affects yield under wheat, a substantial yield gain can be achieved by implementing no tillage along with residue retention[26–28].

The adoption of no-tillage in rice had a negative effect in terms of yield in the IGP compared to CT. The yield reduction in rice under CA is mainly due to low crop stands and high weed infestations compared to CT[19]. In addition, early sowing of direct seeded rice before the monsoon season and improper irrigation management also had a negative effect on no-tilled rice[29,30]. Many studies in South Asia reported a reduction in rice yield under no-tillage in comparison with CT[19,23,26]. In contrast, Gathala *et al.*[7] reported higher rice yield under no-till directed seeded rice compared to CT. Similarly, the present study indicated

NW IGP, North-Western Indo-Gangteic Plains; E IGP, Eastern Indo-Gangteic Plains

Figure 1. Region-wise change in grain yield under no tillage (%).

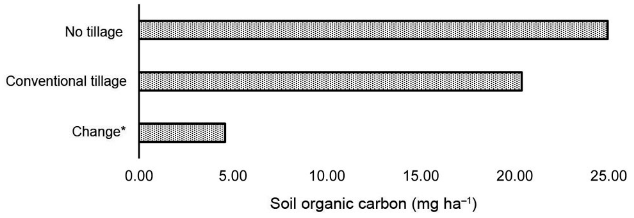

Figure 2. Effect of no tillage and conventional tillage on carbon sequestration potential (Mg ha^{-1}). *indicates 1% level of significance.

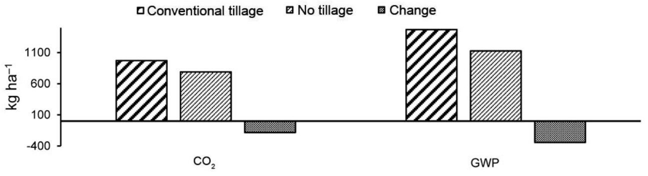

Figure 3. Carbon dioxide emission and global warming potential (GWP) of no tillage and conventional tillage under the rice–wheat (R–W) system (kg/ha).

higher rice yield in the Eastern IGP compared to the Northwestern IGP under no-till practices relative to CT.

Carbon sequestration, GHG emission and water-saving

CA practices offer nature-based, sustainable solutions to address the detrimental impacts of climate change and adaptation. Tillage practices determine the carbon sequestration potential of soils. Carbon sequestration in the R–W system was found to be significantly higher in CA-based practices compared to conventional practices. No-tillage enhanced 4.60 Mg ha^{-1} (+22.60%) of additional soil organic carbon (SOC) stock in the R–W system compared to CT practices (Figure 2). The increase in soil carbon sequestration in CA-based practices is mainly attributed to higher carbon inputs, microbial activity, and a lower rate of mineralization[31,32]. Thus, with no tillage, agriculture acts as a sink for the storage of atmospheric carbon.

Conventional crop production practices call for higher carbon-intensive inputs and emit a large amount of carbon into the atmosphere. It is estimated that the application of 1 kg NPK fertilizer has the potential to emit 1.15 kg of carbon into the atmosphere[33]. In addition, CT operations such as mouldboard ploughing, chisel ploughing, subsoiler and rotary hoeing emit 4.5–13.4 kg of carbon emission[34]. However, a significant reduction in GHG emissions was observed under CA-based practices. Compared to CT, CO_2 and global warming potential (GWP) reduced by 18.80% and 23.26% in CA in the R–W system (Figure 3). CO_2 emission and GWP were relatively lower under CA due to the slowing down of the organic carbon oxidation process which impedes the release of CO_2 from agricultural soils[35]. In addition, many studies also reported a reduction in methane emission under no-tillage practice[36,37].

Agriculture is a major user of freshwater; more than two-thirds of water is used for food production[38]. However, indiscriminate water withdrawal over the last century has seriously threatened its sustainable and optimal use. It is estimated that 1500 liters of water are required to produce 1 kg of wheat, whereas 2497 liters of water are required to produce 1 kg of rice[39]. In this context, CA practices have emerged with greater potential for water saving as they utilize less water. The amount of irrigation water used in wheat crops under CA-based management practices was found to be significantly lower (–19.78%) compared to CT. Similarly, on-farm water consumption of rice crops was lower (–2.67%) than CT. Overall, about 93 mm ha^{-1} (–4.04%) of irrigation water can be saved by CA practices in the R–W system (Table 3). The evaporation losses are relatively less under no-tilled R–W systems due to no/minimum soil disturbance and soil cover[40,41]. The higher water-use efficiency observed in CA-based practices is mainly due to soil moisture conservation[42].

Cost and net returns

CA has emerged as the most effective and sustainable strategy to enhance farm income, particularly for small and marginal holders in the IGP of South Asia. The cost of cultivation of rice and wheat crops was estimated to be 8.57% and 12.21% less under CA than CT (Table 4). CA has demonstrated an economically feasible technology in the R–W system as a significant amount of net returns were generated compared to CT. The net returns had increased by 38.37% and 8.54% for wheat and rice crops respectively (Table 5). Overall, implementation of CA practices in the R–W cropping system results in an additional return of US$ 102 ha^{-1} (+16.86%) than the conventional practices. Less cost of cultivation in the R–W system under no-tillage practice can be due to the low cost of tillage, increase in resource use efficiency and decrease in dependency on other external inputs[40]. Similarly, the higher net return of wheat under no-tillage is mainly due to incremental yield gain along with the low cost of production. On the other hand, although rice had a positive return under no till practice, it was not significant as no tillage negatively affected rice yield.

Table 3. Effect of CA practices on water use in the R–W system (mm ha^{-1})

Particulars	Practice	Rice	Wheat	R–W system
Water use (mm ha^{-1})	NT	1971	375	2217
	CT	2025	468	2311
	Difference	–54***	–93**	–93***
	Change (%)	–2.67	–19.78	–4.04
Median	NT	2368	328	2715
	CT	2425	382	2807
Standard deviation	NT	819	378	942
	CT	860	621	1005
Minimum	NT	712	142	712
	CT	782	148	782
Maximum	NT	2715	2235	2995
	CT	2770	3583	3152
Response ratio		0.97	0.80	0.96

*** and **indicates 1% and 5% level of significance respectively.

Table 4. Cost of cultivation of R–W cropping system under CA and CT

Particulars	Practice	Rice	Wheat	R–W system
Cost of cultivation (US$ ha^{-1})	NT	416	328	763
	CT	455	374	846
	Difference	–39***	–46***	–83
	Change (%)	–8.57	–12.21	–9.77
Median	NT	416	274	763
	CT	455	329	846
Standard deviation	NT	14	172	6
	CT	24	180	60
Minimum	NT	406	167	759
	CT	438	211	804
Maximum	NT	426	677	768
	CT	472	754	888
Response ratio		0.91	0.87	0.90

***indicates 1% level of significance.

Table 5. Net returns of R–W cropping system under CA and CT

Particulars	Practice	Rice	Wheat	R–W system
Net returns (US$ ha^{-1})	NT	432	274	709
	CT	398	198	607
	Difference	34	76***	102
	Change (%)	8.54	38.37	16.86
Median	NT	432	309	660
	CT	398	238	572
Standard deviation	NT	531	164	624
	CT	463	131	542
Minimum	NT	57	55	112
	CT	70	13	83
Maximum	NT	807	549	1356
	CT	726	440	1166
Response ratio		1.08	1.38	1.17

***indicates 1% level of significance.

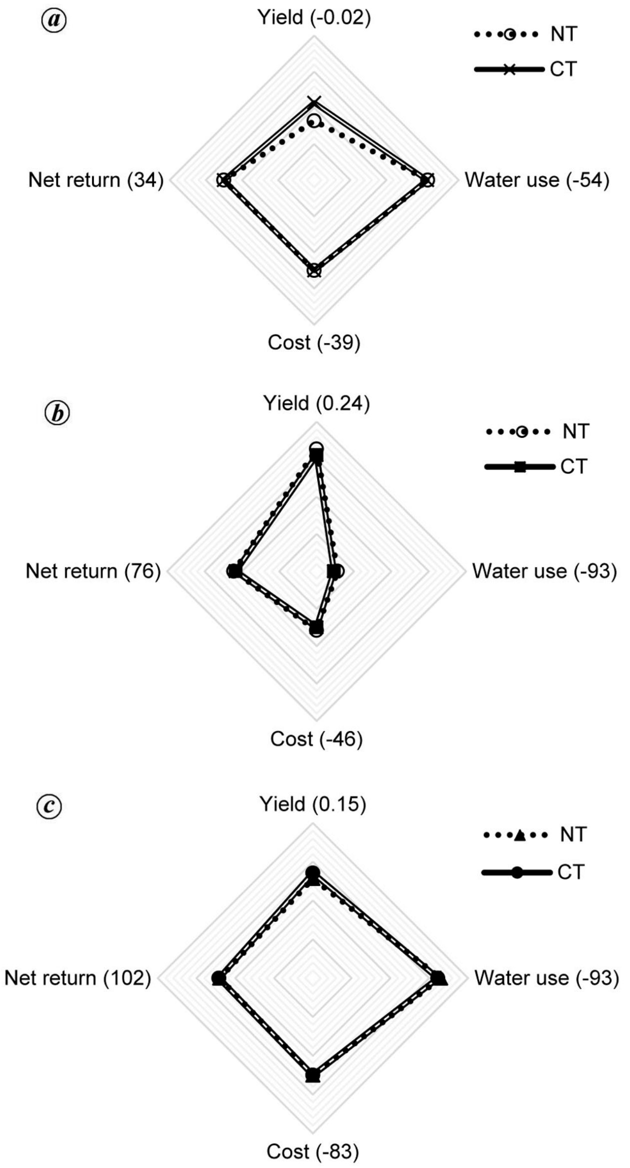

Figure 4. Trade-offs among different indicators as affected by crop management in (***a***) rice, (***b***) wheat and (***c***) R–W system in conservation agriculture and conventional agricultural practices.

Table 6. Potential yield, water-saving and changes in carbon emission under the optimal scenario of CA practices in the R–W system of the Indo-Gangetic Plains in India

Scenario	Area under the R–W system (m ha)	Additional yield (mt)	Carbon emission reduction (mt CO_2e)	Water-saving (million kl)
Optimal scenario	10.0	1.50	1.83	9300

Trade-offs and potential benefits from the adoption of CA

Adoption of CA practices in rice led to higher net returns, lower cost and less water consumption in trade-off with lower yield (Figure 4). In wheat crops, a higher yield, net return, lower cost and less water consumption were achieved through the implementation of CA-based practices. Besides yield reduction in rice, other parameters were significantly higher in both the crops individually as well as in the R–W system compared to CT.

Table 6 shows the potential economic and environmental benefits of the adoption of CA in the R–W cropping system. The additional gain was estimated under the optimal scenario, i.e. if CA is implemented over 10 m ha area of the R–W system of the IGP in India. It was observed that the adoption of CA practices can lead to a remarkable gain in crop yield of up to 1.5 million tonnes (mt) compared to CT. In addition, CA can also reduce the emission of CO_2e by 1.83 mt and provide significant water savings of up to 9300 Mkl.

Conclusion and policy implications

This study explores evidence of the perceived on-farm economic and environmental benefits of no-tillage in the RW cropping system of the IGP in India. The results show that the adoption of no-tillage resulted in significant economic and environmental advantages over CT. Overall, no-tillage had a positive response in the R–W cropping system compared to CT. The on-farm wheat grain yield was significantly higher with no-tillage practice, whereas a marginal reduction was observed in rice yield. No-tillage can be targeted in the Eastern IGP with irrigation facilities to reap the maximum potential of rice. Further, no tillage had higher carbon sequestration and water saving compared to CT in the R–W system. It is also an eco-friendly production system that helps reduce GHGs. From the present study, we can conclude that no-tillage is an economically viable practice and has the potential to enhance the income of R–W farmers in the IGP of India.

Thus, it is evident that the adoption of no-tillage in the R–W cropping system enhances multiple ecosystem services, thereby representing a key strategy to mitigate climate change in the IGP of India. Although the on-farm benefits of CA-based practices are well documented, farm-level adoption is still low. Therefore, strengthening extension services and custom-hiring centres is necessary for the successful implementation of CA. Further, additional monetary incentives in terms of payment for ecosystem services can be given to the farmers for the adoption of CA practices. Therefore, a top-to-bottom approach is required to promote CA in the R–W system in order to address the impacts of climate change and enhance the food security of smallholders in the study region.

---

1. Regmi, A. P. *et al.*, Yield and soil fertility trends in a 20-year rice–rice–wheat experiment. *Better Crops Int.*, 2003, **17**(2), 30.
2. Ladha, J. K. *et al.*, How extensive are yield declines in long-term rice–wheat experiments in Asia? *Field Crops Res.*, 2003, **81**, 159–180.
3. Gupta, R. and Seth, A., A review of resource conserving technologies for sustainable management of the rice–wheat cropping systems of the Indo-Gangetic plains (IGP). *Crop Prot.*, 2007, **26**(3), 436–447.
4. Samal, S. K. *et al.*, Evaluation of long-term conservation agriculture and crop intensification in rice–wheat rotation of Indo-Gangetic Plains of South Asia: carbon dynamics and productivity. *Eur. J. Agron.*, 2017, **90**, 198–208.
5. Pal, D. K., Bhattacharyya, T., Srivastava, P., Chandran, P. and Ray, S. K., Soils of the Indo-Gangetic Plains: their historical perspective and management. *Curr. Sci.*, 2009, **96**(9), 1193–1202.
6. Sekar, I. and Pal, S., Rice and wheat crop productivity in the Indo-Gangetic Plains of India: changing pattern of growth and future strategies. *Indian J. Agric. Econ.*, 2012, **67**(2), 1–15.
7. Gathala, M. K. *et al.*, 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.*, 2013, **177**, 85–97.
8. Kumar, P. *et al.*, Economic analysis of total factor productivity of crop sector in Indo-Gangetic Plain of India by district and region. Agricultural Economics Research Report, Indian Agricultural Research Institute, New Delhi, India, 2002, No. 2.
9. Bhattacharyya, R., Tuti, M. D., Bisht, J. K., Bhatt, J. C. and Gupta, H. S., Conservation tillage and fertilization impact on soil aggregation and carbon pools in the Indian Himalayas under an irrigated rice–wheat rotation. *Soil Sci.*, 2012, **177**(3), 218–228.
10. Ghimire, R., Adhikari, K. R., Chen, Z. S., Shah, S. C. and Dahal, K. R., Soil organic carbon sequestration as affected by tillage, crop residue, and nitrogen application in rice–wheat rotation system. *Paddy Water Environ.*, 2012, **10**(2), 95–102.
11. Erenstein, O. and Laxmi, V., Zero tillage impacts in India's rice–wheat systems: a review. *Soil Till. Res.*, 2008, **100**(1–2), 1–14.
12. Aryal, J. P., Sapkota, T. B., Jat, M. L. and Bishnoi, D. K., On-farm economic and environmental impact of zero-tillage wheat: a case of North-West India. *Exp. Agric.*, 2015, **51**(1), 1–16.
13. Humphreys, E., Kukal, S. S., Christen, E. W., Hira, G. S. and Sharma, R. K., Halting the groundwater decline in north-west India – which crop technologies will be winners? *Adv. Agron.*, 2010, **109**, 155–217.
14. Sapkota, T. B., Jat, M. L., Aryal, J. P., Jat, R. K. and Khatri-Chhetri, A., Climate change adaptation, greenhouse gas mitigation and economic profitability of conservation agriculture: some examples from cereal systems of Indo-Gangetic Plains. *J. Integr. Agric.*, 2015, **14**, 1524–1533.

15. Godfray, H. C. J. and Garnett, T., Food security and sustainable intensification. *Philos. Trans. R. Soc., London, Ser. B*, 2014, **369**(1639), 1–10.
16. FAO, What is conservation agriculture, Food and Agricultural Organization, Rome, Italy, 2014; http://www.fao.org/ag/ca/1a.html
17. Hobbs, P. R., Sayre, K. and Gupta, R., The role of conservation agriculture in sustainable agriculture. *Philos. Trans. R. Soc., London, Ser. B*, 2008, **363**(1491), 543–555.
18. Kumara, K. T. M., Kandpal, A. and Pal, S., Determinants and impacts of conservation agriculture in South Asia: a meta-analysis of the evidences. *Indian J. Agric. Econ*., 2019, **74**, 311–320.
19. Kumara, T. K., Kandpal, A. and Pal, S., A meta-analysis of economic and environmental benefits of conservation agriculture in South Asia. *J. Environ. Manage.*, 2020, **269**, 110773.
20. Erenstein, O., Conservation agriculture-based technologies and the political economy: lessons from South Asia. In *Contested Agronomy*, Routledge, London, 2012, pp. 59–75.
21. Kumar, V., Saharawat, Y. S., Gathala, M. K., Jat, A. S., Singh, S. K., Chaudhary, N. and Jat, M. L., Effect of different tillage and seeding methods on energy use efficiency and productivity of wheat in the Indo-Gangetic Plains. *Field Crops Res.*, 2013, **142**, 1–8.
22. Kassam, A., Friedrich, T. and Derpsch, R., Global spread of conservation agriculture. *Int. J. Environ. Stud.*, 2019, **76**(1), 29–51.
23. Pittelkow, C. M. *et al.*, Productivity limits and potentials of the principles of conservation agriculture. *Nature*, 2015, **517**(7534), 365–368.
24. Hedges, L. V. and Gurevitch, J., The meta-analysis of response ratios in experimental ecology. *Ecology*, 1999, **80**, 1150–1156; https://doi.org/10.1890/0012-9658(1999)080[1150:TMAORR]2.0.CO;2
25. Mehlka, R. S., Verma, J. K., Gupta, R. K. and Hobbs, P. R., Stagnation in the productivity of wheat in the Indo-Gangetic Plains: zero-till-seed-cum-fertilizer drill as an integrated soluction (No. CIMMYT), 2000.
26. Jat, M. L., Gathala, M. K., Saharawat, Y. S., Ladha, J. K. and Singh, Y., Conservation agriculture in intensive rice–wheat rotation of western Indo-Gangetic Plains: effect on crop physiology, yield, water productivity and economic profitability, 2019.
27. Sidhu, H. S., Humphreys, E., Dhillon, S. S., Blackwell, J. and Bector, V., The Happy Seeder enables direct drilling of wheat into rice stubble. *Aust. J. Exp. Agric.*, 2007, **47**(7), 844–854.
28. Sidhu, H. S., Singh, M., Singh, Y., Blackwell, J., Singh, V. and Gupta, N., Machinery development for crop residue management under direct drilling. In Fifth World Congress on Conservation Agriculture, Brisbane, Australia, 2011.
29. Devkota, M., Devkota, K. P., Acharya, S. and McDonald, A. J., Increasing profitability, yields and yield stability through sustainable crop establishment practices in the rice–wheat systems of Nepal. *Agric. Syst.*, 2019, **173**, 414–423.
30. Magar, S. T., Timsina, J., Devkota, K. P., Weili, L. and Rajbhandari, N., Conservation agriculture for increasing productivity, profitability and water productivity in rice–wheat system of the Eastern Gangetic Plain. *Environ. Challeng.*, 2022, **7**, 100468.
31. Al-Kaisi, M. M. and Yin, X., Tillage and crop residue effects on soil carbon and carbon dioxide emission in corn–soybean rotations. *J. Environ. Qual.*, 2005, **34**(2), 437–445.
32. Singh, Y., Crop residue management for improving soil and crop productivity. In *Resource Conserving Techniques in Crop Production* (eds Sharma, A. R. and Behera, U. K.), Scientific Publishers, India, 2011, pp. 166–189.
33. West, T. O. and Marland, G., Net carbon flux from agricultural ecosystems: methodology for full carbon cycle analyses. *Environ. Pollut.*, 2002, **116**(3), 439–444.
34. Lal, R., Soil carbon sequestration to mitigate climate change. *Geoderma*, 2004, **123**(1–2), 1–22.
35. La Scala Jr., N., Lopes, A., Spokas, K., Bolonhezi, D., Archer, D. W. and Reicosky, D. C., Short-term temporal changes of soil carbon losses after tillage described by a first-order decay model. *Soil Till. Res.*, 2008, **99**(1), 108–118.
36. Feng, J., Li, F., Zhou, X., Xu, C., Ji, L., Chen, Z. and Fang, F., Impact of agronomy practices on the effects of reduced tillage systems on CH_4 and N_2O emissions from agricultural fields: a global meta-analysis. *PLoS ONE*, 2018, **13**, 1–17.
37. Mangalassery, S., Sjogersten, S., Sparkes, D. L., Sturrock, C. J., Craigon, J. and Mooney, S. J., To what extent can zero tillage lead to a reduction in greenhouse gas emissions from temperate soils? *Sci. Rep.*, 2014, **4**, 1–8.
38. FAO, The State of the World's Land and Water Resources for Food and Agriculture (SOLAW): Managing Systems at Risk. Food and Agriculture Organization of the United Nations, Rome, Italy and Earthscan, London, UK, 2011; http://www.fao.org/docrep/017/i1688e/i1688e.pdf
39. Institute of Mechanical Engineers, Global Food Report: waste not, want not, 2013; https://www.imeche.org/docs/default-source/reports/Global_Food_Report.pdf
40. Parihar, C. M. *et al.*, Conservation agriculture in irrigated intensive maize-based systems of north-western India: effects on crop yields, water productivity and economic profitability. *Field Crops Res.*, 2016, **193**, 104–116.
41. Jat, M. L., Gathala, M. K., Saharawat, Y. S., Tetarwal, J. P. and Gupta, R., Double no-till and permanent raised beds in maize–wheat rotation of north-western Indo-Gangetic Plains of India: effects on crop yields, water productivity, profitability and soil physical properties. *Field Crops Res.*, 2013, **149**, 291–299.
42. Siddique, K. H. *et al.*, Innovations in agronomy for food legumes. a review. *Agron. Sustain. Dev.*, 2012, **32**(1), 45–64.

Received 21 December 2022; accepted 23 January 2023

doi: 10.18520/cs/v124/i10/1188-1193