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ARTICLE

Energy and greenhouse gas footprint analysis of conventional and reduced tillage practices in rainfed and irrigated rice–wheat systems

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Abstract

Conventional tillage practices in rice–wheat cropping systems of the Indo-Gangetic Plains are not only energy-intensive but also release large quantities of greenhouse gases (GHGs) resulting in calls for more sustainable tillage practices. To assess total energy use, energy-use efficiency, GHG emissions and total global warming potential, three reduced tillage rice–wheat systems were compared to standard conventional practice. Dry direct-seeded rice, unpuddled transplanted rice and puddled transplanted rice were paired with zero tillage wheat systems for two years in 84 on-farm trials in two Terai districts of Nepal, and compared to the puddled transplanted rice-conventional tillage wheat. In both districts, the total energy use was lower ($p < 0.05$) by 17–18% in dry direct-seeded rice and 15–17% in unpuddled transpanted rice than in puddled transplanted rice, and lower by 12.5–19% in zero tillage wheat than in conventional tillage. In both crops, the total global warming potential was lower for reduced tillage practices compared with the conventional counterparts. Higher energy-use efficiency with lower global warming potential could be a resilient and risk minimization strategy for crops in the rice–wheat systems established with reduced tillage under both irrigated and rainfed environments. To offer the most promising incentive for a transition from conventional to reduced tillage practices, availability and optimum use of herbicides, easy access to planting machines, and availability of skilled service providers are necessary.

Keywords Energy-use efficiency · Total global warming potential · Unpuddled transplanting · Dry direct-seeded rice · Greenhouse gas emission · Nepal

Introduction

In conventional farming methods with intensive soil tillage, a large amount of fossil fuel is often used which can accelerate greenhouse gas (GHG) emission (Soni et al. 2018; IEA 2020). The inefficient use of inorganic fertilizers and pesticides in conventional farming can further exacerbate the problem by emitting nitrous oxide (N_2O), methane (CH_4) and other gases. The puddling practice followed for conventionally grown transplanted rice in Asian rice cropping systems is a major source of CH_4 emission (Tirol-Padre et al. 2016). Continuous use of intensive tillage and excessive fertilizer in conventional rice-based cropping systems will increase the atmospheric pollution by increasing GHGs emissions from such practices in rice producing countries.

Rice, followed by wheat (Rice–wheat; R–W), is the main cropping system practiced by more than 14 million farmers in the Indo-Gangetic Plains (IGP) of south Asia (Timsina and Connor 2001) and by most of the smallholder farmers

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in the Terai and mid-hills regions of Nepal (Krupnik et al. 2021; Bhatt et al. 2021; Gathala et al. 2020a,b). This cropping system is practiced with intensive soil tillage. This practice consumes a large amount of water and nutrients resulting in high energy demands (Ladha et al. 2003; Kumar and Ladha 2011; Johansen et al. 2012; Bhatt et al. 2021). Different edaphic requirements of rice and wheat in the R–W system can adversely affect the productivity and sustainability of this cropping system (Timsina et al. 1995; Timsina and Connor 2001; Chauhan et al. Chauhan et al., 2011). Conventionally cultivated puddled transplanted rice (PTR) using wet tillage (puddling) is labor, water, and energy-intensive (Rashid et al. 2019). Also, the wet tillage compacts soil and deteriorates soil structure, limits nutrient availability, and ultimately affects subsequent wheat establishment and its productivity (Timsina et al. 1995; Timsina and Connor 2001; Gathala et al. 2011; Rashid et al. 2019; Bhatt et al. 2021). The intensive tillage practice can degrade soil structure by rapidly oxidizing soil organic matter, emit a significant amount of GHG from improper water and nutrient management, and increase production costs due to high labor, water and energy use (Johansen et al. 2012).

Sustainable farming practices aim to use cost-effective and energy-efficient technologies while minimizing environmental pollution (Martinho, 2020). Promising reduced tillage practices attempting to address this sustainability trilemma are zero tillage for wheat (ZTW), and dry direct-seeding (DDSR) and unpuddled transplanting (UPTR) for rice (Thapa Magar et.al. 2020; Bhatt et al. 2021). In particular, ZTW and DDSR can result in low soil disturbance, increase soil organic matter, minimize soil erosion and soil compaction, and lower GHG emissions (Tirol-Padre et al. 2016; Kumar et al. 2018). Thus, these practices are considered to be effective and sustainable for rice-based cropping systems of the IGP of south Asia (Laik et al. 2014; Pratibha et al. 2015; Rashid et al. 2019; Gathala et al. 2020a,b).

Several studies have reported on the agronomic and economic performance of various tillage methods in R–W and rice-maize (R-M) cropping systems (Erenstein 2009; Saharawat et al. 2010; Islam et al. 2019; Jat et al. 2019; Rashid et al., 2019), but very few have addressed the trade-offs among energy use, energy-use efficiency (EUE), GHG emission, and total global warming potential (TGWP) of these practices (Pratibha et al. 2015; Tirol-Padre et al. 2016). Recently, International Maize and Wheat Improvement Centre (CIMMYT) and its partners in Bangladesh, eastern India, and Nepal in the eastern IGP completed a multi-year field project comparing three reduced tillage practices (DSR, UPTR, ZTW) with the conventional tillage (CT) practice in R–W cropping systems in over 400 on-farm trials in eight districts of those countries, during 2014 to 2017 (Islam et al. 2019). The synthesis results from the three countries demonstrated an increase in EUE and a reduction in CO_2-equivalent emission from reduced tillage practices relative to CT (Gathala et al. 2020a,b). Recently, Thapa Magar et al. (2022) presented a detailed analysis comparing the performance of reduced tillage practices and CT in terms of productivity, profitability, yield stability, and irrigation water-use efficiency in the R–W system under contrasting moisture regimes (rainfed vs. irrigated) for the two districts of Nepal. However, a detailed comparative study on EUE and TGWP comparing the reduced tillage practices with CT and trade-offs among different energy-related prameters, water productivity, and GHG emissions or TGWP for the R–W system has not yet been reported. In response to the above gaps, a full suite of data on EUE, GHG emissions and TGWP trade-offs in both rainfed and irrigated R–W systems in the eastern Terai region of Nepal under different tillage practices were compared and analyzed. It was hypothesized that with better management of irrigation water and reduced tillage, energy use, GHG emissions and TGWP from rice and wheat fields under R–W cropping systems can be significantly minimized under both irrigated and rainfed production environments across locations in the eastern IGP.

Materials and methods

Soil and climate

The study was conducted during 2014 – 2017 in Dhanusha (26º 35' – 27º 50' N to 85º 52' – 86 º20' E) and Sunsari (26º 33' – 26º 55' N to 87º 05' – 87 º16' E) districts in the eastern IGP in Nepal (Fig. 1). These districts have predominantly a sandy loam to silty clay loam soil texture, low to medium soil organic carbon (0.25–1.77%), and low total soil nitrogen (0.005 to 0.16%) (Sinha et al. 2019). The climate is typical sub-tropical with a mean rainfall of 1500–2000 mm (75–80% occurring from June to September) and monthly minimum temperature ranging from 9 ºC to 21 ºC and monthly maximum temperature from 21 ºC to 38 ºC in both districts. The experimental sites in Sunsari had higher average annual rainfall (1341 mm) than in Dhanusha (1195 mm) (Thapa Magar et al. 2022).

In both districts, crops were grown in three seasons, i.e., wet season (kharif or monsoon; June/July – October), dry season (rabi or winter; November – March), and spring (pre-monsoon) season (March/April – May/June). In Dhanusha, the R–W system is typically rainfed while in Sunsari, it is mostly under irrigation. The crop management practices, inputs use, machinery and fuel consumption related data under different tillage practices, and amounts of residue retention and of pesticide applied were recorded. In addition, the yields from all farmers' fields from a 400 m^2 area were recorded and expressed in 14% grain moisture content. All raw data were obtained from the CIMMYT network repository database (https://data.cimmyt.

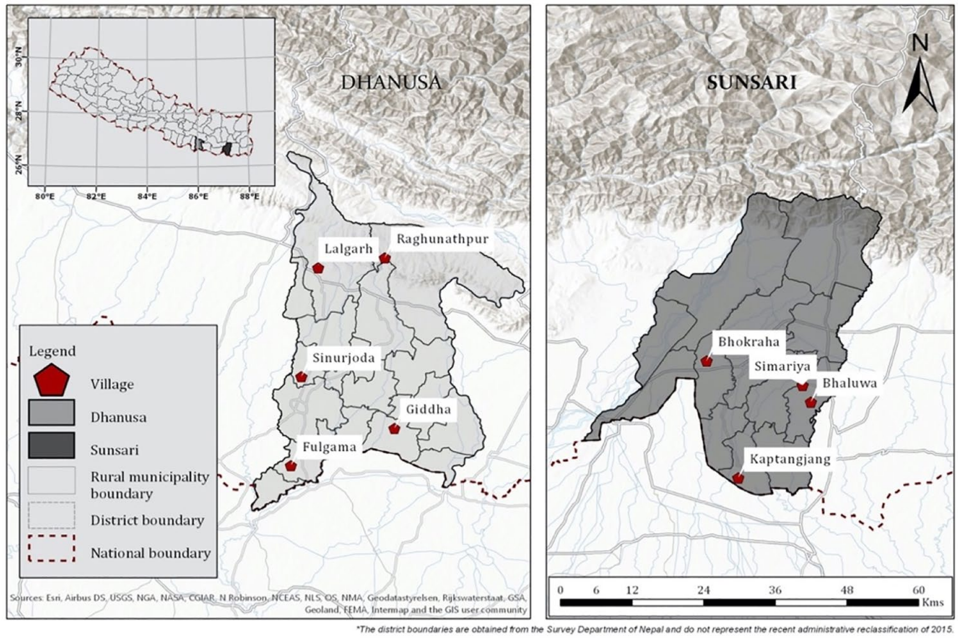

Fig. 1 Map showing two districts and nine villages of Nepal where on-farm trials were conducted duirng 2014–2017

org/dataverse/srfsidvn/?q=Nepal). Experimental and field and crop management practices are presented in detail in Thapa Magar et al. (2022).

Experimental design and treatments

Farmers participatory on-farm trials were conducted across nine villages of Dhanusha (rainfed) and Sunsari (irrigated) districts. These non-replicated trials in each farmer's field were established with the following four treatments. Each field was considered as one replication, thus forming 84 replications for each crop in the R–W sequence.

(1) Puddled transplanted rice followed by zero tillage wheat (PTR-ZTW; CT in rice but reduced tillage in wheat)
(2) Dry direct-seeded rice followed by zero tillage wheat (DDSR-ZTW; reduced tillage in both crops)
(3) Unpuddled transplanted rice followed by zero tillage wheat (UPTR-ZTW; reduced tillage in both crops)
(4) Puddled transplanted rice followed by conventional tillage wheat (PTR-CTW; CT in both crops).

The details of the treatments and the crop management practices used in each crop and treatment are presened in Table 1.

Data analysis

Energy use efficiencies

Energy use and its efficiency parameters were computed for comparing the energy performance of the R–W cropping system with different treatments (tillage practices) and input management practices. To calculate total energy use and output of the R–W system for each treatment, a complete record of inputs (labor, machinery, fuel, chemical fertilizer, herbicides, insecticides, and seeds) and outputs (grain yield, straw yield) was collected. Inputs and outputs were converted to energy equivalent through multiplying by conversion coefficients (Table 2). The total energy use, total energy output, EUE, and specific energy (SE) were calculated using the following equations (Pokhrel and Soni 2017; Nasseri 2019; Singh et al. 2019a, b).

Total energy use (TEU) is the total energy required to produce a crop. TEU was calculated by converting physical inputs to energy units using respective energy coefficients for each crop and were added to estimate the total energy use (Eq. 1).

$$\text{TEU}\left(\text{MJ ha}^{-1}\right) = [E_l + E_f + E_m + E_i] \quad (1)$$

Table 1 Description of on-farm trial treatments and crop management in rice and wheat in two districts of Nepal during 2014–2017

Treatments	Rice (tillage and seeding/transplanting)	Wheat (tillage and sowing)	Irrigation	Fertilization	Weed management
PTR-CTW	After 2–3 dry tillage, rice field puddled (wet tillage) 1–2 times keeping 3–5 cm standing water after pre-monsoon rainfall; 25–30 days old rice-seedlings transplanted manually	The field for wheat was tilled 1–2 times followed by the manual broadcasting of the wheat seed and seeds covered by shallow tillage using cultivator connected wooden plank to mix the seed into the soil	Supplemental irrigation given in rice crop when required; wheat crop irrigated based on visual observation on soil moisture content and plant demand	For all four treatments in both crops, P and K applied basally during land preparation and crop establishment. N was applied in three splits; one third basally and remaining two-third top-dressed in two splits: 1st after three weeks of seeding or transplanting and 2nd after another three weeks	In PTR, pretilachlor was applied 1–2 days after transplanting rice seedlings into standing water In ZTW, glyphosate (Roundup) with 500 L ha^{-1} water for 3–10 days before sowing of wheat. Later during the season, weeds were controlled by applying 2–4-D In DDSR and UPTR, pre-emergence herbicides pendimethalin, pyrasulfuron and bisypribac sodium were applied as a tank mixture at 2–3 weed-leaf stage which is 15–20 days after seeding or transplanting
PTR-ZTW	Same as above	In wheat, if weeds were present, non-selective herbicide applied and pre-sowing irrigation and wheat directly sown in a single pass using 9 or 11 row multi-crop seed-cum-fertilizer drill	Same as above		
DDSR-ZTW	After 2–3 dry soil tillage, field was levelled and rice directly seeded using 4-wheel tractor drawn a multi-crop planter without puddling of field	Same as above	One irrigation was applied for rice after seeding. Wheat crop irrigation as above		
UPTR-ZTW	After 2–3 dry soil tillage, rice field was levelled (not puddled) and 17–25 days old rice seedlings transplanted under 3–5 cm standing water using a mechanical transplanter	Same as above	Supplement irrigation in rice when required. Wheat was irrigated as above		

*PTR-CTW—Puddled transplanted rice followed by conventional tillage wheat; PTR-ZTW—Puddled transplanted rice followed by zero tillage wheat; DDSR-ZTW—Dry direct-seeded rice followed by zero tillage wheat; UPTR-ZTW—Un-puddled transplanted rice followed by zero tillage wheat

Table 2 Equivalent energy coefficients for inputs and outputs used in the calculations of various energy parameters

Particulars	Units	Equivalent energy (MJ unit^{-1})	References
1. Inputs			
a. Human labor	h	1.96	Pokhrel and Soni (2017);,Yuan et al. (2018)
b. Machinery	h	62.7	Singh et al. (2019a)
c. Diesel fuel	l	56.31	Pokhrel and Soni (2017), Yuan et al. (2018)
d. Chemical fertilizers			
i. Nitrogen	kg	60.60	Singh et al. (2019a)
ii. Phosphorus	kg	11.10	Singh et al. (2019a)
iii. Potassium	kg	6.70	Singh et al. (2019a)
e. Herbicides	kg	238	Yuan et al. (2018)
f. Insecticides	kg	101.2	Yuan et al. (2018)
g. Seed	kg		
Rice		14.7	Singh et al. (2019b)
Wheat		20.10	Unakıtan and Aydın (2018)
2. Outputs			
i. Grain yield	kg		
Rice		14.7	Singh et al. (2019b)
Wheat		14.48	Yuan et al. (2018), Unakıtan and Aydın (2018)
ii. Straw yield	kg		
Rice		12.5	Singh et al. (2019b)
Wheat		9.26	Yuan et al. (2018), Unakıtan and Aydın (2018)

where, E_l is manual energy from labor, E_f is energy from fuel, E_m is energy from machinery, and E_i is all energy from crop inputs (fertilizer, herbicides, insecticides, and seed).

Total energy output (TEO) is the energy produced in grain and straw products. TEO was calculated by first converting grain and straw yield to energy equivalent by multiplying by their respective energy coefficients and then added to obtain the equivalent energy of grain and straw (Nasseri 2019) (Eq. 2).

$$\text{TEO}\left(\text{MJ ha}^{-1}\right) = \text{Grain yield} \times \text{energy coefficient of grain}\left(\text{MJ kg}-^{1}\right) + \text{straw yield} \times \text{energy coefficient of straw}\left(\text{MJ kg}^{-1}\right) \quad (2)$$

Energy use efficiency **(EUE)** is the ratio of TEO to TEU. It indicates the efficient or non-efficient use of energy and the effectiveness of reduced tillage or CT practices in the R–W system. Any increase/decrease in EUE indicates efficient/inefficient use of available energy for the system and vice versa (Soni et al. 2018) (Eq. 3).

$$\text{EUE} = \frac{\text{TEO}}{\text{TEU}} \quad (3)$$

Specific energy (SE) is the ratio of TEU (MJ ha^{-1}) and grain yield (kg ha^{-1}) (Gathala et al. 2020a) (Eq. 4).

$$\text{SE} = \frac{\text{Grain yield}}{\text{TEU}} \quad (4)$$

Estimation of methane emission from rice field

Methane (CH_4) emision from rice fields was estimated by multiplying the daily emission factor by the cultivation period and its harvested area as in Eq. 5 below (IPCC 2006). The harvested area of DDSR or PTR under each treatment was multiplied by the respective cultivation period and emission factor that is representative of the condition (Sass 2002). Emission factors for PTR and DDSR used were 12.8 and 5.6 kg ha^{-1} season^{-1}, respectively (Tirol-Padre et al. 2016).

$$CH_4\text{emission from rice field} = \text{EF} \times \text{t} \times \text{A} \quad (5)$$

where EF = Emission factor for rice; t = Cultivation time period; A = Annual harvested area.

Estimation of N_2O emission

N_2O gas emission from N fertilizer application from each crop and tillage practice in each season was estimated from N_2O-N and emission factors for N_2O using Eqs. 6 and 7 below (IPCC 2006). The N_2O emission factors in rice and wheat were 0.51 and 0.33, respectively. These were calculated as the difference between N_2O-N emitted from the N-fertilized and the zero-N treatments and divided by the amount of fertilizer N added (Tirol-Padre et al. 2016).

$$N_2O - N = \frac{(N_2O - N) \times 44}{28} \quad (6)$$

$$N_2O = \frac{N_2O \text{ emission factor } \times 44}{\frac{28}{100}} \times \text{total N applied in wheat or rice} \quad (7)$$

Estimation of total global warming potential

The TGWP [carbon dioxide (CO_2) equivalent] for each treatment was calculated by estimating the emissions associated with the production and use of different inputs and multiplying by the respective emission factors (Table 3) and then adding them together (Kumar et al. 2013).

Statistical analysis

Analysis of variance (ANOVA) with a general linear model (GLM) was conducted using statistical software IBM SPSS Version 24. The ANOVA was conducted considering the experiment as a randomized complete block design (RCBD) and farmers (84) as the replication. The pairwise comparison of differences between individual treatments for the explanatory variables (energy use and outputs, EUE and SE, and CH_4 and N_2O gas emissions) was performed using Fisher's Protected Least Significant Difference (LSD) for the comparison among the treatments. Fisher's Protected LSD for the multiple treatments mean comparison was used when the ANOVA for treatment was statistically significant at $p < 0.05$ and the values were significantly different when the difference value (between treatment) was less than the LSD value at $p < 0.05$. All data were assembled and figures prepared using MS Excel 13 and SigmaPlot 13. Trade-offs among energy use, output, EUE, SE and the TGWP were analyzed using normalized (0–1) scale spider/radar graphs and different tillage practices compared across locations/districts, crops and the R–W system. Water productivity was calculated as the ratio of grain yield (kg) and the amount of irrigation water applied (L).

Results

Total energy use (input) and total energy output

The total amount of energy use (TEU) and output (TEO) across the four tillage practices in rice, wheat and R–W system in Dhanusha and Sunsari districts are presented in Table 4. In Dhanusha (rainfed system), in rice, among the three tillage practices (with ZTW), TEU was significantly lower in DDSR (by 18%) and UPTR (by 15%) than in PTR. The TEO in rice for all three tillage practices was not significant. However, in wheat, TEU was significantly higher ($p < 0.05$) in CTW (by 19%) compared to ZTW (in two tillage practices with PTR), but the TEO was not significantly different for both treatments. The annual TEU of the R–W system was the highest in PTR-CTW (28 GJ ha^{-1}) followed by PTR-ZTW, DDSR-ZTW, and UPTR-ZTW.

In Sunsari (irrigated system), in rice, TEU was significantly higher in conventional practices in rice (PTR-CTW and PTR-ZTW) than in reduced tillage practices (Table 4). Among the three tillage practices (with ZTW), DDSR and UPTR exhibited significantly lower TEU (by 17% in both DDSR and UPTR) than PTR (12.0 GJ ha^{-1}). As in Dhanusha, TEO among three tillage practices was not significantly different at 5% level of significance. In wheat, TEU was significantly higher (by 12.5%) in CTW compared to the average of ZTW (14.0 GJ ha^{-1}) with two PTR tillage practices under the R–W system. As for Dhanusha, the TEO for Sunsari was also non-significant in all treatments. The annual TEU of the R–W system was the highest ($p < 0.05$) in PTR-CTW (29 GJ ha^{-1}), followed by PTR-ZTW, UPTR-ZTW, and DDSR-CTW, while the TEO was not significant in all four treatments.

Table 3 Greenhouse gas emission factors for different inputs

Input	Emission factor (kg CO_2 eq. per unit of input)	References
Fuel (l^{-1})	2.68	US-EIA (2011)
Nitrogen (kg)	0.994	CFT (2014)
Phosphorus (kg)	4.95	CFT (2014)
Potassium (kg)	0.73	CFT (2014)
Pesticide (kg^{-1} a.i.)	26.63	Audsley et al. (2009)
Herbicide (kg^{-1} a.i.)	24.20	Grassini and Cassman (2012)

a.i.—active ingredient

Table 4 Total energy use, total energy output, energy-use efficiency, and specific energy in different tillage practices for rice, wheat, and rice–wheat system in two Terai districts of Nepal during 2014–2017

Energy parameters	Tillage practices	Dhanusha			Sunsari			Means of Dhanusha and Sunsari		
		Rice	Wheat	Rice–wheat system	Rice	Wheat	Rice–wheat system	Rice	Wheat	Rice–wheat system
Total energy use (TEU; GJ ha^{-1})	PTR-CTW	12a	16a	28a	12a	16a	29a	12a	16a	29a
	PTR-ZTW	12a	13b	25a	12a	14b	25ab	12a	13b	25ab
	DDSR-ZTW	10b	13b	23b	10b	14b	24b	10b	13b	23b
	UPTR-ZTW	11b	13b	24b	10b	14b	25ab	11b	13b	24ab
Total energy output (TEO; GJ ha^{-1})	PTR-CTW	140a	90a	229a	130a	74a	203a	136a	84a	220a
	PTR-ZTW	138a	90a	227a	127a	77a	203a	133a	86a	219a
	DDSR-ZTW	141a	90a	230a	122a	77a	199a	142a	86a	228a
	UPTR-ZTW	139a	89a	227a	132a	74a	207a	141a	85a	224a
Energy-use efficiency (EUE)	PTR-CTW	11.2b	5.6b	8.0b	7.5b	4.9b	8.2b	11.1b	14.6b	3.0b
	PTR-ZTW	11.3b	6.9a	9.0ab	7.7b	5.7a	8.5b	11.1b	16.8a	3.4a
	DDSR-ZTW	13.9a	7.0a	10.1a	8.9a	5.6a	9.9a	14.1a	17.6a	3.7a
	UPTR-ZTW	13.2a	6.7a	9.6a	8.4a	5.6a	9.4a	13.3a	17.2a	3.5a
Specific energy (SE; kg grain MJ^{-1} energy)	PTR-CTW	2.6b	5.0b	3.6a	2.7a	5.9a	4.1a	2.6b	5.3a	3.7a
	PTR-ZTW	2.6b	4.0a	3.1b	2.7a	4.8b	3.5b	2.6b	4.3b	3.3b
	DDSR-ZTW	2.1a	3.9a	2.8b	2.4b	4.9b	3.4b	2.2a	4.2b	3.0b
	UPTR-ZTW	2.3a	4.1a	3.0b	2.3b	5.1b	3.4b	2.2a	4.4b	3.2b

[*]Means followed by the same letters at the tail (a, b) in a column do not differ between the tillage practices for the specified energy parameters for Sunsari and Dhanusha districts and the average of two districts, and rice, wheat and rice–wheat system by the Fishers Protected Least Significant Difference (LSD) test at $p<0.05$. The values are significantly different when the difference value (between treatment) is less than the LSD value at $p<0.05$. Note: 1 GJ = 1000 MJ. Tillage practices: PTR-CTW—Puddled transplanted rice followed by conventional tillage wheat; PTR-ZTW—Puddled transplanted rice followed by zero tillage wheat; DDSR-ZTW—Dry direct-seeded rice followed by zero tillage wheat; UPTR-ZTW—Unpuddled transplanted rice followed by zero tillage wheat

When three years' results were averaged for the two districts, the TEU in rice for the three tillage practices (with ZTW) was significantly lower ($p<0.05$) in DDSR (by 17%) and UPTR (by 14%) than in PTR. The TEO for these three treatments was, however, insignificant. In wheat, for the two tillage practices (with PTR), the TEU of ZTW was 16% lower ($p<0.05$) than CTW (16 GJ ha^{-1}). However, the TEO was not significant for both treatments. The annual TEU of the R–W system averaged over two districts was the highest in PTR-CTW (28 GJ ha^{-1}), followed by PTR-ZTW, UPTR-ZTW, and the lowest in DDSR-ZTW.

Energy use efficiency and specific energy

In Dhanusha (rainfed system), in rice, among the three tillage practices, EUE was higher ($p<0.05$) in DDSR and UPTR compared to PTR. However, the SE of rice in all three tillage practices with ZTW was higher ($p<0.05$) in PTR than in DDSR and UPTR. In wheat also, for the two tillage practices with PTR, EUE was higher in ZTW (by 23%) than in CTW, while SE was significantly higher in CTW (by 20%) compared to ZTW. The annual EUE among the four tillage practices was significantly higher in DDSR-ZTW and UPTR-ZTW compared to PTR-CTW, while SE was highest in PTR-CTW followed by PTR-ZTW and UPTR-ZTW, and lowest in DDSR-CTW.

In Sunsari (irrigated system), for the rice crop in three R–W systems (with ZTW), EUE was higher ($p<0.05$) in DDSR (8.9) and UPTR (8.4) compared to PTR (7.5). However, the SE was higher ($p<0.05$) in PTR (by 11%) and UPTR (by 15%) than DDSR. For wheat, in the two tillage practices with PTR, EUE was not significantly different between treatments with ZTW and CTW, while the SE was significantly higher (by 1.1 MJ kg^{-1}) in CTW compared to ZTW. The annual EUE in the four treatments was higher ($p<0.05$) in DDSR-ZTW than PTR-CTW.

When the results for the rice of two districts for three years were averaged, the EUE was higher ($p<0.05$) in DDSR (by 21%) and UPTR (by 20%) compared to PTR for the three tillage practices with ZTW. The SE was significantly higher in PTR (2.6 MJ kg^{-1}) than DDSR (2.2 MJ kg^{-1}) and UPTR (2.2 MJ kg^{-1}). In wheat, the two tillage practices with PTR showed that EUE was higher ($p < 0.05$) in ZTW (16.8) than in CTW (14.6), while the SE was significantly higher in CTW than ZTW. The annual EUE was the highest in DDSR-ZTW, followed by UPTR-ZTW, PTR-ZTW, and PTR-CTW, while the SE was highest in PTR-CTW, followed by PTR-ZTW, UPTR-ZTW, and DDSR-CTW.

Distribution of energy use across different tillage practices

The distribution of energy use for the four treatments of rice, wheat and R–W systems in Dhanusha and Sunsari districts is presented in Fig. 2. In Dhanusha (rainfed system), the

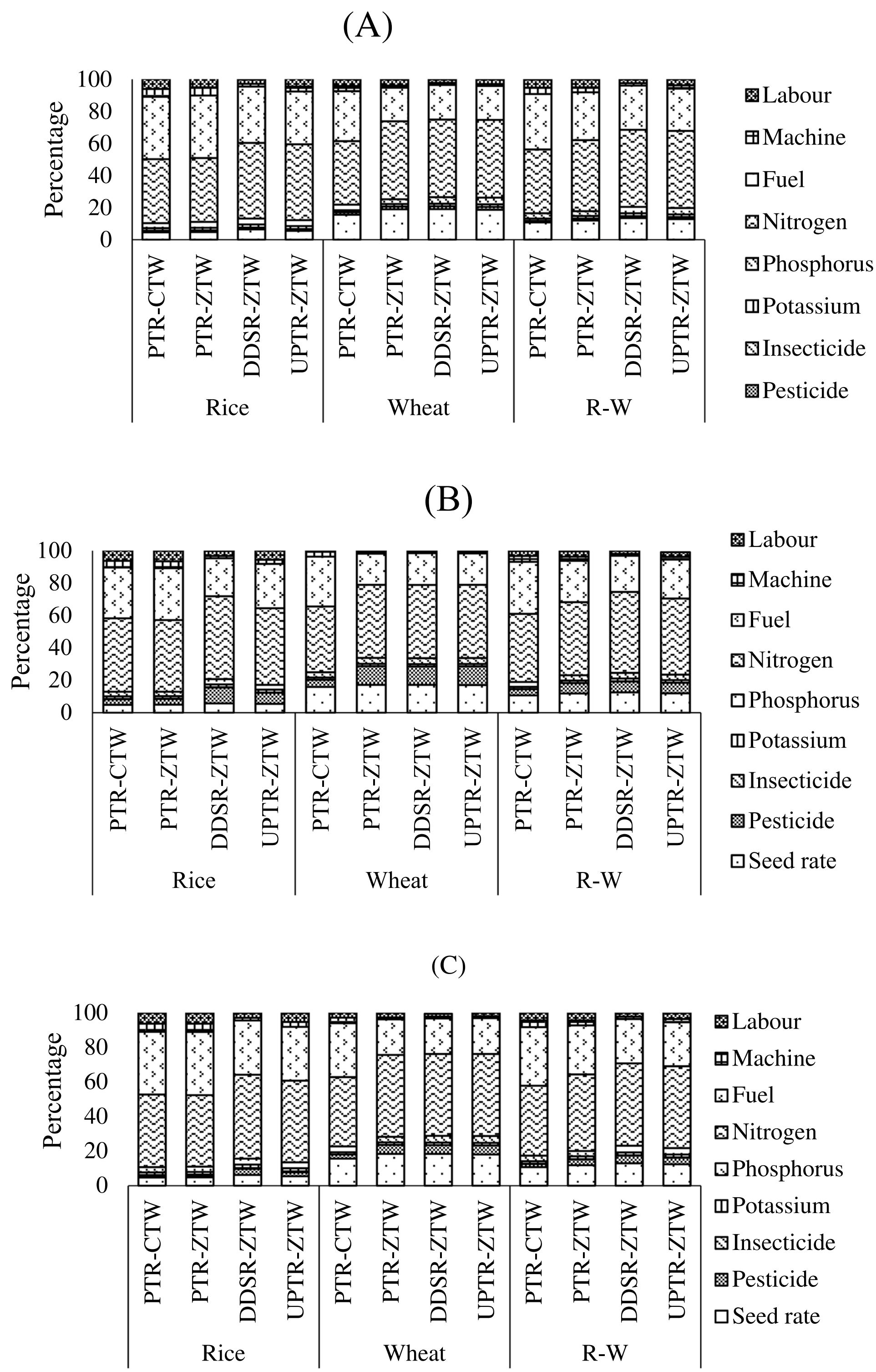

Fig. 2 Percentage distribution of the total energy use for conventional tillage and three reduced tillage practices in Dhanusha (**a**), Sunsari (**b**) and combined over Dhanusha and Sunsari (**c**). For a detailed description of the tillage practices, see Table 4

share of insecticide application was less than 1% for rice and wheat. In rice, the most energy demanding input was fertilizer application (52% in DDSR, 53% in UPTR, and 45% in PTR) in three tillage practices with ZTW. All three tillage practices for rice with ZTW exhibited the highest input energy utilization followed by fuel, seed, labor, machines, insecticides and pesticides. Pesticides were only used in DDSR. In wheat established after PTR under two tillage practices, the contribution of fertilizer application was highest (44% for CTW and 54% for all ZTW) followed by fuel, seed, labor, machines and pesticides. Therefore, in the R–W system, irrespective of tillage practices, the contribution to TEU by fertilizer application was highest followed by fuel and seed rate.

In Sunsari (irrigated system), the share of energy use in insecticide and pesticide application in the TEU was less than 1% for rice and wheat. In rice, as in Dhanusha, the most energy demanding input was fertilizer application in three tillage practices with ZTW (56% in DDSR, 52% in UPTR, and 52% in PTR). The trend of input energy utilization in all three tillage practices was highest in fertilizers, followed by fuel, seed, machines, labor, insecticides and pesticides. The wheat crops established after PTR in two treatments showed that the energy contribution from fertilizer application was the highest (45% in CTW and 51% in ZTW) followed by fuel, seed, machine, labor, and insecticides and pesticides. In Sunsari R–W system, as in other district, the contribution of input energy by fertilizer application was highest, followed by fuel use.

Total global warming potential

The TGWP due to all inputs application (diesel, fertilizer, herbicides) and N_2O and CH_4 emissions (from rice) for four tillage practices of rice, wheat and R–W systems for both districts are presented in Table 5. In Dhanusha (rainfed system), for the rice crop (established after the three reduced tillage practices in wheat—ZTW), the TGWP was lower ($p < 0.05$) by 18% and 8% in DDSR and UPTR, respectively, compared to PTR (738 kg CO_2 eq ha^{-1}). The GHG emission from diesel (for land preparation and seeding) was lower ($p < 0.05$) by 26% in DDSR and 28% in UPTR compared to PTR. The GHG emission from fertilizer was also significantly lower in DDSR and UPTR compared to PTR in all, while emission from herbicides was 4.8 kg CO_2 eq ha^{-1} in DDSR. The CH_4 emission was lower ($p < 0.05$) by 55% in DDSR than in PTR but it was non-significant between UPTR and PTR. The N_2O emission was, however, not significant between the treatments. In wheat, the two tillage practices (established after PTR) showed an insignificant difference in TGWP between ZTW and CTW. The GHG emission from fuel was significantly lower by 46% in ZTW compared to CTW, while the emission from fertilizer was insignificant among the treatments. Further, the emission from herbicides was not significant between ZTW and CTW. In the annual system, TGWP was highest in PTR-CTW, followed by PTR-ZTW, DDSR-ZTW, and UPTR-ZTW.

In Sunsari (irrigated system), for the rice crops in the three tillage practices with ZTW, the TGWP was 18% and 8.2% lower in DDSR and UPTR (741 kg CO_2 eq. ha^{-1}), respectively, compared to PTR. The GHG emission from fuel was 46% and 27% lower in DDSR and UPTR, respectively, compared to PTR. The GHG emission from fertilizer was not significant among the three treatments, while the emission from herbicides was 58 kg CO_2 eq ha^{-1} and 32 kg CO_2 eq ha^{-1} higher in DDSR and UPTR, respectively, compared to PTR. The CH_4 emission was 65% lower in DDSR than PTR, but non-significant between UPTR and PTR. Likewise, N_2O emissions were insignificant in all three treatments. In wheat crops, the two tillage practices established after PTR showed an insignificant difference in TGWP between ZTW and CTW. The GHG emission from fuel was 45% lower in ZTW compared to CTW while the emission from fertilizer was not significant between the treatments. However, GHG emissions from herbicides were much higher (by 135%) in ZTW than CTW, contributing 19% to the TGWP in ZTW. Annually, TGWP was highest in PTR-CTW, followed by PTR-ZTW, DDSR-ZTW, and UPTR-ZTW.

Trade-offs among energy use and output, EUE and TGWP

In both crops and districts, there were significant trade-offs among energy use and energy output, EUE and TGWP (Fig. 3). In both crops under CT (PTR-CTW), the highest energy use for labor, machinery, and fuel led to the highest TGWP. Despite higher herbicide use in DDSR-ZTW, the TGWP was low indicating the trade-offs among energy use through other sources. In the irrigated R–W system (Sunsari), machinery and fuel use contributed to the highest TGWP while in the rainfed system (Dhanusha), the highest energy use through labor, machinery and fuel was found in CT while the lowest use was observed in the reduced tillage practices.

Discussion

The need to maximize the global food and feed production for the increasing human and livestock production under limited arable land has increased the adoption of intensive tillage practices with higher inputs (Ghasemi et al. 2010; Tandon and Singh 2010; Tubiello et al. 2013); this has however exacerbated air pollution through emissions of the GHGs. In this study, the energy use, EUE, GHG emissions, and TGWP among three reduced tillage practices and CT

Table 5 CO_2-equivalent emission as N_2O from N fertilizer (kg ha^{-1}), CO_2-equivalent emission as CH_4 from rice field (kg ha^{-1}), CO_2-equivalent emissions (kg ha^{-1}) from inputs (fuel, herbicide, fertilizers), and total global warming potential (TGWP; kg CO_2 eqivalent emission ha^{-1}) as affected by tillage practices in rice, wheat, and rice–wheat system of two districts in Nepal during 2014–2017

Emissions (kg ha^{-1})	Tillage practices	Rice			Wheat			Rice- wheat system		
		Sunsari	Dhanusha	Mean of Dhanusha and Sunsari	Sunsari	Dhanusha	Mean of Dhanusha and Sunsari	Sunsari	Dhanusha	Mean of Dhanusha and Sunsari
CO_2-equivalent N_2O emission from N fertilizer	PTR-CTW	0.7a	0.7a	0.7a	0.5a	0.5a	0.5a	1.2a	1.2a	1.2a
	PTR-CTW	0.7a	0.6a	0.7a	0.5a	0.5a	0.5a	1.2a	1.1a	1.2a
	DDSR-ZTW	0.6a	0.6a	0.6a	0.5a	0.5a	0.5a	1.1a	1.1a	1.1a
	UPTR-ZTW	0.6a	0.7a	0.6a	0.5a	0.5a	0.5a	1.1a	1.2a	1.2a
CO_2-equivalent CH_4 emission from rice field	PTR-CTW	62a	72a	55a	–	–	–	62a	72a	55a
	PTR-CTW	63a	74a	49b	–	–	–	63a	74a	49b
	DDSR-ZTW	22b	33b	41b	–	–	–	22b	33b	41b
	UPTR-ZTW	62a	72a	55a	–	–	–	62a	72a	55a
CO_2-equivalent emission from fuel	PTR-CTW	176a	230a	210a	226a	237a	232a	404a	467a	435a
	PTR-ZTW	177a	227a	208a	125b	128b	127b	302b	356b	329b
	DDSR-ZTW	96b	169b	141b	128b	131b	130b	224c	300c	262c
	UPTR-ZTW	129c	164b	151b	125b	132b	129b	255b	296c	275c
CO_2-equivalent emission from herbicides	PTR-CTW	41b	0.0b	12b	70b	24a	39b	111b	24b	51b
	PTR-ZTW	41b	0.0b	15b	165a	23a	70a	206ab	23b	85ab
	DDSR-ZTW	99a	4.8a	36a	162a	24a	68a	261a	28a	104a
	UPTR-ZTW	73ab	0.0b	24ab	165a	24a	70a	238a	24b	94b
CO_2-equivalent emission from fertilizers	PTR-CTW	479a	448a	460a	561a	560a	566a	1039a	1007a	1028a
	PTR-ZTW	456ab	439a	446ab	562a	564a	556a	1019a	1003a	1005a
	DDSR-ZTW	384b	431a	413b	562a	560a	558a	947a	991a	966a
	UPTR-ZTW	412ab	448a	434ab	562a	555a	567a	974a	1003a	996a
TGWP	PTR-CTW	760a	751a	738a	857a	821a	838a	1617a	1572a	1571a
	PTR-ZTW	738a	741a	718a	853a	716b	753b	1591a	1456b	1468b
	DDSR-ZTW	602b	639b	632b	853a	715b	756b	1455b	1354b	1374b
	UPTR-ZTW	677b	685b	681b	853a	711b	767b	1530b	1396b	1448b

*Means followed by the same letter at the tail (a, b) in a column do not differ between the tillage practices for specific GHG emission parameters for rice, wheat and rice–wheat system in Sunsari and Dhanusha districts and the average of two districts by the Fishers Protected Least Significant Difference (LSD) test at $p < 0.05$; CH_4 emission not computed for wheat. For detailed description of the tillage practices, see Table 4

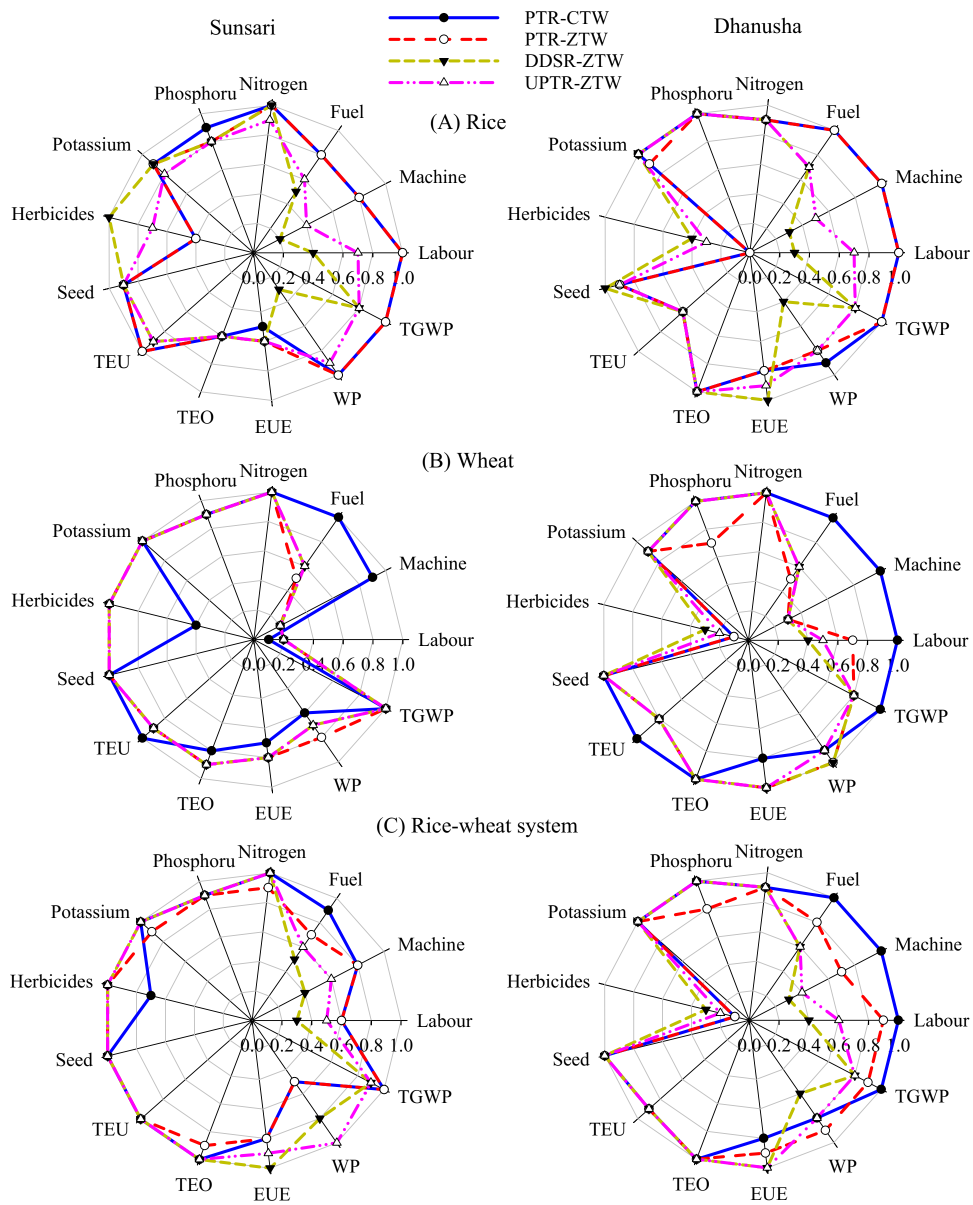

Fig. 3 Trade-offs among different sources of energy use, total energy use (TEU), total energy output (TEO), energy-use efficiency (EUE), water productivity (WP), and total global warming potential (TGWP) in conventional tillage and three reduced tillage practices in rice (**a**), wheat (**b**), and rice–wheat system (**c**) in Sunsari and Dhanusha districts of Nepal. For a detailed description of the tillage practices, see Table 4

in rice, wheat and R–W systems under rainfed and irrigated environments in two districts of Nepal were compared.

Potential of reduced tillage practices for reducing energy use and increasing EUE in the R–W system

Energy analysis was estimated and compared between reduced tillage practices and the CT practice in two districts of Nepal in the eastern IGP. In both districts, TEU was lower in DDSR than PTR, which was attributed to the reduced machinery use in trade-off with high herbicides application in both crops. This result is consistent with several studies in rice in IGP (Laik et al. 2014; Eskandari and Attar 2015; Kumar et al. 2018; Basavalingaiah et al. 2020). Similarly, in this study, the TEU for wheat was lower in ZTW than CTW which is also in consistent with previous studies that displayed a decrease in energy use in ZTW compared to CTW (Arvidsson 2010; Saharawat et al. 2012; Nasseri 2019). In both districts, the highest percentage of energy use in all reduced tillage practices (DDSR, UPTR, ZTW) and CT stemmed from fertilizer (nitrogen) use. The highest TEU from fertilizer indicated that there is a prospect to reduce fertilizer rates and adopt precision fertilizer application in both crops. For instance, considering the low nitrogen-use efficiency in rice field, there could be the need to adjust the average fertilizer application rate of 80:32:28 kg (N: P_2O_5:K_2O) to suit the crop demand and soil nutrient supply. This argument is supported by Aravindakshan et al. (2015) and Krupnik et al. (2015) who reported highest energy demand through fertilizer amongst various inputs. Herbicide application was higher in all tillage practices in the Sunsari district due to higher weed infestation. This is consistent with previous studies where difficulty in weed control at the beginning of rice seeding in DDSR and UPTR are reported. This was attributed to drought which was later alleviated by irrigation and rainfall. However, high weed pressure and excessive herbicide application in both DDSR and ZTW were common in the IGP, which could be attributed to the low adoption rate of those practices despite several advantages. Weed infestations and weed biomass production in DDSR and ZTW offer opportunities for reducing weed pressure and weed seed bank through the valorization of its biomass via green and organic manure production. It might offer the opportunity for a circular economy and incentive for the adoption by the farmers.

The energy output in the R–W system for reduced tillage and CT was highly influenced by yield rather than tillage. Also, this study showed that DDSR and UPTR in both districts had a higher EUE with lower SE compared to PTR. Similarly, previous studies in the IGP showed higher EUE and lower SE in alternative reduced tillage practices (Saharawat et al. 2012; Aravindakshan et al. 2015; Krupnik et al. 2015). For wheat, EUE was not significant between ZT and CT, but the SE was significantly lower in ZTW compared to CTW. This indicated a decline in energy use in ZTW. However, previous findings comparing EUE between eastern Terai districts with their counterparts in the eastern IGP showed higher energy use and lower EUE for the former over the latter (Gathala et al. 2020a,b). This was attributed mainly to the differences in weed pressure and the variation in the amount of fertilizer application. With proper weed control, optimized fertilizer and irrigation amounts, appropriate low fuel consuming machinery, and increasing efficiency of fertilizer, irrigation and weed control through better time scheduling in reduced tillage practices need to be researched. This will help increase the EUE,reduce emissions, and improve the sustainability of R–W cropping systems in the eastern IGP.

Potential of reduced tillage practices for reducing total global warming potential in R–W systems

The TGWP significantly varied among three reduced tillage practices and CT in the R–W system. In both districts, reduced tillage practices in rice (DDSR and UPTR) and wheat (ZTW) had higher GHG emissions from herbicides but lower TGWP. This study also showed a significant decrease in GHG emissions from diesel fuel under DDSR, UPTR and ZTW in both districts but an insignificant difference in GHG emissions from fertilizer and pesticide application amongst the reduced tillage practices and CT practice in both crops. In all three years and in both rice and wheat growing seasons, there was higher rainfall in Sunsari which accelerated weed growth. This might be due to the external environmental factors such as rainfall pattern, soil and crop management practices, water and residue management practices, or the existing weed seed bank., Or it may be due to the timely operation of all management practices including seeding time which contribute significantly to the success of alternative tillage methods and provides a roadmap for further research and implementation of these methods precisely. Consistent with these results, DDSR in northwest IGP also resulted in decline of TGWP by 35% (Kumar et al. 2018). Also, in parts of southwest India, the total GHG emissions were 86% and 65% in PTR and DDSR, respectively (Basavalingaiah et al. 2020). Likewise, in another study, R–W and M–W systems under DDSR and ZTW reduced TGWP by 16–26% compared to the R–W system under CT (Tirol-Padre et al. 2016).

There was a significant decline in methane emission in DDSR due to reduced tillage; this result is consistent with Ladha et al. (2016) and Chakraborty et al. (2017). Lack of tillage increases soil bulk density by also reducing soil poration and methane emission due to organic matter deficit (Ahmad et al. 2009). Methane emissions are also affected by hydration levels (Tirol-padre et al. 2016). It was also reported that the N application rates and water status in the soil determine the N_2O emission in the rice field (Tirol-padre et al. 2016). This study used almost identical N application rates in all treatments (coefficient of variation of 11% in rice and 13% in wheat). Under similar number of irrigation applications, N_2O emissions were insignificant across reduced tillage and CT practices. This observation shows that alternative reduced tillage practices in the R–W system of Nepal are energy-efficient with low GHG emissions. However, the high occurrence of weeds in ZT might be attributed to unfavorable weed pressure, sub-optimal irrigation management, and high rainfall. Faster weed seed emergence, and their rapid growth, development, flowering and seed formation were boosted under high rainfall which can accumulate more weed seeds in the soil. This calls for a better water management for suppressing weed pressure in rice production (Becker and Johnson 2001). It is noteworthy that discrepancies between this study and previous ones reviewed here might arise from the fact that the coefficients used for estimation of TGWP as well as energy parameters were derived from previous, but relevant, literature (Kumar et al. 2018). This suggests a need for actual measurements of energy and GHGs coefficients and parameters. This will provide a robust analysis of the EUE and environmental footprint of alternative reduced tillage practices vs CT practice in the R–W system of the IGP that will help transit from conventional to more sustainable farming practices discussed above. For instance, DDSR, ZTW and UPTR could be increased in the IGP, with the introduction of more sustainable weed control practices combined with other practices such as mulching, intercropping and crop rotation, and precision irrigation and fertilization methods (Islam et al. 2019).

From the significant trade-offs among energy use and outputs, EUE and TGWP across reduced tillage and CT practices in both crops it is evident that the implementation of the reduced tillage and improved crop production practices is a prerequisite for the IGP especially in the current context of the declining availability of water and labor (Fig. 3). These reduced tillage practices enhance micronutrients transformation and soil microbial activities, improve soil health, and improve and sustain ecosystem services (Timsina and Connor 2001; Gathala et al. 2011; Rashid et al. 2019; Bhatt et al. 2021). Despite being difficult to measure, they can also improve the aesthetic of the farm, and the outward-looking as well as the market acceptance of the products.

Despite several benefits, the uptake of DDSR in rice in the IGP is low (Kumar and Ladha 2011). The follow-up study after two years in the experimental sites in the Dhanusha district showed that excess weed pressure, lack of land levelling and inaccessibility of ZT drill machines, and lack of skilled person to provide the service for ZT machines hindered the adopton of reduced tillage practices by farmers in DDRS and ZTW (Thapa Magar et al. 2022). Scaling out of DDSR technology requires precise land levelling, suitable cultivars, scale-appropriate seeders for good crop establishment, integrated weed control, precise water and fertilizer management, sufficient technical knowledge of the farmers, changed mindset, and appropriate land and irrigation facilities (Gathala et al. 2020b). For the promotion of these cleaner production practices and technologies, some sort of incentive mechanisms, for example, availability of machinery and service providers, effective herbicide molecules, organic waste recycling (weed and crop residues), and technical backstopping are required. There is a need for effective support systems incentivizing land levelling, ZT machines, technical knowledge dissemination, and the development of integrated weed management practices in the R–W systems of the eastern IGP in general and Nepal in particular (Gathala et al. 2020b; Thapa Magar et al. 2022).

Conclusions

To achieve sustainable intensification and reduce environmental footprints from agriculture, reduced tillage practices are being increasingly adopted. This study compared the energy use and total global warming potential between the three reduced tillage practices and CT in the R–W cropping system in two districts of Nepal in the eastern IGP. The results showed lower total energy use and GHG emissions from all the reduced tillage practices compared to the CT practice in the two districts. Also, methane emission was reduced from dry direct-seeded rice compared to puddled transplanted rice due to avoidance of puddling. For both crops, zero tillage showed higher EUE and lower total global warming potential compared to conventional tillage due to reduced energy demand and reduced greenhouse gas emission. Our results are the indirect estimates of the environmental footprint from the R–W systems, so there is a need for further research for the direct estimations of energy use and GHG emissions under various reduced tillage methods in the region. Also, with sustainable weed control and irrigation methods under dry direct-seeded rice and unpuddled transplanted rice, reduced tillage practices for the R–W system could be the most promising options for smooth transition from the conventional to more sustainable practices.

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Code availability Not applicable.

Declarations

Conflicts of interest There was no conflict of interest between the authors.

Ethics approval Not applicable.

References

Ahmad S, Li C, Dai G, Zhan M, Wang J, Pan S, Cao C (2009) Greenhouse gas emission from direct seeding paddy field under different rice tillage systems in central China. Soil till Res 106:54–61. https://doi.org/10.1016/j.still.2009.09.005

Aravindakshan S, Rossi FJ, Krupnik TJ (2015) What does benchmarking of wheat farmers practicing conservation tillage in the eastern Indo-Gangetic Plains tell us about energy use efficiency? An application of slack-based data envelopment analysis. Energy 90:483–493. https://doi.org/10.1016/j.energy.2015.07.088

Arvidsson J (2010) Energy use efficiency in different tillage systems for winter wheat on a clay and silt loam in Sweden. Eur J Agron 33:250–256. https://doi.org/10.1016/j.eja.2010.06.003

Audsley E, Stacey K, Parsons DJ, Williams AG (2009) Estimation of the greenhouse gas emissions from agricultural pesticide manufacture and use. Cranfield University, Cranfield, Bedford

Basavalingaiah K, Ramesha YM, Paramesh V, Rajanna GA, Lal Jat S, Misra SD, Gaddi AK, Girisha HC, Yogesh GS, Raveesha S, Roopa TK, Shashidhar KS, Kumar B, El-Ansary DO, Elansary HO (2020) Energy budgeting, data envelopment analysis and greenhouse gas emission from rice production system: a case study from puddled transplanted rice and direct-seeded rice system of Karnataka, India. Sustain 12:16 (6439). https://doi.org/10.3390/SU12166439

Becker M, Johnson DE (2001) Improved water control and crop management effects on lowland rice productivity in West Africa. Nutr Cycl Agroecosyst 59:119–127. https://doi.org/10.1023/A:1017585328904

Chakraborty D, Ladha JK, Rana DS, Jat ML, Gathala MK, Yadav S, Rao AN, Ramesha MS, Raman A (2017) A global analysis of alternative tillage and crop establishment practices for economically and environmentally efficient rice production. Sci Rep 7:1–11. https://doi.org/10.1038/s41598-017-09742-9

Chauhan BS, Mahajan G, Sardana V, Timsina J, Jat ML (2011) Productivity and sustainability of the rice-wheat cropping system in the Indo-Gangetic Plains of Indian sub-continent: problems, opportunities, and strategies. Adv Agron 117:315–369. https://doi.org/10.1016/B978-0-12-394278-4.00006-4

CFT (2014) The Cool Farm Tool Version 2.0 beta 3. Copyright © 2014 Cool Farm Alliance. Lincolnshire, NG31 6LE England

Erenstein O (2009) Zero Tillage in the rice-wheat systems of the Indo-Gangetic Plains. IFPRI Discuss Pap 00916:1–19

Eskandari H, Attar S (2015) Energy comparison of two rice cultivation systems. Renew Sustain Energy Rev 42:666–671. https://doi.org/10.1016/j.rser.2014.10.050

Gathala MK, Ladha JK, Saharawat YS, Kumar V, Kumar V, Sharma PK (2011) Effect of tillage and crop establishment methods on physical properties of a medium-textured soil under a seven-year rice−wheat rotation. Soil Sci Soc Am J 75:1851–1862. https://doi.org/10.2136/sssaj2010.0362

Gathala MK, Laing AM, Tiwari TP, Timsina J, Islam S, Bhattacharya PM, Dhar T, Ghos A, Sinha AK, Chowdhury AK, Hossain S, Hossain I, Molla S, Rashid M, Kumar S, Kumar R, Dutta SK, Srivastwa PK, Chaudhary B, Jha SK, Ghimire P, Bastola B, Chaubey RK, Kumar U, Gérard B (2020a) Energy-efficient, sustainable crop production practices benefit smallholder farmers and the environment across three countries in the Eastern Gangetic Plains. South Asia J Clean Prod 246:118982. https://doi.org/10.1016/j.jclepro.2019.118982

Gathala MK, Laing AM, Tiwari TP, Timsina J, Islam S, Chowdhury A, Chattopadhyay C, Singh AK, Batt BP, Shrestha R, Barman NCD, Gerard B (2020b) Enabling smallholder farmers to increase productivity while achieving environmental and economic benefits: a meta-analysis of conservation agriculture-based sustainable intensification in the Eastern Gangetic Plains. Renew Sust Energ Rev 120:109645. https://doi.org/10.1016/j.rser.2019.10964

Ghasemi MH, Keyhani A, Mohammadi A, Rafiee S, Akram A (2010) Sensitivity analysis of energy inputs for barley production in Hamedan province of Iran. Agric Ecosyst Environ 137:367–372

Grassini P, Cassman KG (2012) High-yield maize with large net energy yield and small global warming intensity. Proc Natl Acad Sci USA 109:1074–1079

IEA (2020) Global Energy Review 2020. IEA, Paris https://www.iea.org/reports/global-energy-review-2020 Accessed 12 October, 2020.

IPCC (2006). IPCC guidelines for national greenhouse gas inventories, In: Eggleston S, Buendia L, Miwa K, Ngara T, Tanabe K (eds), IPCC Guidelines for national greenhouse gas inventories. Institute for Global Environmental Strategies, Japan

Islam S, Gathala MK, Tiwari TP, Timsina J, Laing AM, Maharjan S, Chowdhury AK, Bhattacharya PM, Dhar T, Mitra B, Kumar S, Srivastwa PK, Dutta SK, Shrestha R, Manandhar S, Sherestha SR, Paneru P, Siddquie NEA, Hossain A, Islam R, Ghosh AK, Rahman MA, Kumar U, Rao KK, Gérard B (2019) Conservation agriculture based sustainable intensification: Increasing yields and water productivity for smallholders of the Eastern Gangetic Plains. Field Crops Res 238:1–17. https://doi.org/10.1016/j.fcr.2019.04.005

Jat RK, Singh RG, Kumar M, Jat ML, Parihar CM, Bijarniya D, Sutaliya JM, Jat MK, Parihar MD, Kakraliya SK, Gupta RK (2019) Ten years of conservation agriculture in a rice–maize rotation of Eastern Gangetic Plains of India: Yield trends, water productivity and economic profitability. Field Crops Res 232:1–10. https://doi.org/10.1016/j.fcr.2018.12.004

Johansen C, Haque ME, Bell RW, Thierfelder C, Esdaile RJ (2012) Conservation agriculture for small holder rainfed farming: Opportunities and constraints of new mechanized seeding systems. Field Crops Res 132:18–32. https://doi.org/10.1016/j.fcr.2011.11.026

Krupnik TJ, Ahmed ZU, Timsina J, Yasmin S, Hossain F, Al Mamun A, Mridha AI, McDonald AJ (2015) Untangling crop management and environmental influences on wheat yield variability in Bangladesh: An application of non-parametric approaches. Agric Syst 133:166–179. https://doi.org/10.1016/j.agsy.2015.05.007

Krupnik T, Timsina J, Devkota K, Tripathi BP, Karki T, Urfels A, Gaihre YK, Choudhary D, Beshir AR, Pandey VP, Brown B, Gartaula H, Shahrin S, Ghimire YN (2021) Agronomic, socio-economic, and environmental challenges and opportunities in Nepal's cereal-based farming systems. Adv Agron (In press)

Kumar V, Jat HS, Sharma PC, Balwinder-Singh GMK, Malik RK, Kamboj BR, Yadav AK, Ladha JK, Raman A, Sharma DK, 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

Kumar V, Ladha JK (2011) Direct seeding of rice: Recent developments and future research needs. Adv Agron 111:297–413. https://doi.org/10.1016/B978-0-12-387689-8.00001-1

Kumar V, Saharawat YS, Gathala MK, Jat AS, Singh SK, Chaudhary N, Jat ML (2013) Effect of different tillage and seeding methods on energy use efficiency and productivity of wheat in the Indo-Gangetic Plains. Field Crops Res 142:1–8. https://doi.org/10.1016/j.fcr.2012.11.013

Ladha JK, Hill JE, Duxbury JM, Gupta RK, Buresh RJ, Grace PR, Harrington L, Jain MC, Robertson GP (2003) Long-term sustainability of the tropical and subtropical rice–wheat system: an environmental perspective. In: Ladha JK et al (ed) Improving the productivity and sustainability of rice-wheat systems: issues and Impacts. ASA Special Publications 65:27–43. https://doi.org/10.2134/asaspecpub65.c2

Ladha JK, Rao AN, Raman AK, Padre AT, Dobermann A, Gathala M, Kumar V, Saharawat Y, Sharma S, Piepho HP, Alam MM, Liak R, Rajendran R, Reddy CK, Parsad R, Sharma PC, Singh SS, Saha A, Noor S (2016) Agronomic improvements can make future cereal systems in South Asia far more productive and result in a lower environmental footprint. Glob Chang Biol 22:1054–1074. https://doi.org/10.1111/gcb.13143

Laik R, Sharma S, Idris M, Singh AK, Singh SS, Bhatt BP, Saharawat Y, Humphreys E, Ladha JK (2014) Integration of conservation agriculture with best management practices for improving system performance of the rice-wheat rotation in the Eastern Indo-Gangetic Plains of India. Agric Ecosyst Environ 195:68–82. https://doi.org/10.1016/j.agee.2014.06.001

Martinho VJPD (2020) Relationships between agricultural energy and farming indicators. Renew Sust Energ Rev vol. 132(C). https://doi.org/10.1016/j.rser.2020.110096

Nasseri A, (2019) Energy use and economic analysis for wheat production by conservation tillage along with sprinkler irrigation. Sci Total Environ 648:450–459. https://doi.org/10.1016/j.scitotenv.2018.08.170

Pokhrel A, Soni P (2017) Performance analysis of different rice-based cropping systems in tropical region of Nepal. J Environ Manage 197:70–79. https://doi.org/10.1016/j.jenvman.2017.03.035

Pratibha G, Srinivas I, Rao KV, Raju BMK, Thyagaraj CR, Korwar GR, Venkateswarlu B, Shanker AK, Choudhary DK, Rao KS, Srinivasarao C (2015) Impact of conservation agriculture practices on energy use efficiency and global warming potential in rainfed pigeonpea – castor systems. Eur J Agron 66:30–40. https://doi.org/10.1016/j.eja.2015.02.001

Rashid MH, Timsina J, Islam N, Islam S (2019) Tillage and residue-management effects on productivity, profitability and soil properties in a rice-maize-mungbean system in the Eastern Gangetic Plains. J Crop Improv 33:683–710. https://doi.org/10.1080/15427528.2019.1661056

Saharawat YS, Gathala MK, Kumar V, Chaudhary N, Singh SK, Jat AS, Jat ML (2012) Effect of different tillage and seeding methods on energy use efficiency and productivity of wheat in the Indo-Gangetic Plains. Field Crops Res 142:1–8. https://doi.org/10.1016/j.fcr.2012.11.013

Saharawat YS, Singh B, Malik RK, Ladha JK, Gathala M, Jat ML, Kumar V (2010) Evaluation of alternative tillage and crop establishment methods in a rice-wheat rotation in North Western IGP. Field Crops Res 116:260–267. https://doi.org/10.1016/j.fcr.2010.01.003

Sass RL (2002) Methods for the mitigation of methane emission to the atmosphere from irrigated rice paddy fields. In: Proceedings 1st agricultural GHG mitigation experts meeting, non-CO_2 network project on agricultural GHG mitigation, Washington DC

Singh AK, Parihar CM, Choudhary M, Jat SL, Kumar B, Parihar N, Parihar MD, Meena BR, Nayak HS (2019) Energy auditing and carbon footprint under long-term conservation agriculture-based intensive maize systems with diverse inorganic nitrogen management options. Sci Total Environ 664:659–668. https://doi.org/10.1016/j.scitotenv.2019.01.425

Sinha AK, Ghosh A, Dhar T, Bhattacharya PM, Mitra B, Rakesh S, Paneru P, Shrestha SR, Manandhar S, Beura K, Dutta S, Pradhan AK, Rao KK, Hossain A, Siddquie N, Molla MSH, Chaki AK, Gathala MK, Islam MS, Dalal RC, Gaydon DS, Laing AM, Menzies NW (2019) Trends in key soil parameters under conservation agriculture-based sustainable intensi fi cation farming practices in the Eastern Ganga Alluvial Plains. Soil Res 57(8):883–893. https://doi.org/10.1071/SR19162

Soni P, Sinha R, Perret SR (2018) Energy use and efficiency in selected rice-based cropping systems of the Middle-Indo Gangetic Plains in India. Energy Rep 4:554–564. https://doi.org/10.1016/j.egyr.2018.09.001

Tandon SK, Singh S, (2010) Energy balance in conservation agriculture and conventional farming: a comparision. In: Joshi PK, Challa J, Virmani SM (eds) Conservation agriculture-innovations for improving efficiency equity and environment. National Academy of Agricultural Sciences (NAAS), New Delhi India, pp 259–280

Thapa Magar S, Adhikari J, Timsina J (2020) Conservation Agriculture as a strategy for recovery from COVID-19 in the Indo-Gangetic Plains, IFSD Policy Insight 01/2021s

Thapa Magar S, Timsina J, Devkota K, Weili L, Rajbhandari N (2022) Conservation agriculture for increasing productivity, profitability and water productivity in the rice-wheat system of the Eastern Gangetic Plain. Environ Chall. https://doi.org/10.1016/j.envc.2022.100468

Timsina J, Connor DJ (2001) Productivity and management of rice-wheat cropping systems: Issues and challenges. Field Crops Res 69:93–132. https://doi.org/10.1016/S0378-4290(00)00143-X

Timsina J, Singh U, Singh Y, Lansigan FP (1995) Addressing sustainability of rice-wheat systems: Testing and application of CERES and SUCROS models. In: Fragile lives in fragile ecosystems: proceedings, International Rice Research Inst., Los Banos, Laguna (Philippines).- Los Banos, Laguna (Philippines): IRRI, 199, p 633–656

Tirol-padre A, Rai M, KumarV GM, Sharma PC, Sharma S, Kumar R, Deshwal S, Singh LK, Jat HS, Sharma DK, Wassmann R, Ladha J (2016) Quantifying changes to the global warming potential of rice-wheat systems with the adoption of conservation agriculture in northwestern India. Agri Ecosyst Environ 219:125–137. https://doi.org/10.1016/j.agee.2015.12.020

Tubiello FN, Salvatore M, Rossi S, Ferrara A, Fitton N, Smith P (2013) The FAOSTAT database of greenhouse gas emissions from agriculture. Environ Res Lett 8:1–15009. https://doi.org/10.1088/1748-9326/8/1/015009

Unakıtan G, Aydın B (2018) A comparison of energy use efficiency and economic analysis of wheat and sunflower production in Turkey: a case study in Thrace Region. Energy 149:279–285. https://doi.org/10.1016/j.energy.2018.02.033

US-EIA (2011) US Energy Information Administration (EIA). www.eia.gov/oiaf/1605/emission_factors.html (Fuel Emission Factors). Assessed 20 Sept 2019

Yuan S, Peng S, Wang D, Man J (2018) Evaluation of the energy budget and energy use efficiency in wheat production under various crop management practices in China. Energy 160:184–191. https://doi.org/10.1016/j.energy.2018.07.006