Journal of Cleaner Production 191 (2018) 144–157

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Energy budget and carbon footprint in a no-till and mulch based rice–mustard cropping system

Gulab Singh Yadav [a, b], Anup Das [c], Rattan Lal [b], Subhash Babu [c],
Ram Swaroop Meena [b, d, *], Poulami Saha [a], Raghavendra Singh [e], Mrinmoy Datta [f]

[a] ICAR Research Complex for NEH Region, Tripura Centre, Lembucherra 799 210, Tripura, India
[b] Carbon Management and Sequestration Centre, The Ohio State University, Columbus 43210, Ohio, USA
[c] ICAR Research Complex for NEH Region, Umiam, 793 103, Meghalaya, India
[d] Institute of Agricultural Sciences, Banaras Hindu University, Varanasi 221005, Uttar Pradesh, India
[e] ICAR Research Complex for NEH Region, Sikkim Centre, Tadong 737102, Sikkim, India
[f] College of Agriculture, Tripura University, Lembucherra 799 210, Tripura, India

ARTICLE INFO

Article history:
Received 18 August 2017
Received in revised form
2 April 2018
Accepted 18 April 2018
Available online 24 April 2018

Handling Editor: Yutao Wang

Keywords:
Farm income
System productivity
Upland ecosystem
Energy use efficiency,Conservation agriculture
Cleaner production technology

ABSTRACT

The increase in emission of greenhouse gases (GHGs) due to anthropogenic perturbation in both the agricultural and natural eco-systems are degrading the environmental quality. Conventional tillage (CT) and residue burning/removal exacerbates the land degradation and GHG emission, and the impacts are much more in the upland ecosystem than valley lands. Therefore, the aim of the present study was to evaluate the energy budget, and carbon footprint (CF) of no-till (NT) and mulches under the upland rice (*Oryza sativa*)–mustard (*Brassica campestris* var. toria) cropping system over CT based system to develop a clean production technology for improving the environmental quality and conservingnatural resources. The novelty of the study is that integrated effect of NT, diverse mulches and cropping system effect has been considered together as a conservation measure for sustainable and clean agricultural practice over those of CT based technologies. The experiment comprised of two tillage systems as the main-plot and four mulch types as the sub-plot treatments under a split-plot design. Two tillage systems included: 1. CT-RI: CT with 100% residue incorporation (RI), and 2. NT-RR: NT with 100% residue retention (RR). Four mulch types included: 1. rice straw mulch (SM), 2. green manure (GM) - *Gliricidia* sp. (a leguminous shrub) mulch, 3. brown manuring (BM) mulch [cowpea (*Vigna unguiculata*) grown as an intercrop and killed with a spray of 2, 4-D, 40 days after sowing (DAS)] and 4. no mulch (NM) control. The adoption of NT-RR significantly ($p = 0.05$) reduced the energy use (16,727 MJ/ha) and the cost of production (INR 54,271/ha, 1 US$ = 64.46 INR) compared with those under CT-RI (27,630 MJ/ha and INR 76,903/ha, respectively). Thus, NT-RR also increased the energy use efficiency (EUE), energy productivity (EP), net returns, and reduced CF of the system compared with those under CT-RI. Use of different mulches also increased the energy use efficiency, system productivity, and net returnscompared with those under NM. The total CO_2-e emission (CF) was higher under CT-RI (2307 kg CO_2-e/ha) as compared to those under NT-RR (2013 kg CO_2-e/ha). The savings of fossil fuel from less number of tillage operations and also low emissions associated with energy consumed in manufacture, transport, repair and use of machines contributed to the lowest GWP under NT-RR. Thus, the study supports and recommended that the NT-RR with BM is an environmentally safe and clean production technology for enhancing the energy use efficiency, reducing the CF and cost of production of direct-seeded upland rice-mustard cropping system in India and similar agro-eco-regions elsewhere in the rice based cropping system in the world.

1. Introduction

The well-being of all life forms (both human and other organisms) present on the planet earth is under jeopardy because of persistent decline in environmental quality (Xue et al., 2016). The

---

[*] Corresponding author. Department of Agronomy, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi-221005, Uttar Pradesh, India.
E-mail addresses: meena.8@osu.edu, rsmeenaagro@gmail.com, meensrs@bhu.ac.in (R.S. Meena).

https://doi.org/10.1016/j.jclepro.2018.04.173
0959-6526/

increase in emission of greenhouse gases (GHGs) due to anthropogenic perturbation in both the agricultural and natural ecosystems are degrading the environmental quality. Annual GHGs emission from land use change is estimated at 5.1–5.9 Gt (gigatonnes) carbon dioxide equivalent (CO_2-e) per year, corresponds to 10–12% of the human-induced global warming effects (IPCC, 2014). Rice-based production systems reported to emit 523 million tonne (Mt) CO_2-e per year, which was comprised of ~8.8–10.2% of total agricultural emission globally in 2012 (FAO, 2017). Rice is a staple food in Asia especially in Viet Nam, Bangladesh, Indonesia, Philippines, China and India with the per capita consumption of 191 kg, 169.5 kg, 163 kg, 121.9 kg and 76.4 kg and 73.4 kg (OECD, 2015), respectively and cultivated on ~162.9 million hectare (Mha) across 114 countries and produced ~742.4 Mt of paddy rice in 2016 (FAO, 2017). In India, rice is cultivated on~43 Mha and emitts 96.2 Mt CO_2-e per year, which contributed ~18.4% of the total emission from world rice fields in 2016 (FAO, 2017). Rice production, from sowing to the marketing of produce, is an important source of GHGs emission and a major consumer of energy. Agricultural operations (i.e., tillage, intercultural practices, irrigation, manure application and use of chemical fertilizers) lead toemission of GHGs into the atmosphere with strong adverse effects on the environment. The burning of fossil fuel for energy during agricultural operations is a major contributor to the emission of GHGs (Tjandra et al., 2016; Ashoka et al., 2017). Hence, it is important to reduce the emission of GHGs from farming and related activities to reduce the rate of climate change (Liu et al., 2016; Meena and Meena, 2017). Therefore, quantification and assessment of the magnitude of the carbon (C) emission and energy consumption in an agro-ecosystem, especiallyfrom the rice-based systems, could provide a potential solution to reducing rate ofclimate change, and addressing the related environmental issues. Such assessment will also enhance the awareness about the environment and facilitate the decision-making process by the public and policy makers to wards identification and promotion of environment friendly technologies (Meena and Yadav, 2014;Xue et al., 2016).

A systematic assessment of energy, carbon footprint (CF) and the economic feasibility of an agro-ecosystem can provide insights on the environmental impacts associated with the crop production technologies and management practices (Gunady et al., 2012;Meena and Yadav, 2014). Among different quantitative indicators, the CF has gained widespread popularity and application in the agriculture sector due to its role in assessing environmental quality and management (Tjandra et al., 2016). Being a quantitative indicatorofthe emission of GHGs, CF is usefulin identification of eco-friendly production systems and climate change mitigation measures (Pandey and Agrawal, 2014). The energy input-output relationship, energy productivity, and specific energy are useful parameters for designing a cleaner production system and in mitigation of GHGs emissions (Chaudhary et al., 2017). Hence, energy balance studies are useful to identify the strategies that save energy and enhance its use efficiency in agricultural production systems and provide a basis for adopting low CF technologies while also supporting the sound management and policy decisions towards its adoption (Chaudhary et al., 2006).

Several studies have been conducted to quantify the energy use and CF of diverseagricultural production systems globally including thewinter wheat (*Triticum aestivum*)-summer maize (*Zea mays*) cropping (Zhang et al., 2016), tillage-based wheat production (Gan et al., 2014; Houshyar and Grundman, 2017; Wang et al., 2016), and cropping system involving the rice-fallow (Yadav et al., 2017). Some other systems in which energy and CF studies have been conducted include tillage practices on wheat-summer corn (Lu and Liao, 2016), open field tomato (*Solanum lycopersicum*) production (Pishgar-Komleh et al., 2017), cotton (*Gossypium* spp.) production (Günther et al., 2017), conventional and organic farming systems (Bos et al., 2014) and plant and animal-based food products (Xu and Lan, 2016). In India, most of the estimates related to energy use and CF are those based onwheat-based systems (Choudhary et al., 2017). Therefore, there is a scarcity of available information about energy use and CF for rice-based cropping system under conventional and conservation systems (Parihar et al., 2017; Pratibha et al., 2015; Saad et al., 2016). So far, information on energy use and CF for direct seeded upland rice-mustard cropping are scanty. Nonetheless, direct seeded rice occupies ~29 Mha in Asia; corresponding to 21% of the total rice area in the region. In India, thedirect seeded upland rice cover ~4.95 Mha, or 12% of total rice areain the country and 17% of directly seeded rice in Asia (Pathak et al., 2011). Rapeseed-mustard (*Brassica* spp.) is cultivated on 5.53 Mha in India and contributes to 28.6% of the total production of oilseeds (Choudhury et al., 2016). Thus, upland rice-mustard system consumes a significant amount of energy and also contribute to GHGs emission to the atmosphere.

Furthermore, resource and energy-intensive practices have high CF especially of GHGs (Tubiello et al., 2013), have increased the global energy budget by 10-times since beginning of the 20th century (Tandon and Singh, 2010), and increased the cost of production by 4–5 times compared to that of the no-till (NT) farming during the same period (Pratibha et al., 2015). Conventionally, crop residues are either burned or removed from the field and repeated tilling is practiced for a fine seed bed preparation, leading to increasing in GHGs emission (Kuotsu et al., 2014). The farm management practices consume a significant amount of energy for agricultural machinery operations (Pishgar-Komleh et al., 2012). The energy consumed in agricultural operations contribute to global warming through emission of GHGs, mainly carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Ntinas et al., 2017; Yadav et al., 2017). Hence, there is an urgent need to increase the energy use efficiency (EUE) and decrease the associated CF in crop production. It is alsopertinent to assess the global warming potential (GWP) of agricultural production practices, quantify emissions of GHGs, and consider adoption of suitable mitigation strategies with minimum energy consumption in cropping systems (Gunady et al., 2012) to provide safe food to the world's evergrowing population.

Tillage is an energy-intensive farm operation (Lal, 2004) which contributes to ~30% of the total energy use in crop production (Singh et al., 2008). The consumption of fossil fuel energy is directly related to the emission of GHGs (Yadav et al., 2017), intensive tillage increases the GHGs emissions (Soni et al., 2013). Consequently, a paradigm shift in farm management practices is warranted, involving conservation- effective high EUE and low GHGs emissions practices in agriculture for safe and cleaner production. The conservation agricultural (CA) based-agro-techniques [NT, residue retention, mulching, etc.) can reduce the energy use and GHGs emission (Lal, 2015), and increase the soil organic carbon (SOC) pool (Lal, 2004). Experimental confirmations from maize and wheat-based systems propose that NT and mulch-based elective culturing can yield both short-term e.g., lessened cost of production, improved crop yields, and enhanced water use efficiency (Yadav et al., 2017), and improved soil quality benefits under long-run (Ladha et al., 2016; Meena et al., 2018). Nevertheless, there is significantly less response of NT in rice based cropping systems, rehearsed transcendently by smallholder farms (Babu et al., 2014; Yadav et al., 2017). Further, information on energy use and reduction CF with the adoption of NT and mulches in directly seeded rice-mustard are not available. Further, reducing fossil fuel consumption and dependency on agro-chemicals may reduce energy input, decrease GHGemissions, reduce the cost of cultivation and enhance the nutrient use efficiency (Johnson et al., 2005; Liebig et al., 2005;

Meena et al., 2017a) in agricultural production systems. Hence, it is important to evaluate the effects of tillage and mulching practices on C flow, energy use and economic parameters to better understand the CF and identify site-specific systems for reducing GHGs released into the atmosphere while also increasing the farm income (Meena and Yadav, 2017; Lu and Liao, 2016).

Thus, the present study was conducted to test the hypothesis that NT in conjunction with residue retention and mulch enhances the EUE, reduces the CF and cost of production without jeopardizing the system productivity as compared to those for theCT-based production system, and provides a clean and environmentally sustainable production technology for the upland ecosystemsof Eastern India. The specific objectives of the study were to: 1) evaluate the energy use and CF of NT and mulch-based farming of upland rice-mustard system, and 2) study the economic feasibility of NT and mulch system over CT system foran upland rice-mustard cropping system. Hence, the present study is designed to enhance the understanding of theCF and GWP of NT and mulch farming relative to the traditional tillage-based farming practices. The data generatedwould contribute to identifying C-neutral farming operations for a cleaner environment. Thus, the small and marginal resource-poor farmersin the fragile hill ecosystems of the region (and elsewhere in the world) would adapt to the changing climateby adoption of clean and sustainable technologies. The findings of the present study may also be important to the policymakers in designing/adaptingthe low-C sustainable rice production systems worldwide in general and in ecologically fragile upland ecosystems in particular, and in regions with predominantly resource-poor farmers which are vulnerable to climate change. The novelty of the study is that integrated effect of NT, diverse mulches and cropping system effect have been considered together as conservation effective measure for sustainable and clean agricultural production practice over those of CT based technologies which are responsible for high GHGs emission. Such technologies are lowcost in nature and easy to adopt and specially suitable for the small and marginal farmers having low resources and adaptation capacities.

2. Materials and methods

2.1. Experimental site and climate

A four-year field experiment was established during 2012–16 to assess the energy budget, CF and economic feasibility of different tillage and mulching practices under rice–mustard system. The experiment was sited at the research farm of the Indian Council of Agricultural Research (ICAR) Research Complex for North Eastern Hill (NEH) Region, Tripura Centre, Lembucherra, Tripura, India. The site is located at 23°54′24.02″ N and 91°18′58.35″E at an altitude of 52 m above sea level. The annual average rainfall of the region is 2200 mm. The soil (*Typic Kandihumults*) of the experimental site is clay loam, deep and free from gravels and hardpan (Yadav et al., 2015). Soil samplesfor baseline analyses were obtained from 0 to 30 cm depth at 10 cm interval from 10 randomly selected spots, and were composited into three samples for each depth. Based on the analysis of the baseline soil sample (0–30 cm depth) following the standard procedure (Prasad et al., 2006), the soil had 5.9 g/kg of organic C, 130.3 mg/kg available N, 24.4 mg/kg available P, 135.7 mg/kg available potassium (K) and pH of 5.2 (1:2.5, soil and water ratio).

2.2. Experimental details

The experiment was laid out in a split-plot design, with tillage and residue management as main-plots and type of mulches as sub-plots with three replications. Thus, in total, there were six main-plots and 24 sub-plots. The size of sub-plot was 4.5 × 2.9 m. The tillage treatments included:1) CT-RI: CT with 100% residue incorporation (RI) and 2) NT-RR: NT with 100% residue retention (RR). The mulch type consisted of: 1) rice straw mulch (SM), 2) green manure mulch (GM) with *Gliricidia* sp. 3) brown manuring mulch (BM) of Cowpea (*Vigna unguiculata*), and 4 no mulch (NM). Residues of the respective crops were retained on the surface after harvest under NT plots, but were incorporated into the soil under CT. Tillage treatments were applied in both rice (summer) and mustard (winter) crops. However, mulch treatments were applied only in rice at the time of sowing. The rate of mulch application was 2.5 Mg/ha for SM on the dry weight basis, and GM was applied by the cut and carry methods. The leaves and twigs (discarding woody portions) of *Glyricidia* spp *(*ashrub) was cut and carried from *Cocotila* farm of the institute and applied at the rate of 2.5 Mg/ha on the dry weight basis. Under BM, a row of cowpea was sown in between every two rows of rice with a seed rate of ~10 kg/ha. Cowpea was killed by spraying 2,4-D (0.5 kg a.i./ha) at 40 days after sowing (DAS), and the dead biomass was retained on the soil surface as a mulch. A constant amount of mulch (2 Mg/ha) was maintained in all plots under BM by adding the cowpea biomass from the nearby general plots outside the experiment. In the main-plots, disc harrowing was done with the tractor-drawn disc harrow (about 20 cm depth), followed by tilling with power tiller and leveling in the case of CT. In NT, however, soil disturbance was limited only to the manual opening of small furrow (with a long-handled two tyne furrow opener) for seeding. One week before seeding the NT plots, glyphosate was applied at the rate of 5 ml/L for weed control. Further, pre-emergence herbicide, pendimethalin was applied at the rate of 1 kg/ha in both crops (rice and mustard within 2 DAS.). The popular high yielding upland rice variety “Sahbhagi” and short duration (85–95 days) mustard variety “TRCT-1-5-1-1” were cultivated following the standard cultural practices. Rice was sown during the 2nd fortnight of June and harvested during the 2nd fortnight of October. Mustard was sown during the 1st fortnight of November and harvested during the last week of February to 1st week of March for each of the 4 years of experimentation.

2.3. System productivity

System productivity in term of the rice equivalent yield (REY) was estimated to compare the effects of different tillage and mulches on crop performances by converting the grain yield of both crops into the equivalent yield of rice on the basis of market price by using Eq (1):

$$\mathrm{REY_p} = \textit{Rice yield} + \left(\mathrm{MY} \times \frac{\mathrm{M}_p}{\mathrm{R}_p}\right) \tag{1}$$

The energy coefficient was estimated by using the Eq.2;

$$\mathrm{REY_e} = \textit{Rice yield} + \left(\mathrm{MY} \times \frac{\mathrm{M}_{ec}}{\mathrm{R}_{ec}}\right) \tag{2}$$

where, REYp is the REY based on price; MY is the mustard yield (Mg/ha); $\mathrm{M_p}$ is the mustard price, and $\mathrm{R_p}$ is the market price of rice. REYe is the REY based on energy; MY is the mustard yield (Mg/ha); $\mathrm{M_{ec}}$ is the energy coefficient of mustard seed, and $\mathrm{R_{ec}}$ is the energy coefficient of rice grain.

2.4. Economic analysis

The economic analysis of different systems was computed by assessing a range of components including the cost of cultivation, gross revenue, and net returns. These components were calculated on the basis of the prevailing market price of the input, output, and services.

Gross revenue was computed by multiplying the main and byproduct of crops with prevailing market price andthe net returns were computed by subtracting the cost of cultivation from the gross revenue.

2.5. *Energy analysis*

The analysis of energy balance in the study was performed by comparing the energy input and output of two tillage and four types of mulches under different inputs and management intensities. Energy fluxes were estimated by using crop management (i.e., types of input, their quantity, and machinery/manual labor used and their duration) and productivity (grain yield) data. To estimate the energy input and output of each treatment, a complete record of all inputs (seeds, fertilizers, agro-chemicals, fuel, human and machinery power) were maintained (Table 3), and outputs (main produce) were systematically itemized. Energy value of every treatment was established based on energy input and output for each crop. Input and output were computed from physical units to energy units through multiplication with the conversion coefficients (Table 1). The energy equivalents of input and output indices; the energy use efficiency (EUE), energy productivity (EP), specific energy and net energy were calculatedby Eqs (3)–(8) (Chaudhary et al., 2017).:

$$\text{Energy input } = \sum_{i=1}^{n} (\text{C1} + \text{C2} + \ldots \text{Ci}) \tag{3}$$

$$\text{Energy output } = SP \times E \tag{4}$$

$$\text{Net energy} = \text{EOP} - \text{EI} \tag{5}$$

$$\text{EUE} = \frac{\text{EOP}}{\text{EI}} \tag{6}$$

$$\text{EP} = \sum_{i=1}^{n} (\text{SP}/\text{EI}) \tag{7}$$

$$\text{SE} = \sum_{i=1}^{n} (\text{EI}/\text{SP}) \tag{8}$$

Table 1
Energy equivalents of inputs and outputs in agricultural production in relation to presented study.

Particulars	Units	Equivalent energy (MJ)
Input		
Human labor	Hour	1.96
Diesel	Liter	56.31
Farm machinery	kg	62.7
Chemical fertilizer		
N	kg	60.6
P_2O_5	kg	11.1
K_2O	kg	6.7
Plant protection chemicals	Liter	120
Plant products		
Rice grain	kg	14.7
Mustard seed	kg	22.72
Stover	kg	12.5

Source: Datta et al. (2014) and Yadav et al. (2017).

Table 2
Emission factors of agriculture inputs used in the estimation in presented study.

Particulars	Units	kg CO_2e/unit	References
Human labor	Day	0.86	Deng (1982)
Diesel	Liter	3.32	Deng (1982)
Farm machinery	Hr	3.32	Deng (1982)
Chemical fertilizer			
N	kg	4.96	Lal (2004)
P_2O_5	kg	1.35	Lal (2004)
K_2O	kg	0.58	Lal (2004)
Plant protection chemicals			
Fungicide	Liter	3.9	Lal (2004)
Herbicide	Liter	6.3	Lal (2004)
Insecticide	Liter	5.1	Lal (2004)
Seeds	kg	1.22	Wang et al. (2015)

Table 3
Agriculture inputs and services used under different tillage and mulching practices in rice-mustard systems.

Treatment	CT-RI				NT-RR			
	SM	GM	BM	NM	SM	GM	BM	NM
Manpower (Days)	226	234	208	206	221	229	203	201
Machine power (Hr)	102	102	101	101	5	5	4	4
Seed (kg)								
Rice	50	50	50	50	50	50	50	50
Cowpea	0	0	10	0	0	0	10	0
Mustard	5	5	5	5	5	5	5	5
Fertilizer (kg)								
Nitrogen	120	120	120	120	120	120	120	120
Phosphorus	80	80	80	80	80	80	80	80
Potassium	80	80	80	80	80	80	80	80
Chemicals								
Fungicide	2	2	2	2	2	2	2	2
Herbicide	2	2	2.7	2	8	8	8.7	8
Insecticide	2	2	2	2	2	2	2	2
Diesel	106	106	101	101	9	9	4	4
Irrigation (Diesel)	30	30	30	30	30	30	30	30

CT- Conventional tillage; NT-No-till; RI- 100% residue incorporation; RR-100% residue retention; SM-Straw mulch; GM-*Gliricidia* mulch; BM-Brown manuring mulch; NM-No mulch.

where, EI-energy input (MJ/ha); C_1+C_2+ … C_i, energy of each component (MJ/ha); EOP- energy output (MJ/ha); SP-System productivity (kg/ha); EC-energy coefficient; NE- net energy (MJ/ha); EUE-energy use efficiency; EP-Energy productivity (kg/MJ) and SE-Specific energy (MJ/kg).

2.6. *Carbon footprint (CF)*

The environmental impacts of tillage and mulches were assessed by estimating the CF on spatial and yield-scale. Spatial CF is the total amount of GHGs emission (CO_2 and N_2O) released during crop production in terms of CO_2 equivalents (Pratibha et al., 2016). Only CO_2 and N_2O gases were considered in the present study becausethe CH_4 emissions may be negligible under the well-drained upldand conditions where the direct seeded rice was grown without inundation. Further, there was noin-field residue burning in any of the treatments used. Both CO_2 and N_2O were converted into CO_2 equivalent by using the GWP equivalent factors of 1 and 265 on the volume basis for CO_2 and N_2O, respectively, for the time frame of 100 years (IPCC, 2013). The GHGs emission from farm operations (tillage, herbicide application, pesticide, planting and fertilizer application, harvest, etc.) and for the production of fertilizer and seeds were calculated as per the standard inputs with the corresponding emission coefficients as presented in Table 2 (Deng, 1982; Lal, 2004; Wang et al., 2015; West and Marland, 2002).

The N_2O emission from applied N fertilizer, manure, and crop

Table 4
Effect of different tillage and mulches on yield attributes and yields of upland direct-seeded rice.

Treatment	Productive tillers/m^2 (mean of four years)	Grain/panicle (mean of four years)	1000 grain weight (g) (mean of four years)	Grain yield (Mg/ha)			
				2012	2013	2014	2015
Tillage							
CT	235.1	85.6	22.5	3.05	2.98	3.10	3.08
NT	232.1	87.5	22.5	2.86	2.90	3.20	3.40
SEm±	3.5	0.2	0.1	0.07	0.12	0.12	0.11
LSD ($p = 0.05$)	NS	NS	NS	NS	NS	NS	NS
Mulch							
SM	229.6	81.5	22.1	2.80	2.84	3.05	3.13
GM	244.9	101.6	24.0	3.47	3.25	3.46	3.54
BM	236.1	88.3	22.8	2.98	3.02	3.23	3.27
NM	223.8	74.8	21.1	2.57	2.65	2.86	3.00
SEm±	6.0	1.1	0.7	0.14	0.15	0.15	0.13
LSD ($p = 0.05$)	18.4	3.4	2.1	0.43	0.45	0.45	0.40

CT- Conventional tillage; NT-No-till; RI- 100% residue incorporation; RR-100% residue retention; SM-Straw mulch; GM-*Gliricidia* mulch; BM-Brown manuring mulch; NM-No mulch.

residue was calculated by Eq (9) (Tubiello et al., 2015).

$$N_2O \text{ emissions} = \text{N applied through synthetic fertilizer, manure, and crop residues} \times EF_1 \times 44/28 \quad (9)$$

where, N_2O emissions = N_2O emissions from synthetic N/manure, crop residue additions to the managed soils, kg N_2O/year; N = Consumption of N from fertilizers, manure, crop residue, etc., kg N input/year; EF_1 = Emission factor 0.01 for N_2O emissions from N inputs, kg N_2O–N/kg N input.

Global warming potential (GWP) calculated with data from CO_2 and N_2O emission by using Eq. (10):

$$GWP = (\text{emission of } N_2O \times 265) + \text{emission of } CO_2 \quad (10)$$

CF was calculated by using Eqs. (11) and (12) (Pandey and Agrawal, 2014):

$$CFs = \sum_{i=1}^{n} GWP \quad (11)$$

$$CFy = \frac{CFs}{System\ productivity} \quad (12)$$

where, CFs is the spatial carbon footprint (kg CO_2-e/ha); CFy is yield-scaled carbon footprint (kg CO_2-e/Mg system productivity).

2.7. Carbon output, carbon efficiency, and carbon sustainability index

Total C output is the sum of the C equivalent of grains, straw and root biomass produced by the crop. The below-ground root biomass was estimated from the shoot: root ratio of paddy rice and mustard (Chaudhary et al., 2017). Total C present in biomass was estimated by multiplying the yield with 40% C, as it was assumed that biomass contains 40% C (Chaudhary et al., 2017). Carbon efficiency (CE) was calculated as the ratio of C output to C input, whereas C sustainability index (CSI) was estimated by computingthe difference between C output and C input and dividing it by C input (Lal, 2004; Chaudhary et al., 2017).

2.8. Statistical analysis

Statistical analyses of the data were performed using the GLM procedure of SAS 9.4 (SAS Institute, 2003) to analyze variance and to determine the statistical significance of the treatment effects. The least significant difference (LSD) at $p = 0.05$ was used to compare treatment means.

3. Results and discussion

3.1. Productivity

Yield parameters [e.g., productive tillers/m^2, the number of grains per panicle and 1000-grain weight (g)] and grain yield of rice

Table 5
Effect of different tillage and mulches on yield parameters and yield of mustard.

Treatment	Branches/plant (mean of four years)	Pods/plant (mean of four years)	Pod length (cm) (mean of four years)	Seeds/pod (mean of four years)	Seed yield (kg/ha)			
					2012–13	2013–14	2014–15	2015–16
Tillage								
CT	21.3	312.3	5.3	18.3	1038.0	1066.9	1094.9	1122.5
NT	19.6	304.8	5.1	18.2	961.0	990.4	1017.1	1062.4
SEm±	0.5	6.3	0.1	0.2	23.6	23.6	23.7	19.9
LSD ($p = 0.05$)	NS	NS	NS	NS	NS	NS	NS	NS
Mulch								
SM	20.6	303.3	5.1	18.0	995.2	1024.1	1050.1	1094.2
GM	21.3	325.7	5.3	19.0	1024.9	1053.9	1080.4	1167.2
BM	21.0	317.6	5.2	18.4	1021.5	1050.6	1078.8	1098.9
NM	18.8	287.6	5.1	17.6	906.4	906.0	914.6	909.4
SEm±	0.7	8.3	0.1	0.5	35.0	36.2	35.4	29.1
LSD ($p = 0.05$)	2.0	25.5	NS	1.5	105.6	108.4	106.2	87.3

CT- Conventional tillage; NT-No-till; RI- 100% residue incorporation; RR-100% residue retention; SM-Straw mulch; GM-*Gliricidia* mulch; BM-Brown manuring mulch; NM-No mulch.

Table 6
Effect of different tillage and mulches on average (four year) cost of cultivation of upland rice-mustard cropping system.

Treatment	Cost of cultivation (INR/ha)[a]							
	Labor	Machine	Seed	Fertilizer	Plant protection chemicals	Diesel	Irrigation	Total
Tillage								
CT-RI	34,960	20,400	1800	9280	3088	5796	1680	76,903
NT-RR	34,160	1000	1800	9280	6088	364	1680	54,271
Mulch								
SM	35,760	10,700	1600	9280	4500	3220	1680	66,739
GM	37,040	10,700	1600	9280	4675	3220	1680	68,194
BM	32,880	10,700	2400	9280	4675	2940	1680	64,354
NM	32,560	10,700	1600	9280	4500	2940	1680	63,059

CT- Conventional tillage; NT-No-till; RI- 100% residue incorporation; RR-100% residue retention; SM-Straw mulch; GM-Gliricidia mulch; BM-Brown manuring mulch; NM-No mulch.

[a] 1USD = 64.46 INR.

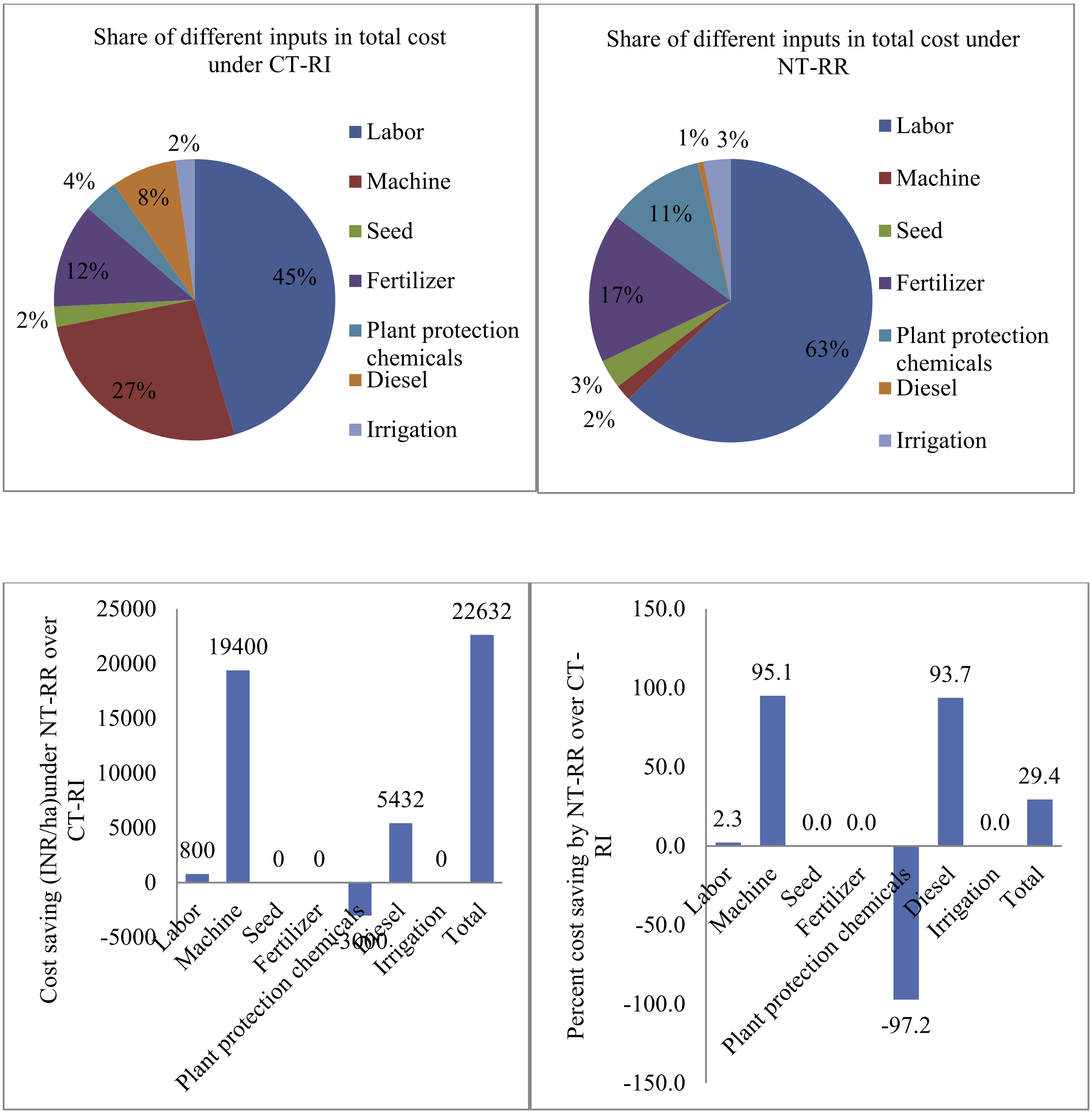

Fig. 1. Share of different component of cost of cultivation and cost saving over respective component under different tillage practices (CT-Conventional tillage; NT-No-till; RI-100% residue incorporation; RR-100% residue retention).

did not significantly differ among tillage practices. However, there was a trend that CT-RI produced somewhat higher rice grain yield than those under NT-RR during the 2012–13. As the experiment duration advanced, the grain yield of rice increased under NT-RR compared with those under CT-RI during the 2014–15 (Table 4). However, some prior experiments have reported a reduction in yield under NT than CT systems, probably due to poor seed germination and low crop stands (Mbah et al., 2010; Yadav et al., 2015). The data presented herein showed no significant differences in grain yield between CT-RI and NT-RR probably due to less weed growth, good profile soil moisture storage, high nutrient availability, high soil organic matter (SOM) content and favorable biological activity under NT plots (Busari et al., 2015). Such favorable growing conditions may have caused a better development of above and below ground biomass, better development of productive tillers and panicles, and a higher rice grain yield (Mbah et al., 2010; Busari et al., 2015). The increase in rice yield during the later years of the experiment under NT management may also be due to improvement in soil structure, favorable water infiltration because of the residue mulch, better root growth and reduced water losses through soil evaporation (Patil et al., 2015; Hosseini et al., 2016). Jemai et al. (2013)also reported that NT based CA enhances crop productivity by improving soil fertility, water retention, and plant available nutrients.

Mulching increased the productive tillers/m^2 from 230 to 244 (mean of four years) as compared to those under NM (224 productive tillers/m^2). Among the mulches, GM produced the maximum productive tillers/m^2 than those under SM, BM, and NM (Table 4). GM also produced the highest number of rice grains per panicle (102) than those under other mulches (82–88 grains per panicle). The number of rice grains per panicle followed the sequence of GM > BM > SM. However, 1000 rice grain weight was also increased with the mulch application. Rice grain yield production followed the order of GM > SM > BM across the years. However, SM and BM did not show any significant differences with respect to rice grain yield (Table 4). Mulching also reduced the weed density and increased the profile soil moisture storage, which probably improved the yield parameters such as productive tillers and grains per panicle and thus enhanced the grain yield of rice (Choudhary et al., 2013). In general, mulch promotes crop development by recycling plant nutrients through its gradual decomposition (Zhao et al., 2014). In addition, mulch application increases the SOM content, reduces bulk density, improves soil porosity and aeration (Duiker and Lal, 1999; Tejada et al., 2008), increases water stable aggregates, and enhances formation of biopores which improve plant growth and development (McConnell et al., 1993; Rasool et al., 2008). The data presented (Table 4) indicated that the rice grain yield was better with the GM than that under SM probably because of favorable edaphic environments for plants and supply of additional N as GM had 2.5% N content (Kumar et al., 2013).

The data on four year mean values of mustard yield parameters, and seed yields showed no significant differences among tillage practices. Despite the lack of statistical significance, there was a general trend indicating that CT-RI had relatively higher number of branches per plant (21.3), number of pods per plant (312), pod length (5.3 cm) and number of seeds per pod (18) than those under NT-RR. Similar to yield parameters, there was also a general trend of relatively more mustard seed yield under CT-RI than that under NT-RR across all the years, but without any statistically significant differences (Table 5). Residue left on the surface under NT-RR might have hindered the emergence of tender mustard seedlings, and affected the subsequent crop stand, growth, and productivity, while residue incorporation under conventional tillage might have favored the growth. Similar results of the hindrance in emergence due to residue retention have been reported by other researchers (Chen et al., 2004; Dam et al., 2005). The increase in crop yield under a conventional system with residue incorporation has been attributed to better root growth and increased water use (Saha et al., 2010; Shekhawat et al., 2016). Similarly, a decrease in yield under NT-RR might be attributed to increased soil strength and consequently retardation in root growth and reduction in water utilization from deeper layers (Saha et al., 2010). The mustard seed yield also increased over time from 1038 to 1122 kg/ha under CT-RI compared to 961 to 1062 kg/ha under NT for 2012–13 to 2015–16. The residual effects of GM and BM were significant over that of the NM with regards to the yield attributes of mustard. The residual effect of GM and BM significantly increased the number of branches per plant, the number of pods per plant, pod length and number of seeds per pod compared to those underNM plots (Table 5). Mustard grown on residual effect of GM and BM had 13–28% and 12–21% higher seed yield, respectively, compared to the seed yield achieved under NM across the years (Table 5). Availability of soil moisture for a longer period due to mulching might have played a key role in boosting yield characteristics (Sarkar et al., 2007). Further, as the experiment progressed, the seed yield of mustard increased because of the positive residual effects of mulch. The cumulative effects of GM and BM increased the mustard seed yield by 14 and 7.5% in 2015–16 over those obtained in 2012–13, respectively.

Table 7
Effect of different tillage and mulches on average (four year) system productivity, gross return, net return and benefit: cost ratio of upland rice-mustard cropping system.

Treatment	System productivity (REY Mg/ha by price)[a]	Gross return from rice grain (INR/ha)[a]	Net return from rice grain (INR/ha)[a]	B:C Ratio
Tillage				
CT-RI	7.37	113,633	36,730	1.48
NT-RR	7.12	109,918	55,647	2.03
SEm±	0.17	2604	2604	0.04
LSD ($p = 0.05$)	NS	NS	15,624	0.24
Mulch				
SM	7.11	109,704	42,964	1.64
GM	7.76	119,812	51,618	1.76
BM	7.38	113,776	49,422	1.77
NM	6.74	103,809	40,750	1.65
SEm±	0.30	4635	4635	0.10
LSD ($p = 0.05$)	0.93	14,283	14,283	0.30

CT- Conventional tillage; NT-No-till; RI- 100% residue incorporation; RR-100% residue retention; SM-Straw mulch; GM-*Gliricidia* mulch; BM-Brown manuring mulch; NM-No mulch.

[a] 1USD = 64.46 INR.

Table 8
Effect of different tillage and mulches on average (four year) energy inputs of upland rice-mustard cropping system.

Treatment	Energy input (MJ/ha)							
	Labor	Machine	Seed	Fertilizer	Plant protection chemicals	Diesel	Irrigation	Total
Tillage								
CT-RI	3427	6364	886	8696	741	5828	1689	27,630
NT-RR	3348	282	886	8696	1461	366	1689	16,727
Mulch								
SM	3505	3354	849	8696	1080	3238	1689	22,411
GM	3630	3354	849	8696	1080	3238	1689	22,536
BM	3223	3291	996	8696	1164	2956	1689	22,015
NM	3191	3291	849	8696	1080	2956	1689	21,753

CT- Conventional tillage; NT-No-till; RI- 100% residue incorporation; RR-100% residue retention; SM-Straw mulch; GM-*Gliricidia* mulch; BM-Brown manuring mulch; NM-No mulch.

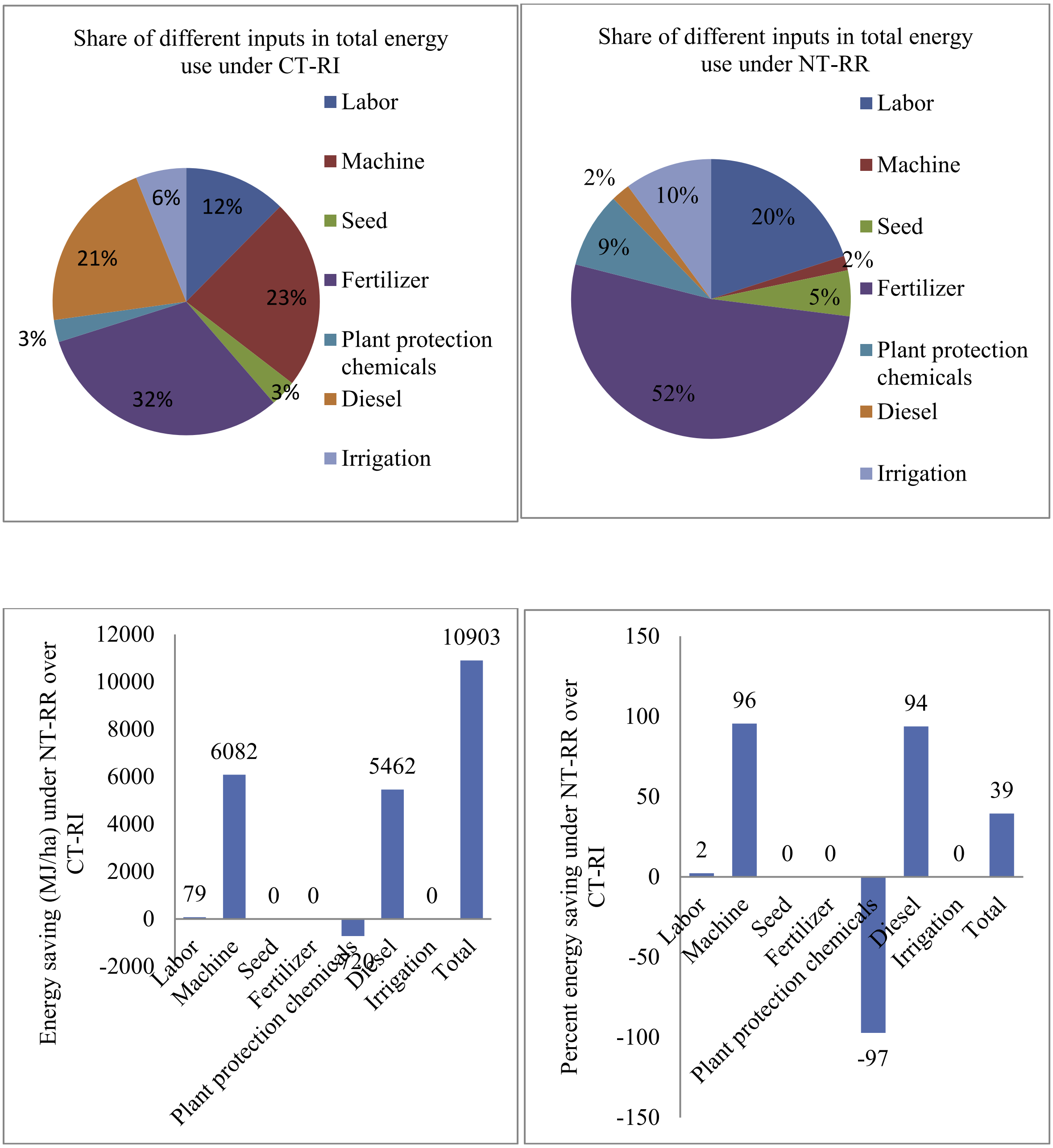

Fig. 2. Share of different component of energy and energy saving over respective component under different tillage (CT- Conventional tillage; NT-No-till; RI- 100% residue incorporation; RR-100% residue retention).

3.2. Economics

The four year mean expenditure incurred on the cultivation of direct-seeded upland rice-mustard cropping system under CT-RI [INR 76,903/ha, (INR is Indian rupees and 1 U.S. $ = 64.46 INR in December 2017)] was substantially higher than that under NT-RR (INR 54,271/ha) (Table 6). The order of the different components of cost analysis was different under two tillage systems (CT-RI and NT-RR). Cost incurred for different component of cost analysis for CT-RI followed the order of labor > machine > fertilizer > diesel > plant protection chemicals > seed > irrigation (Table 6). The order and share of different components was changed under NT-RR because of reduction in the cost involved in machine operations by 95.1% (INR 19,400/ha), diesel by 93.7% (INR 5432/ha), and labor by 2.3% (INR 800/ha), and increase in cost of plant protection chemicals by 97.2% (INR 3000/ha) compared with thoseunder CT-RI. The adoption of NT-RR reduced the cost of cultivation of direct-seeded upland rice-mustard cropping system by 29.4% (INR 22,632/ha) over that for the CT-RI (Fig. 1). The reduction in the cost of cultivation was primarily due to the exclusion of plowing and leveling expenses under NT-RR. Mulching increased the cost of cultivation by 2–8% (INR 1295–5135/ha) compared with incurred under the NM. The increase in the cost of cultivation was higher under GM followed by that for the SM because of more labor for carrying and application of mulch materials.

The gross revenue was higher under CT-RI than that under NT-RR because of higher system productivity in this treatment. However, the gross revenue did not statistically differ among CT-RI and NT-RR (Table 7). Mulching also increased the gross revenue compared with thatobtained under the NM, and followed the trend of GM > BM > SM application. The higher gross revenue under mulch treatments was primarily due to the higher yield of rice and mustard under mulch than those under NM plots (Table 5). Net returns were significantly higher under NT-RR (INR 55,647/ha) than those under CT-RI (INR 36,730/ha). The net return of the system under NT-RR was 1.5 times higher than that for the CT-RI (Table 7). The higher net return for NT-RR was attributed to the lower cost of cultivation under than that under CT-RI. Mulching also increased the net returns over those of the NM plots. The GM treated plots recorded the higher net returns (INR 51,618/ha) as compared to those obtained under other treatments. Despite the high cost of cultivation under GM and BM, higher net returns were due to higher gross revenue and the system productivity (Table 7).

Economics, particularly the net returns, is an important decision-making tool on the composition of enterprise, management options, and in the assessment of the profitability, energy requirement and CF of a system (Choudhury et al., 2016). Higher net returns under NT-RR in the present study suggest that the CA technology is profitable with respect to per unit return because of the low cost of cultivation and no yield difference between NT-RR and CT-RI. Higher net returns with GM suggest that, despite the initial additional labor/cost, these measures are still profitable concerning per unit return because of higher gross revenue and system productivity (Choudhury et al., 2016). Thus, efficient utilization of resources (i.e., energy, water, human labor) through NT-RR and mulch application in rainfed hill agriculture arefeasible options to increase crop productivity and profitability, while providing a clean and safe environment to the rural resource-poor farming community in India (Choudhury et al., 2016; Mukherjee, 2010). Therefore, CA (i.e., NT with residue retention and mulch application) is a suitable option for reducing the cost of production, increasing crop productivity, and improving profitability. Similar observations on the low cost of production and higher net returns under NT than CT based systems were previously reported by Ghosh et al. (2015).

3.3. Energy budget

The machine operation and diesel consumption are the major energy requiring components of any production systems (Yadav et al., 2017). Therefore, it is necessary to reduce the use and consumption of these components in the production system to overcome the growing energy demands in agriculture. In the present study, NT-RR reduced the energy requirement from 27,630 MJ/ha under CT-RI to 16,727 MJ/ha (Table 8). The reduction in energy input under NT-RR system is mainly because of the exclusion of tillage operations, which consumed a major part of energy inputs used under CT-RI because intensive tillage operations accounted for higher machinery use and fossil fuel consumption (Pratibha et al., 2015). Other researchers (Houshyar et al., 2015; Pratibha et al., 2015) also reported the lower energy input under NT-RR system than those used under CT-RR. Besides fossil fuel consumption, minimum intercultural and manual weeding operations also contributed to the reduction of energy use under NT-RR (Küsterman et al., 2013). Overall, adoption of NT-RR saved 10,903 MJ/ha energy (~39%) over that used under CT-RI (Fig. 2). The reduction in energy requirement under NT-RR was mainly due to change in energy consumption pattern for the machinery use and diesel consumption. A total of 6082 MJ/ha (~96%) of energy was saved by the reduction in machine operations under NT-RR over the energy used for the same component under CT-RI (Fig. 2). Similarly, diesel energy use was also reduced by 94% (5462 MJ/ha) under NT-

Table 9

Effect of different tillage and mulches on average (four year) system productivity, energy output, net energy, energy use efficiency, energy productivity and specific energy of upland rice-mustard cropping system.

Tillage	System productivity (REY by Energy-Mg/ha)	Energy output (MJ/ha)	Net energy (MJ/ha)	Energy use efficiency	Energy productivity (kg/MJ)	Specific energy (MJ/kg)
CT-RI	4.72	69,384	41,754	2.51	0.17	5.93
NT-RR	4.65	68,332	51,604	4.08	0.28	3.62
SEm±	0.05	723	723	0.04	0.006	0.05
LSD ($p = 0.05$)	NS	NS	4402	0.24	0.02	0.31
Mulch						
SM	4.56	67,060	44,649	3.23	0.22	5.03
GM	5.10	75,028	52,492	3.48	0.24	4.39
BM	4.77	70,103	48,088	3.37	0.23	4.60
NM	4.30	63,243	41,490	3.10	0.21	5.07
SEm±	0.15	2237	2237	0.11	0.01	0.14
LSD ($p = 0.05$)	0.47	6892	6892	NS	NS	0.44

CT- Conventional tillage; NT-No-till; RI- 100% residue incorporation; RR-100% residue retention; SM-Straw mulch; GM-*Gliricidia* mulch; BM-Brown manuring mulch; NM-No mulch.

Table 10
Effect of different tillage and mulches on average (four year) carbon footprint of upland rice-mustard cropping system.

Treatment	Carbon footprint (CO_2-e kg/ha)							CFy (CO_2-e kg/Mg)
	Diesel	Fertilizer	Plant protection chemicals	Seed	Labor	N_2O from farm	Total	
Tillage								
CT-RI	443	750	31	67	188	825	2307	313
NT-RR	115	750	69	67	184	826	2013	283
Mulch								
SM	287	750	49	67	192	739	2085	293
GM	287	750	49	67	199	993	2346	302
BM	271	750	54	67	177	894	2224	301
NM	271	750	49	67	175	674	1986	295

CT- Conventional tillage; NT-No-till; RI- 100% residue incorporation; RR-100% residue retention; SM-Straw mulch; GM-*Gliricidia* mulch; BM-Brown manuring mulch; NM-No mulch, CFy: Carbon footprint on yield scale.

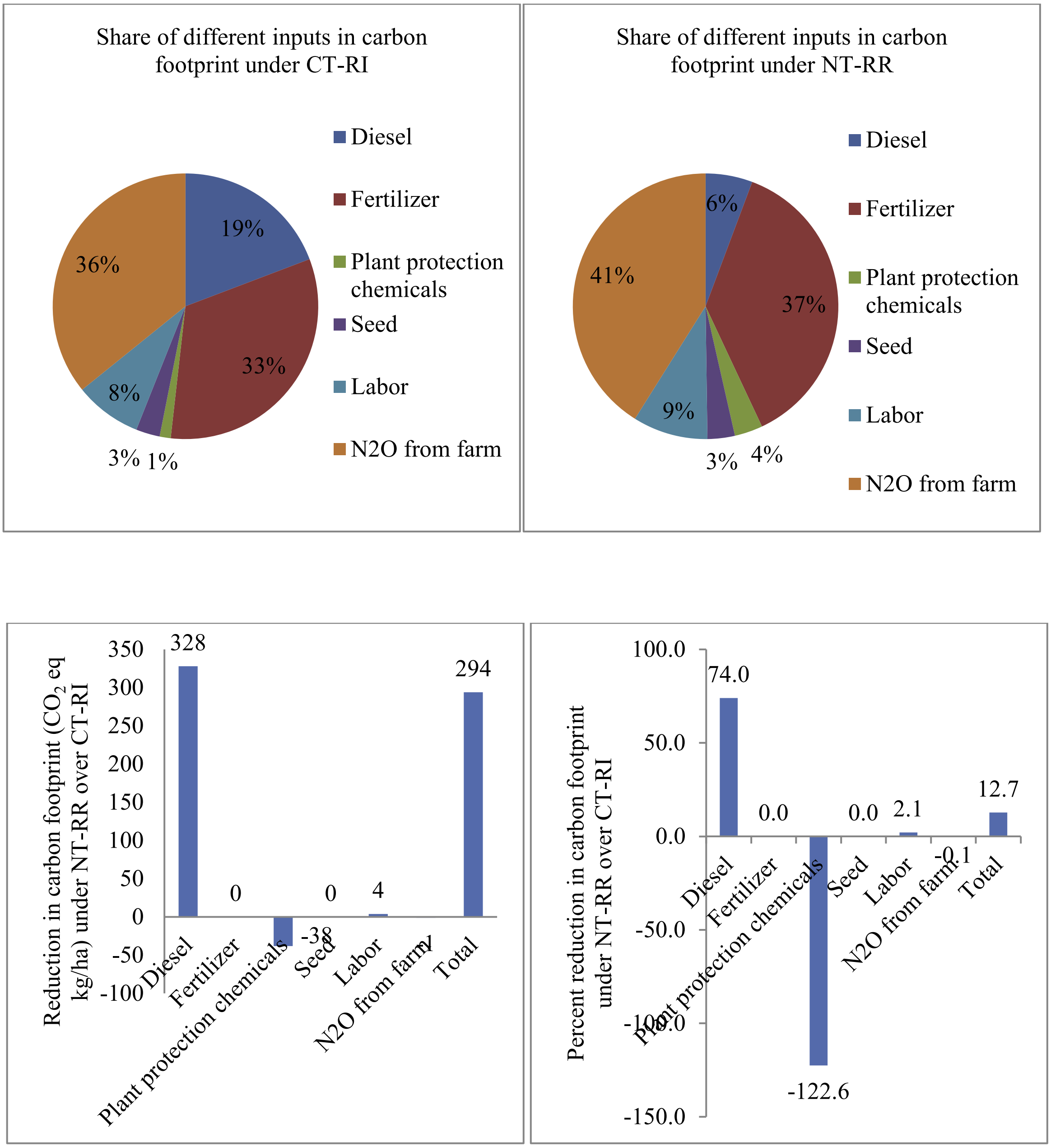

Fig. 3. Share of different inputs of component carbon footprint and reduction in carbon footprint under different inputs (CT- Conventional tillage; NT-No-till; RI- 100% residue incorporation; RR-100% residue retention).

RR over those used for different operations under CT-RI. However, adoption of NT-RR slightly increased the energy used for plant protection chemicals as compared to those for CT-RI. In general, the order of energy use by different inputs under CT-RI was fertilizer > machine > diesel > labor > irrigation > seed > plant protection chemicals, and differed from input energy use order of NT-RR: fertilizer > labor > irrigation > plant protection chemicals > seed > diesel > machine (Fig. 2). Mulching increased the energy use and followed the order of GM > SM > BM application (Table 8). The increase in energy use with mulch application might be due to a concomitant increase in labor, machine and diesel use for cut, carrying and spreading of mulches.

The energy-based system productivity, EOP, NE, EUE, EP, and SE are the important indicators for efficient management of energy resources of an agricultural production system. Energy-based system productivity and EOP from the system were not affected by the tillage systems (Table 9). NE and EUE are important indicators for planning and designing the production system. These indicators also help in decision making regarding enterprize composition and adoption of management practices, and most importantly in assessing the feasibility of energy requirements of a production system. In the present study, plots managed under NT-RR had the higher NE (51,604 vs. 41,754 MJ/ha), EUE (4.08 vs.2.51) and EP (0.28 vs.0.17 yield kg/MJ) as compared to those under CT-RI (Table 9). Similar observations on NE, EUE, and EP under NT were also reported by Pratibha et al. (2015). Barut et al. (2011)reported higher EUE in NT as compared to that under CT. However, SE use was higher under CT-RI (5.93 MJ/kg) than that under NT-RR (3.62 MJ/kg). Mulch application increased the system productivity (4.56–5.10 vs. 4.30 REY Mg/ha), EOP (67,060–75,028 vs. 63,243 MJ/ha), NE (44,649–52,492 vs. 41,490 MJ/ha), EUE (3.23–3.48 vs. 3.10), EP (0.22–0.24 vs. 0.21 kg/MJ) and decreased the SE (5.03–4.39 vs. 5.07 MJ/kg) as compared to those under the NM treatments (Table 9). In the present study, the mulch application increased the EOP which was significantly higher than that under NM. These findings are in accord with those reported by Goglio et al. (2014) and Pratibha et al. (2015).

3.4. *Carbon footprint*

The data on analysis of different subsystems to the emission of GHGs, performed to assess the influence of different factors on GHGs emissions under different tillage and mulch systems, indicated that CO_2-emissions from N_2O based estimation contributed the maximum followed by that by the fertilizer use in both the tillage systems (Table 10). The difference in CF between CT-RI and NT-RR were attributed to the emission from fuel and the input of plant protection chemicals. The data on CO_2-e/ha indicated that NT-RR emitted 328 kg (~74%) less GHGs from diesel than those emitted under the CT-RI. However, CO_2-e emission was slightly increased with the application of plant protection chemicals under NT-RR as compared to those under CT-RI (Fig. 3). Other researchers (Harada et al., 2007; Pratibha et al., 2015) also reported that NT haslow GHGs emissions as compared to those under CT. CO_2-e emission from N_2O (N from fertilizer, crop residues, root, and mulch) contributed most to the total GWP, which was approximately 41 and 36% followed by that through fertilizer use as 37 and 33% under NT-RR and CT-RI, respectively (Fig. 3). Diesel consumption was the third most important contributor to GWP under CT-RI, but these values changed with the adoption of NT-RR system. The total CO_2-e emission was higher under CT-RI (2307 kg CO_2-e/ha) as compared to those under NT-RR (2013 kg CO_2-e/ha). The differential GWP between NT-RR and CT-RI was due to the difference in the quantity of diesel consumed. The lowest GWP under NT-RR was due to savings of fossil fuel from less number of tillage operations and also low emissions associated with energy consumed in manufacture, transport, repair and use of machines (Pratibha et al., 2015). Mulching increased the CO_2-e emissions as compared to those under the NM (Table 10). Among the mulches, GM and BM caused higher CO_2-e emission as compared to those under SM and NM. This increase in GWP was due to the addition of N- rich residues as mulch. Gan et al. (2009) and Goglio et al. (2014)observed similar increase in GWP with an increase in the quantity of residues as compared to no residue. The variation in CO_2-e emission under different mulch treatment was mainly due to N_2O based CO_2-e emission because GM and BM had higher N_2O based CO_2e emission as compared to that for the SM and NM (Table 10). The CF in respect of yield (CFy) had a different trend than those of CF in respect of space. CT-RI recorded the higher CFy (313 CO_2-e kg/Mg REY) as compared to those under NT-RR (283 CO_2-e kg/Mg REY). Among the mulches, GM and BM had higher CFy as compared to those under the SM and NM (Table 10).

Table 11

Effect of different tillage and mulches on average (four year) carbon input, carbon output, carbon efficiency and carbon sustainability index of upland rice-mustard cropping system.

Treatment	Carbon input (kg/ha)	Carbon output (kg/ha)	Carbon efficiency	Carbon sustainability index
Tillage				
CT-RI	629	5668	9.01	8.01
NT-RR	549	5672	10.36	9.36
SEm±	0	25	0.04	0.04
LSD ($p = 0.05$)	0	NS	0.22	0.22
Mulch				
SM	569	5674	10.06	9.06
GM	640	5965	9.33	8.33
BM	607	5729	9.49	8.49
NM	542	5312	9.86	8.86
SEm±	0	85	0.14	0.14
LSD ($p = 0.05$)	0	262	0.45	0.45

CT- Conventional tillage; NT-No-till; RI- 100% residue incorporation; RR-100% residue retention; SM-Straw mulch; GM-*Gliricidia* mulch; BM-Brown manuring mulch; NM-No mulch.

Averaged over four years, C input and output differed among both tillage systems. NT-RR system required lower C input (549 kg/ha) and produced more C output (5672 kg/ha) as compared to those under the CT-RI (Table 11). In the context of the global climate change and anthropogenic emissions of GHGs into the atmosphere, sustainability of a production system increases with increase in use efficiency of C-based inputs (Lal, 2004). Averaged across years, CE (10.36) and CSI (9.36) were higher under NT-RR system than those of under CT-RI (Table 11). Several other researchers (Dubey and Lal, 2009; Pratibha et al., 2015) also reported a significant effect of tillage practices on CE and CSI. This higher CSI and CE in NT was due to higher C output (grain yield) even with lower C input, and the C input was higher under CT than that under NT (Pratibha et al., 2015). Application of mulches on soil surface increased the C input (569–640 vs. 542 kg/ha) and output (5674–5965 vs. 5312 kg/ha) in the system as compared to NM plots. However, CE and CSI were higher under SM as compared to other mulch treatments and NM plots (Table 11). The application of residue or mulches on soil increased the C output, CE and CSI as have also been reported by others (Chaudhary et al., 2017; Pratibha et al., 2015).

4. Conclusions

The fossil fuel based CO_2 emissions are major contributors to energy input and GWP in agroecosystems. Hence, the data presented herein quantified the GWP and energy input in agriculture with the adoption of NT and mulches in upland rice-mustard cropping system in India. The adoption of NT-RR reduced the cost of cultivation of direct-seeded upland rice-mustard cropping system by 29.4% and increased net returns by 1.5 times over those obtained under CT-RI. Similarly mulch (BM, GM, SM) application also substantially increased the net returns over NM plots. The NT-RR reduced the energy requirement by 39% relative to that under CT-RI. NT-RR emitted ~74% lesser GHGs from diesel consumption than those under CT-RI. However, total CO_2-e emission was 13% less under NT-RR as compared to CT-RI. Thus, the improving EUE and farmers' income by a system-based CA (NT along with residue retention and mulching) approach may decrease the inputs of non-renewable energy and consequently reduce the emission of GHGs from agroecosystems. Therefore, conversion from CT to CA system can reduce fossil fuel consumption and improve the environmental sustainability. Adoption of mulch-based CA (NT-RR) can save energy, increases EUE, enhance net farm income and reduce the CF and enhancing the food security and environmental quality in the studied ecosystem of India, as well as in similar agro-ecosystems of the world.

Conflict of interest

Note: Confirmed that there is no conflict of interest by the authors.

Acknowledgments

The authors are thankful to the Director of ICAR Research Complex for NEH Region, Umiam, Meghalaya, India, and NICRA (National Innovations on Climate Resilient Agriculture) for providing necessary facilities and financial support to conduct the study.

Abbreviations

GHGs	Greenhouse gases
CO_2-e	Carbon dioxide equivalent
C	Carbon
CF	Carbon footprint
NT	No-till
GWP	Global warming potential
EHR	Eastern Himalayas Region
CT	Conventional tillage
RI	Residue incorporation
RR	Residue retention
GM	Green manure mulch
SM	Rice straw mulch
BM	Brown manuring mulch
NM	No mulch
DAS	Days after sowing
REY	Rice equivalent yield
EI	Energy input
EOP	Energy output
SP	System productivity
NE	Net energy
EUE	Energy use efficiency
EP	Energy productivity
SE	Specific energy
CFs	Spatial carbon footprint
CFy	Yield scaled carbon footprint
CE	Carbon efficiency
CSI	Carbon sustainability index
SOM	Soil organic matter
INR	Indian rupees

References

Ashoka, P., Meena, R.S., Kumar, S., Yadav, G.S., Layek, J., 2017. Green nanotechnology is a key for eco-friendly agriculture. J. Clean. Prod. 142, 4440–4441.

Babu, S., Singh, R., Avasthe, R.K., Yadav, G.S., Chettri, T.K., 2014. Production potential, economics and energetics of rice (*Oryza sativa*) genotypes under different methods of production in organic management conditions of Sikkim Himalayas. Indian J. Agron. 59 (4), 602–606.

Barut, Z.B., Ertekin, C., Karaaga, H.A., 2011. Tillage effects on energy use for corn silage in Mediterranean Coastal of Turkey. Energy 36, 5466–5475.

Bos, J.F., de Haan, J., Sukkel, W., Schils, R.L., 2014. Energy use and greenhouse gas emissions in organic and conventional farming systems in The Netherlands. NJAS Wagening. J. Life Sci. 68, 61–70.

Busari, M.A., Kukal, S.S., Kaur, A., Bhatt, R., Dulazi, A.A., 2015. Conservation tillage impacts on soil, crop and the environment. Int. Soil Water Conserv. Res. 3 (2), 119–129.

Chaudhary, V.P., Gangwar, B., Pandey, D.K., June, 2006. 2006. Auditing of energy use and output of different cropping systems in India. Agric. Eng. Int. CIGR Ejournal VIII. Manuscript EE 05 001.

Chaudhary, V.P., Singh, K.K., Pratibha, G., Bhattacharyya, R., Shamim, M., Srinivas, I., Patel, A., 2017. Energy conservation and greenhouse gas mitigation under different production systems in rice cultivation. Energy 130, 307–317.

Chen, Y., Monero, F.V., Lobb, D., Tessier, S., Cavers, C., 2004. Effects of six tillage methods on residue incorporation and crop performance in a heavy clay soil. Trans. Am. Soc. Agric. Eng. 47, 1003–1010.

Choudhary, V.K., Choudhury, B.U., Bhagawati, R., 2017. Seed priming and in situ moisture conservation measures in increasing the adaptive capacity of rain-fed upland rice to moisture stress at Eastern Himalayan region of India. Paddy Water Environ. 15, 343. https://doi.org/10.1007/s10333-016-0553-z.

Choudhary, V.K., Kumar, P.S., Bhagawati, R., 2013. The response of tillage and in situ moisture conservation on alteration of soil and morpho-physiological differences in maize under Eastern Himalayan region of India. Soil Tillage Res. 134, 41–48.

Choudhury, B.U., Fiyaz, A.R., Mohapatra, K.P., Ngachan, S., 2016. Impact of land uses, agrophysical variables and altitudinal gradient on soil organic carbon concentration of north-eastern Himalayan region of India. Land Degrad. Dev. 27, 1163–1174. https://doi.org/10.1002/ldr.2338.

Dam, R.F., Mehdi, B.B., Burgess, M.S.E., Madramootoo, C.A., Mehuys, G.R., Callum, I.R., 2005. Soil bulk density and crop yield under eleven consecutive years of corn with different tillage and residue practices in a sandy loam soil in central Canada. Soil Tillage Res. 84, 41–53.

Datta, M., Yadav, G.S., Chakraborty, S., 2014. Integrated nutrient management in groundnut (*Arachis hypogaea*) in a subtropical humid climate of north-east India. Indian J. Agron. 59 (2), 322–326.

Deng, J.L., 1982. Grey controlling system. Cent. Inst. Technol. 10, 9–18.

Dubey, A., Lal, R., 2009. GWP and sustainability of agricultural production systems in Punjab, India, and Ohio, USA. J. Crop. Improv. 23, 332–350.

Duiker, S.W., Lal, R., 1999. Crop residue and tillage effects on carbon sequestration in a Luvisol in central Ohio. Soil Tillage Res. 52, 73–81.

FAO, 2017. FAOSTAT Database Collections. Food and Agriculture Organization of the United Nations, Rome. Access date: 17-12-2017. URL: http://faostat.fao.org.

Gan, Y., Liang, C., Chai, Q., Lemke, R.L., Campbell, C.A., Zentner, R.P., 2014. Improving farming practices reduces the carbon footprint of spring wheat production. Nat. Commun. 5, 5012. https://doi.org/10.1038/ncomms6012.

Gan, Y.T., Campbell, C.A., Jansen, H.H., Lemke, R., Liu, L.P., Basnyat, P., McDonald, C.L., 2009. Carbon input to the soil by oilseed and pulse crops in a semiarid environment. Agric. Ecosyst. Environ. 132, 290–297.

Ghosh, B.N., Dogra, P., Sharma, N.K., Bhattacharyya, R., Mishra, P.K., 2015. Conservation agriculture impact for soil conservation in maize-wheat cropping system in the Indian sub-Himalayas. Int. Soil Water Conserv. Res. 3 (2), 112–118.

Goglio, P., Grant, B.B., Smith, W.N., Desjardins, R.L., Worth, D.E., Zentner, R., Malhi, S.S., 2014. Impact of management strategies on the global warming potential at the cropping system level. Sci. Total Environ. 490, 921–933.

Gunady, M.G., Biswas, W., Solah, V.A., James, A.P., 2012. Evaluating the global warming potential of the fresh produce supply chain for strawberries, romaine/cos lettuces (*Lactuca sativa*), and button mushrooms (*Agaricusbisporus*) in Western Australia using life cycle assessment (LCA). J. Clean. Prod. 28, 81–87.

Günther, J., Thevs, N., Gusovius, H.J., Sigmund, I., Brückner, T., Beckmann, V., Abdusalik, N., 2017. Carbon and phosphorus footprint of the cotton production in Xinjiang, China, in comparison to an alternative fibre (*Apocynum*) from Central Asia. J. Clean. Prod. 148, 490–497.

Harada, H., Kobayashi, H., Shindo, H., 2007. Reduction in greenhouse gas emissions by no-tilling rice cultivation in Hachirogata polder, northern Japan: life-cycle inventory analysis. Soil Sci. Plant Nutr. 53, 668–677.

Hosseini, S.Z., Firouzi, S., Aminpanah, H., Sadeghnejhad, H.R., 2016. Effect of tillage system on yield and weed populations of soybean (*Glycine max* L.). An Acad. Bras Ciências 88 (1), 377–384.

Houshyar, E., Dalgaard, T., Tarazkar, M.H., Jørgensen, U., 2015. Energy input for tomato production. What economy says, and what is good for the environment? J. Clean. Prod. 89, 99–109.

Houshyar, E., Grundmann, P., 2017. Environmental impacts of energy use in wheat tillage systems: a comparative life cycle assessment (LCA) study in Iran. Energy

122, 11–24.

IPCC, 2013. Climate change 2013: the physical science basis. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midglev, P.M. (Eds.), Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, and New York, pp. 710–716.

IPCC, 2014. Climate change 2014: mitigation of climate change. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York.

Jemai, I., Aissa, N.B., Guirat, S.B., Ben-Hammouda, M., Gallali, T., 2013. Impact of three and seven years of no-tillage on the soil water storage, in the plant root zone, under a dry subhumid Tunisian climate. Soil Tillage Res. 126, 26–33.

Johnson, J.M.F., Reicosky, D.C., Allmaras, R.R., Sauer, T.J., Venterea, R.T., Dell, C.J., 2005. Greenhouse gas contributions and mitigation potential of agriculture in the central USA. Soil Tillage Res. 83, 73–94.

Kumar, B., Kumar, R., Kalyani, S., Haque, M., 2013. Integrated weed management studies on weed flora and yield in Kharif maize. Trends Biosci. 6 (2), 161–164.

Kuotsu, K., Das, Anup, Lal, R., Munda, G.C., Ghosh, P.K., Ngachan, S.V., 2014. Land forming and tillage effects on soil properties and productivity of rainfed groundnut (*Arachis hypogaea* L.) – rapeseed (*Brassica campestris* L.) cropping system in northeastern India. Soil Till. Res. 142, 15–24.

Küsterman, B., Munch, J.C., Hülsbergen, K.J., 2013. Effects of soil tillage and fertilization on resource efficiency and greenhouse gas emissions in a long-term field experiment in Southern Germany. Eur. J. Agron. 49, 61–73.

Lal, R., 2004. Carbon emission from farm operations. Environ. Int. 30, 981–990.

Lal, R., 2015. Sequestering carbon and increasing productivity by conservation agriculture. J. Soil Water Conserv. 70 (3), 55A–62A.

Liebig, M.A., Morgan, J.A., Reeder, J.D., Ellert, B.H., Gollany, H.T., Schuman, G.E., 2005. Greenhouse gas contributions and mitigation potential of agriculture practices in the north-western USA and western Canada. Soil Tillage Res. 83, 25–52.

Liu, Q., Liu, B., Ambus, P., Zhang, Y., Hansen, V., Lin, Z., Shen, D., Liu, G., Bei, Q., Zhu, J., Wang, X., 2016. Carbon footprint of rice production under biochar amendment–a case study in a Chinese rice cropping system. Gcb Bioenergy 8 (1), 148–159.

Lu, X., Liao, Y., 2016. Effect of tillage practices on net carbon flux and economic parameters from farmland on the Loess Plateau in China. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2016.09.044.

Mbah, C.N., Nwite, J.N., Njoku, C., Ibeh, L.M., Igwe, T.S., 2010. Physical properties of an ultisol under plastic film and no mulch and their effect on the yield of maize. World J. Agric. Sci. 6 (2), 160–165.

McConnell, D.B., Shiralipour, A., Smith, W.H., 1993. Compost application improves soil properties. Biocycle 34, 61–63.

Meena, R.S., Gogaoi, N., Kumar, S., 2017. Alarming issues on agricultural crop production and environmental stresses. J. Clean. Prod. 142, 3357e3359.

Meena, H., Meena, R.S., 2017. Assessment of sowing environments and bioregulators as adaptation choice for clusterbean productivity in response to current climatic scenario. Banglad J. Bot. 46 (1), 241–244.

Meena, R.S., Yadav, R.S., 2014. Phonological performance of groundnut varieties under sowing environments in the hyper arid zone of Rajasthan, India. J. Appl. Nat. Sci. 6 (2), 344–348.

Meena, R.S., Kumar, V., Yadav, G.S., Mitran, T., 2018. Response and interaction of *Bradyrhizobium japonicum* and *Arbuscular mycorrhizal* fungi in the soybean rhizosphere: a review. Plant Growth Regul. 84, 207–223.

Mukherjee, D., 2010. Productivity profitability and apparent nutrient balance under different crop sequence in mid hill condition. Indian J. Agric. Sci. 80 (5), 420–422.

Ntinas, G.K., Neumair, M., Tsadilas, C.D., Meyer, J., 2017. Carbon footprint and cumulative energy demand of greenhouse and open-field tomato cultivation systems under Southern and Central European climatic conditions. J. Clean. Prod. 142, 3617–3626.

OECD, 2015. Rice projections: Consumption, per capita, in OECD-FAO Agricultural Outlook 2015. OECD Publishing, Paris. https://doi.org/10.1787/agr_outlook-2015-table125-en.

Pandey, D., Agrawal, M., 2014. Carbon footprint estimation in the agriculture sector. In: Assessment of Carbon Footprint in Different Industrial Sectors, vol. 1. Springer, Singapore, pp. 25–47.

Parihar, C.M., Jat, S.L., Singh, A.K., Majumdar, K., Jat, M.L., Saharawat, Y.S., Pradhan, S., Kuri, B.R., 2017. Bio-energy, water-use efficiency and economics of maize-wheat-mungbean system under precision-conservation agriculture in semi-arid agro-ecosystem. Energy 119, 245–256.

Pathak, H., Tewari, A.N., Sankhyan, S., Dubey, D.S., Mina, U., Singh, V.K., Jain, N., Bhatia, A., 2011. Direct-seeded rice: potential, performance and problems–A review. Curr. Adv. Agric. Sci 3 (2), 77–88.

Patil, S.B., Balakrishna Reddy, B.C., Chitgupekar, S.C., Patil, B.B., 2015. Modern tillage and integrated nutrient management practices for improving soil fertility and productivity of groundnut (*Arachis hypogaea* L.) under the rainfed farming system. Int. Lett. Nat. Sci. 29, 1–12.

Pishgar-Komleh, S.H., Akram, A., Keyhani, A., Raei, M., Elshout, P.M.F., Huijbregts, M.A.J., van Zelm, R., 2017. Variability in the carbon footprint of open-field tomato production in Iran-A case study of Alborz and East-Azerbaijan provinces. J. Clean. Prod. 142, 1510–1517.

Pishgar-Komleh, S.H., Ghahderijani, M., Sefeedpari, P., 2012. Energy consumption and CO_2 emissions analysis of potato production based on different farm size levels in Iran. J. Clean. Prod. 33, 183–191.

Prasad, R., Shivay, Y.S., Kumar, D., Sharma, S.N., 2006. Learning by Doing Exercise in Soil Fertility- a Practical Manual for Soil Fertility, Division of Agronomy. IARI, New Delhi.

Pratibha, G., Srinivas, I., Rao, K.V., Raju, B.M.K., Thyagaraj, C.R., Korwar, G.R., Venkateswarlu, B., Shanker, A.K., Choudhary, D.K., Srinivasrao, K., Srinivasarao, Ch, 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.

Pratibha, G., Srinivas, I., Rao, K.V., Shanker, A.K., Raju, B.M.K., Choudhary, D.K., Rao, K.S., Srinivasarao, C., Maheswari, M., 2016. Net global warming potential and greenhouse gas intensity of conventional and conservation agriculture system in rainfed semi-arid tropics of India. Atmos. Environ. 145, 239–250.

Rasool, R., Kukal, S.S., Hira, G.S., 2008. Soil organic carbon and physical properties as affected by the long-term application of FYM and inorganic fertilizers in maize-wheat system. Soil Tillage Res. 101, 31–36.

Saad, A.A., Das, T.K., Rana, D.S., Sharma, A.R., Bhattacharyya, R., Lal, K., 2016. Energy auditing of a maize–wheat–greengram cropping system under conventional and conservation agriculture in irrigated north-western Indo-Gangetic Plains. Energy 116, 293–305.

Saha, S., Chakraborty, D., Sharma, A.R., Tomar, R.K., Bhadraray, S., Sen, U., Behera, U.K., Purakayastha, T.J., Garg, R.N., Kalra, N., 2010. Effect of tillage and residue management on soil physical properties and crop productivity in maize (*Zea mays*)-Indian mustard (*Brassica juncea*) system. Indian J. Agric. Sci. 80 (8), 679–685.

Sarkar, S., Paramanick, M., Goswami, S.B., 2007. Soil temperature, water use and yield of yellow sarson (*Brassica napus* L. var. glauca) in relation to tillage intensity and mulch management under rainfed lowland ecosystem in eastern India. Soil Tillage Res. 93 (1), 94–101.

SAS Institute, 2003. The SAS System for Microsoft Windows Release 9.4, fourth ed. SAS Institute, Inc., Cary, NC.

Shekhawat, K., Rathore, S.S., Kandpal, B.K., Premi, O.P., Singh, D., Chauhan, B.S., 2016. Crop establishment techniques affect productivity, sustainability, and soil health under mustard-based cropping systems of Indian semi-arid regions. Soil Tillage Res. 158, 137–146.

Singh, K.P., Prakash, V., Srinivas, K., Srivastva, A.K., 2008. Effect of tillage management on energy-use efficiency and economics of soybean (*Glycine max*) based cropping systems under the rainfed conditions in North-West Himalayan region. Soil Tillage Res. 100, 78–82.

Soni, P., Taewichit, C., Salokhe, V.M., 2013. Energy consumption and CO_2 emissions in rainfed agricultural production systems of Northeast Thailand. Agric. Syst. 116, 25–36.

Tandon, S.K., Singh, S., 2010. Energy balance in conservation agriculture and conventional farming: a comparison. In: Joshi, P.K., Challa, J., Virmani, S.M. (Eds.), Conservation Agriculture–innovations for Improving Efficiency Equity and Environment. National Academy of Agricultural Sciences (NAAS), New Delhi, India, pp. 259–280.

Tejada, M., Gonzalez, J.L., García-Martínez, A.M., Parrado, J., 2008. Effects of different green manures on soil biological properties and maize yield.Bioresour. Technol. 99, 1758–1767.

Tjandra, T.B., Ng, R., Yeo, Z., Song, B., 2016. Framework and methods to quantify carbon footprint based on an office environment in Singapore. J. Clean. Prod. 112, 4183–4195.

Tubiello, F.N., Cóndor-Golec, R.D., Salvatore, M., Piersante, A., Federici, S., Ferrara, A., Rossi, S., Flammini, A., Cardenas, P., Biancalani, R., Jacobs, H., 2015. Estimating Greenhouse Gas Emissions in Agriculture: a Manual to Address Data Requirements for Developing Countries. Estimating Greenhouse Gas Emissions in Agriculture: a Manual to Address Data Requirements for Developing Countries. Food and Agriculture Organization of the United Nations, Rome, 2015. www.fao.org/publications.

Tubiello, F.N., 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.

Wang, H., Yang, Y., Zhang, X., Tian, G., 2015. Carbon footprint analysis for mechanization of maize production based on life cycle assessment: a case study in Jilin Province, China. Sustainability 7 (11), 15772–15784.

Wang, Z.B., Zhang, H.L., Lu, X.H., Wang, M., Chu, Q.Q., Wen, X.Y., Chen, F., 2016. Lowering carbon footprint of winter wheat by improving management practices in North China Plain. J. Clean. Prod. 112, 149–157.

West, T.O., Marland, G., 2002. A synthesis of carbon sequestration carbon emissions and net carbon flux in agriculture: comparing tillage practices in the United States. Agric. Ecosyst. Environ. 91, 217–232.

Xu, X., Lan, Y., 2016. A comparative study on carbon footprints between plant-and animal-based foods in China. J. Clean. Prod. 112, 2581–2592.

Xue, J.F., Pu, C., Liu, S.L., Zhao, X., Zhang, R., Chen, F., Xiao, X.P., Zhang, H.L., 2016. Carbon and nitrogen footprint of double rice production in Southern China. Ecol. Indicat. 64, 249–257.

Yadav, G.S., Datta, M., Babu, S., Das, A., Bhowmik, S.N., Ranebennur, H., Debnath, C., Saha, P., 2015. Effect of tillage and crop-establishment techniques on productivity, profitability and soil health under maize (*Zea mays*)-maize-field pea (*Pisumsativum*) cropping system. Indian J. Agron. 60 (3), 360–364.

Yadav, G.S., Lal, R., Meena, R.S., Datta, M., Babu, S., Das, A., Layek, J., Saha, P., 2017. Energy budgeting for designing sustainable and environmentally clean/safer cropping systems for rainfed rice fallow lands in India. J. Clean. Prod. 158, 29–37.

Zhang, X.Q., Pu, C., Zhao, X., Xue, J.F., Zhang, R., Nie, Z.J., Chen, F., Lal, R., Zhang, H.L., 2016. Tillage effects on carbon footprint and ecosystem services of climate regulation in a winter wheat–summer maize cropping system of the North China Plain. Ecol. Indicat. 67, 821–829.

Zhao, Y., Pang, H., Wang, J., Huo, L., Li, Y., 2014. Effects of straw mulch and buried straw on soil moisture and salinity in relation to sunflower growth and yield. Field Crop. Res. 161, 16–25.