Europ. J. Agronomy 66 (2015) 30–40

Contents lists available at ScienceDirect

European Journal of Agronomy

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

Impact of conservation agriculture practices on energy use efficiency and global warming potential in rainfed pigeonpea–castor systems

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ARTICLE INFO

Article history:
Received 4 September 2014
Received in revised form 16 January 2015
Accepted 3 February 2015
Available online 23 February 2015

Keywords:
Tillage
Cajanus cajan (L.)
Ricinus communis (L.)
Energy balance
Greenhouse gas emissions

ABSTRACT

Identification of agricultural practices which maximize crop productivity, energy use efficiency (EUE) and minimize greenhouse gas (GHG) emissions is essential. There is dearth of information in rainfed agriculture in general and conservation agriculture in particular, hence a study was conducted to assess the EUE and GHG emissions of different tillage practices like conventional tillage (CT), reduced tillage (RT) and zero tillage (ZT) and residue levels (harvesting heights resulting in 0, 10 and 30 cm anchored residue) in pigeonpea–castor systems under semi-arid rainfed regions of India. CT recorded 30 and 31% higher energy inputs than ZT in pigeonpea and castor, respectively. The fuel consumption in ZT was 58 and 81% lower than CT in pigeonpea and castor, respectively. This lower fuel consumption in ZT reduced the GHG emissions by 21 and 23% in pigeonpea and castor, respectively, in comparison with CT. EUE and energy productivity were maximum in ZT with 10 cm anchored residue. Further, castor grown on pigeonpea residue recorded 10 and 20% higher energy inputs and GHG emissions over pigeonpea grown on castor residues. Our results indicate that, reduction in one tillage operation with residue have a minimal impact on the crop yields but have a substantial environmental benefits.

1. Introduction

One of the biggest challenges in agriculture during the 21st century is to meet the food and fodder demands of the growing population and livestock from decreasing per capita land availability without environmental degradation. To meet these growing demands improved agronomic practices such as intensive tillage, optimized use of fertilizers, improved crop protection practices and burning of crop residues for disposing of the residues from the field are being adopted (Ghasemi Mobtaker et al., 2010). These practices are highly productive but are energy intensive, hence have contributed to a 10-fold increase in the global energy budget since the start of the 20th century (Tandon and Singh, 2010) and increase in anthropogenic emissions of greenhouse gases (GHG) especially non-CO_2 emissions grew by 0.9% year^{-1}, with a slight increase in growth rates after 2005 (Tubiello et al., 2013). This increase in energy inputs and GHG emissions in agriculture is mostly due to higher fossil fuel combustion during farm operations especially tillage (Koga et al., 2003). Globally, with growing concern on climate change, the focus is to reduce anthropogenic GHG emissions in general and from agriculture in particular. Since the fossil energy inputs and CO_2 emissions are directly related (Tzilivakis et al., 2005) studies on increasing the energy use efficiency in crop production is need of the hour. Further, these studies help in development of sustainable practices with higher productivity, energy use efficiency, and preservation of natural resources and also offer opportunities for mitigation of climate change (Dalgaard et al., 2011; Dyer and Desjardins, 2003).

Among the different agro techniques, soil tillage is one of the greatest fossil fuel energy consumers and contributes about 30% of the total energy use in crop production (Singh et al., 2008) and in turn increases greenhouse gas emissions (Soni et al., 2013). Thus, reducing the energy consumption from fossil fuels in agricultural systems will lead to reduction of GHG emissions. Hence, in the current context of growing environmental concerns, reduced or zero tillage is essential, as it can reduce the negative effects of agriculture on the environment by reducing fossil fuel consumption which in turn reduces energy input, CO_2 emissions, wind and water erosion of soil along with the reduction in cost of cultivation (Johnson

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http://dx.doi.org/10.1016/j.eja.2015.02.001
1161-0301/

et al., 2005; Liebig et al., 2005). But zero tillage has not been adopted widely due to yield variability and also low yields under rainfed conditions (Giller et al., 2009). Hence, in recent times conservation agriculture (CA) which includes minimum soil disturbance, residue retention and crop rotation has emerged as an important management strategy to fight climate change while maintaining crop productivity. The benefits of individual components of CA like reduced tillage, crop rotation are well known, but the components have not been integrated properly. Many studies have been conducted on CA in rice-wheat system in irrigated Indo-Gangetic plains of south Asia (Kumar et al., 2013; Jat et al., 2009), but research in rainfed regions is limited. Further, the success of CA depends on the soil cover or residues. However, the major constraint in adoption of CA is non availability of crop residues due to competing demands of residue for fodder, fuel and also lack of suitable implements to sow the crop (Giller et al., 2009).

In India, 2/3rd of total arable land is rainfed which contributes about 44% of the food production. In the rainfed areas crop production is uncertain due to irregular weather conditions, degraded soil with low inherent soil fertility and low water holding capacity. Pigeonpea {*Cajanus cajan* (L.) Millsp.} and castor {*Ricinus communis* (L.)} are important pulse and oilseed crops of semi arid rainfed regions of India. Pigeonpea is fifth prominent grain legume crop in the world and occupies second position among pulse crop in India. More than 90% of the pigeonpea area is under rainfed conditions, which is typically characterized by recurring droughts, resulting in lower productivity. Also, castor is an important industrial oilseed crop and India accounts for 60% of area and 68% of global production. These crops require less input and are highly suitable for marginal environment. In India, these crops are largely grown by small holders, although the productivity of these crops is low due to erratic monsoon and low soil fertility.

Several studies have evaluated the energy balance (Moreno et al., 2011; Arvidsson, 2010; Tabatabaeefar et al., 2009; Singh et al., 2008) and greenhouse gas emission (Filipovic et al., 2006; Koga et al., 2003; West and Marland, 2002) in different cropping systems but very few studies have combined the energy analysis and GHG emissions from agricultural systems (Mohammadi et al., 2014; Küsterman et al., 2013; Soltani et al., 2013; Soni et al., 2013). Also, there is limited information from rainfed production systems combining different tillage methods and residue management system. Hence this study was conducted with following objectives: (i) to assess the energy input, output and energy use efficiency of CA and CT systems, and (ii) to determine the carbon input, output, CO_2 eq. emissions, carbon sustainability index and carbon efficiency of CA systems in pigeonpea and castor cropping systems under rainfed production systems.

2. Materials and methods

2.1. Cropping systems and treatments

Field experiments were initiated in 2009 at Hayathnagar Research Farm (HRF) of the Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad, India (17°23′N latitude, 78°29′E longitude, altitude 540 m above mean sea level) in

Table 1
Package of practices in different tillage treatments in pigeonpea–castor cropping systems.

Crop	Month	Operation	CT	RT	ZT
Pigeonpea	April/May	Land preparation	Disk plowing once	–	–
	June		Cultivator once	Cultivator once	–
	June (second fortnight depending on rainfall)		Disk harrow once	Disk harrow once	–
		Sowing + basal dose of fertilizer + pre emergence herbicide	Sowing + 25:50 N:P Kg ha^{-1}	Sowing +25:50 N:P Kg ha^{-1}	Sowing +25:50 N:P Kg ha^{-1}
		Pre emergence herbicide	–	Pendimethalin	Pendimethalin
	July	Inter-cultivation	Bullock pair + hand weeding	–	–
	August	Inter-cultivation/post emergence herbicides	Bullock pair + hand weeding	Quizalofop–*p*-ethyl	Quizalofop–*p*-ethyl
	September	Inter- cultivation	Bullock pair + hand weeding	Bullock pair + hand weeding	
	October and November	Plant protection	Need based plant protection measures	Need based plant protection measures	Need based plant protection measures
	January	Harvesting	Combiner	Combiner	Combiner
Castor	April/May	Land preparation	Diskplowing once	–	–
	June		Cultivator once	Cultivator once	–
	June		Disk harrow once	Disk harrow once	–
	June (second fortnight depending on rainfall	Sowing + basal dose of fertilizer + pre emergence herbicide	Sowing + 25:50 N:P kg ha^{-1}	Sowing + basal fertilizer	Sowing + basal fertilizer
		Pre emergence herbicide	–	Pendimethalin	Pendimethalin
	July	Inter-cultivation	Bullock pair + hand weeding	–	–
	August	Inter-cultivation/herbicides	Bullock pair + hand weeding	Quizalofop–*p*-ethyl	Quizalofop–*p*-ethyl
	September	Inter-cultivation	Bullock pair + hand weeding	Bullock pair + hand weeding	–
	September	Top dressing	N fertilizer 25 kg ha^{-1}	N fertilizer 25 kg ha^{-1}	N fertilizer 25 kg ha^{-1}
	October and November	Plant protection	Need based plant protection measures	Need based plant protection measures	Need based plant protection measures
	December–February	Harvesting – 3 pickings, final harvest in February	Manual	Manual	Manual

CT – conventional tillage, RT – reduced tillage, ZT – zero tillage.

the semi-arid region of Southern part of India. Average seasonal (June–January) rainfall during the experimental period was 720 mm, which accounts for approximately 42% of annual potential evapo-transpiration. Average annual maximum and minimum temperature during experimental period was 32 °C and 20 °C, respectively. The soil at the experimental site represents Typic Haplustalf. The arable part of the soil consists of 62.8% sand, 6.2% silt and 31% clay.

Pigeonpea–castor bean annual crop rotation was followed during rainy season from 2009–10 to 2013–14. Though the experiment was initiated in year 2009, the results from year 2010 onwards were considered as the first year of experiment did not have any residue cover in the experimental plot. The experiment was laid out in split-plot design with three tillage system as main plots and residue levels as subplots, replicated three times. Tillage treatments were assigned to the main plots ($300\,m^2$) which were split randomly into three sub plots ($100\,m^2$) based on the harvest height (anchored residues). 5 m buffer strips were maintained between the large plots. Recommended cultivation practices of the crops for this region were adopted in all the treatments. The sequence of field operations performed in pigeonpea and castor in different treatments are presented in Table 1. Tillage implements and operations done in different treatments were defined as per American Society of Agricultural and Biological Engineers (ASABE) standards (ASAE, 2004a, b).

The tillage treatments included CT, which was the usual farmers practice in the region and consists of one pass with disk plough (15–20 cm depth) in off season during April/May with summer showers, followed by one pass of cultivator (10 cm depth) and disk harrow after the onset of monsoon in second fortnight of June just before sowing of the crop. Weed control was done by inter-cultivation with bullock drawn harrow and hand weeding. Reduced tillage (RT) consists of one pass of cultivator followed by disk harrowing before sowing with onset of monsoon in June. Weed control was achieved by pre-emergence herbicide pendimethalin spray at the rate of 1.0 kg a.i. ha^{-1} at the time of sowing followed by one inter-cultivation operation with bullock drawn harrow, hand weeding once at 40 days after sowing and application of post-emergence herbicide Quizalofop–*p*-ethyl at the rate of 0.05 kg a.i. ha^{-1}. The third treatment was direct sowing without tillage (ZT) in which direct sowing was done without any tillage and weed control was achieved with pendimethalin spray at the rate of 1.0 kg a.i ha^{-1} and Quizalofop–*p*-ethyl at the rate of 0.05 kg a.i. ha^{-1} as pre and post-emergence herbicides, respectively. In all the three tillage systems, crop was sown with precision planter cum herbicide applicator developed at CRIDA (Plate1). The sub plot treatments involved harvesting at different heights which resulted in different residue heights, since they are anchored to soil standing in the field they were referred to as anchored residues i.e., harvesting at base (0 cm), (10 cm) and (30 cm) resulting in different residue quantities.

Seed, stalk, anchored residue and flat residue (leaf fall) yields of pigeonpea and castor were recorded after 12% moisture content was attained during all the experimental years. Root shoot ratio, carbon and nitrogen content in the grain, biomass, residue and root was determined in pigeonpea and castor once during the study period and these values were used to estimate the root biomass, N input, carbon output and calculation of N_2O emissions.

Plate 1. CRIDA precision planter with herbicide and fertilizer applicator.

2.2. Energy balance

Energy input of different tillage and residue treatments in pigeonpea–castor systems were estimated by using both direct (amount of fossil fuel used in tillage, sowing, harvesting, human labor, bullock labor and electricity) and indirect (energy used in production of machinery and raw materials like mineral fertilizers, pesticides and seeds) energy inputs. The energy input is the conversion of all the inputs in to energy values by multiplying with corresponding energy coefficients and summing up of all these energy inputs. The direct and indirect energy coefficients used were taken from the literature and are presented in Supplementary Table 1 (Thyagaraj, 2012; Singh and Mittal, 1992; Mittal and Dhawan, 1988; Green, 1987). Energy coefficients reported in the literature varied; this differential values are due to difference in calculation, spatial and temporal system boundaries used (Hülsbergen et al., 2001). Due to this differential coefficient values the results of different studies using different methodologies are not comparable. However, in this study energy coefficient values from Indian studies were used since this study has more relevance in Indian context. In this study only the energy used in crop production was considered but the renewable/built-in source of energy (solar radiation, wind, inbuilt fertility in the soil) was excluded since it has no opportunity cost and moreover these inputs are independent of the management practices. However, in this study manual labor, bullock power input was considered unlike the other studies of developed countries since significant amount of human labor was used for weeding and inter-cultural operations in CT like in any developing country, and the value corresponds to the biochemical energy potentially consumed by a person (Sartori et al., 2005).

Energy input of a machine (indirect energy use) was calculated by using equation (Canakci, 2010)

$$\mathrm{ME} = \frac{G \times \mathrm{MP}}{TC_{\mathrm{ef}}}$$

where 'ME' is the energy use of machine (MJ ha^{-1}), 'G' the weight of machine (kg), 'MP' is the energy use in the machine manufacturing, MJ kg^{-1}; 'T' the economic life of machinery (h) and 'C_{ef}' the effective field capacity (ha h^{-1}).

Fuel consumption in different tillage treatments depends on depth and width of ploughing, soil type, moisture content, size of the tractor and the implement used for ploughing. So the fuel consumption in different tillage treatments which were done with different tillage implements pulled by a 48HP two wheel drive tractor was estimated during treatment imposition and at sowing on volume basis.

The energy output of seed and stalk of castor and pigeonpea for each treatment was calculated based on the total yield (kg ha^{-1}) and its corresponding calorific values. Crop residues left over in the field were not considered in the energy balance calculation (Moreno et al., 2011). The formulae used for estimation of the energy efficiency variables (energy use efficiency, energy productivity and net energy) are presented in Table 2.

2.3. Greenhouse gas emissions

Environmental impacts of CA practices were assessed by calculating the Global warming potential (GWP). The GWP is the total set of GHG emissions (CO_2, N_2O and CH_4) produced directly and indirectly in crop production and they were converted into CO_2

Table 2
Description and units of energy and carbon parameters used in this study.

Parameters	Description	Abbreviation	Unit
Direct energy	Diesel + labor + bullock + electricity	DE	GJ ha^{-1}
Indirect energy	Machinery + fertilizers + pesticides + seeds	IDE	GJ ha^{-1}
Renewable Energy	Labor + bullock + seed	E_R	GJ ha^{-1}
Non renewable energy	Machinery + diesel + electricity + chemical fertilizers + pesticides	E_{NR}	GJ ha^{-1}
Total energy input	Sum of direct and indirect energy or sum of renewable and non renewable energy	EI	GJ ha^{-1}
Grain energy output	Energy in the harvested grain (main product)	Eo_g	GJ ha^{-1}
Total energy output	Energy in the harvested total biomass (grain + straw)	Eo_t	GJ ha^{-1}
Grain net energy	Grain energy output – energy input	NE_g	GJ ha^{-1}
Total net energy	Total energy output – energy input	NE_t	GJ ha^{-1}
Grain energy use efficiency	Grain energy output/energy input	EUE_g	–
Total energy use efficiency	Total Energy output/energy input	EUE_t	–
Grain energy productivity	Grain yield/energy input	EP_g	kg MJ^{-1}
Total energy productivity	Total biomass yield/energy input	EP_t	kg MJ^{-1}
Global warming Potential	Sum of total CO_2 and N_2O emission converted into CO2 eq.	GWP	kg CO_2 eq. ha^{-1}
GHG emission	Sum of total CO_2 and N_2O emission converted into CO2 eq.	GHG	kg CO_2 eq. ha^{-1}
Carbon input	(Sum of total GHG emission in CO_2 eq.) × 12/44	CI	kg $C_{eq.}$ ha^{-1}
Carbon output	Total biomass × 0.4	CO	kg $C_{eq.}$ ha^{-1}
Carbon sustainability index	(Coutput – Cinput)/Cinput	CSI	–
Carbon efficiency	C output/Cinput	CE	–

equivalent by using global warming potential equivalent factors of 1 and 310 for CO_2 and N_2O, respectively (IPCC, 2006). In this study only CO_2 and N_2O gases were considered. CH_4 emissions were not considered since the study was in rainfed crops and not low land rice further residue burning was absent. In this experiment the amount of GHG emissions in terms of CO_2 equivalent was estimated by multiplying the input (diesel fuel, chemical fertilizer and biocide) with its corresponding emission coefficient. In line with previous studies (Dalgaard et al., 2001), the emission coefficients used in the study are presented in Supplementary Table 1 (Lal, 2004; West and Marland, 2002). However the emission coefficient for each individual pesticide and herbicide are unavailable, so we assumed that the emission during the processes of production, transportation, storage, and field application are same for the pesticides within a class (Lal, 2004).

Besides the CO_2 equivalent emission from farm operations in crop production, direct and indirect N_2O emissions from the synthetic fertilizer application and N_2O released during decomposition of crop residues left in the soil (Forster et al., 2007) were estimated by using IPCC methodology (IPCC, 2006). The anchored residue, leaf and root biomass obtained in different treatments were used for the calculation of N_2O emissions (Supplementary Table 2).

The direct (emission factor) and indirect N_2O emission (fraction of leaching and volatilization) factors are variable, uncertain and moreover they depend on oxygen status of the soil, amount of fertilizer, soil type, crop and temperature etc. (Dobbie and Smith, 2003). In spite of the variations in emission factors the IPCC recommended use of a common default factors for these emissions. But in India some studies have reported a specific emission factor which is lower than IPCC default factor (Tirado et al., 2010; Bhatia et al., 2004; Singh et al., 1991). Hence in this study methodology suggested by Rochette et al. (2008) was used for estimating direct N_2O emission factors and indirect emissions ($FRAC_{Leach}$). Further in these equations the direct and indirect emissions from crop residue decomposition and synthetic N fertilizer application are considered as function of the ratio of precipitation to potential evapo-transpiration.

$$EF = 0.022 \times (P/PE) - 0.0048$$

where EF is the emission factor with a unit of kg N_2O-N kg^{-1} N; P/PE is the ratio of precipitation to potential evapo-transpiration during the growing season based on long-term data. The direct soil N_2O emissions (N_2O_{Direct}) from the application of synthetic N fertilizer (N_{SNF}) and crop residue N (N_{CR}) were estimated as follows:

$$N_2O_{Direct} = (N_{SNF} + N_{CR}) \times EF \times (44/28) \times 310$$

where 44/28 is a coefficient converting N_2O–N into N_2O, 310 is the global warming potential.

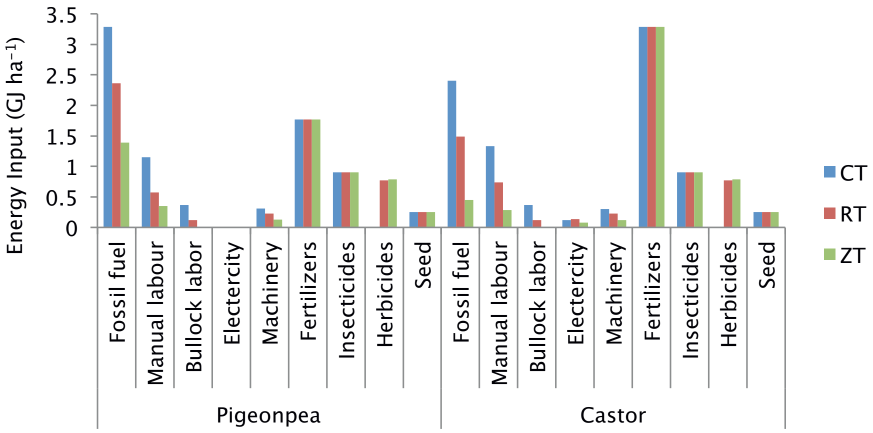

Fig. 1. Source-wise energy consumption (GJ ha^{-1}) in different tillage treatments in pigeonpea–castor cropping systems. CT – conventional tillage; RT – reduced tillage; ZT – zero tillage.

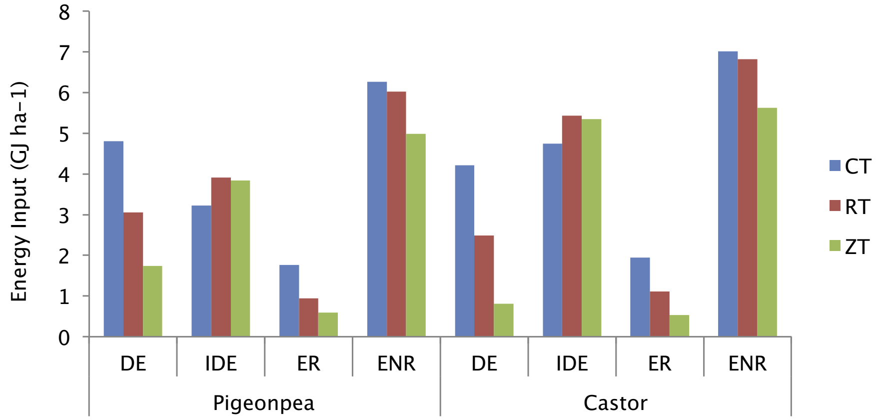

Fig. 2. Direct, indirect, renewable and non renewable energy input (GJ ha^{-1}) in different tillage treatments in pigeonpea–castor cropping systems. CT – conventional tillage; RT – reduced tillage; ZT – zero tillage. DE – direct energy; IDE – indirect energy; ER – renewable energy and ENR – non renewable energy.

The indirect soil N_2O emissions ($N_2O_{Indirect}$) from nitrate leaching and volatilization of NH_3 and NO_x were calculated as follows:

$$N_2O_{Indirect} = \{(N_{SNF}+N_{CR})\times FRAC_{Leach}\times EF_{Leach} + (N_{SNF}\times FRAC_{Gasm}\times EF_{VD})\}\times(44/28)\times 310$$

where, $Frac_{Leach}$ is the fraction of N lost by leaching and runoff.

$$FRAC_{Leach} = 0.3247\times(P/PE)-0.0247$$

$FRAC_{Gasm}$ is the fraction of volatilized nitrogen from synthetic fertilizer and crop residues. Various studies conducted in India reported the volatilization to be about 15% (Parashar et al., 1998; Aggarwal and Kaul, 1978) as against 10% of the IPCC default value. The higher value is due to high annual temperature in India as compared to temperate countries. The IPCC recommended and revised emission factors used in this study are presented in Supplementary Table 3.

Total carbon output is the sum of the carbon equivalent of grain, straw and root biomass produced by the crop. The carbon sustainability index which is ratio of difference between total carbon output and input to the total carbon input and carbon efficiency of different tillage practices and cropping systems were calculated as suggested by Lal (2004).

2.4. *Statistical analysis*

An experiment was laid out using split plot design with three replications to study the effect of tillage and residue levels on various parameters of energy and carbon. Tillage practices viz., conventional, reduced and zero tillage was introduced as main plot treatments and different anchored residue heights (0 cm, 10 cm and 30 cm harvesting height) as subplot treatments. The statistical analysis was carried out using proc glm of SAS software version 9.2. Tukey's studentized range test (HSD) was employed to offer corrections to *P*-values while doing multiple comparisons. *P* value less than 0.05 has been used as the criteria for rejecting the null hypothesis of equality of means for main plot treatments, subplot treatments and interaction between main plot and subplot treatments separately.

3. Results and discussion

In year 2009, experiment was initiated without in-situ residues hence we did not consider the results of 2009 in this paper and considered the results from 2010–11 to 2013–14. Differences in crop yields were observed in different years in both castor and pigeonpea. These differences in yields across years were mainly due to inter-annual variation in the total amount and distribution of rainfall but the variations within year were attributed to the treatments (Data not shown). However we did not observe any significant interaction between tillage and different years. Significantly higher seed yield was obtained in CT in pigeon pea (1191 kg ha^{-1}) and castor (2037 kg ha^{-1}) and this was on par with RT. ZT recorded 19 and 20% lower yield as compared to CT and 17 and 18% over RT in both pigeonpea and castor, respectively. These results are in agreement Alvarez and Steinbach (2009). This relative yield increase in zero tillage over time and transition period has been attributed to improved soil conditions with residue retention, such as organic carbon, soil enzyme activity, microbial biomass, porosity and structural stability (So et al., 2009). These results indicate the importance of long term experiments.

3.1. *Energy balance*

The present study compared the energy analysis between different tillage operations and crop residue levels in pigeonpea and castor rotation. Globally, energy analysis have been done to compare various variables. Hernanz et al. (1995), Borin et al. (1997), Zentner et al. (1998, 2004), and Rathke et al. (2007) compared conservation systems (minimum tillage, zero tillage) and conventional systems. However the differential energy coefficients reported in the literature, can affect the conclusions derived from these studies when differences among treatments are less. Different tillage systems significantly influenced the energy inputs whereas residue levels did not differ significantly. Total energy inputs averaged across castor and pigeonpea was 8.5, 7.5 and 5.9 GJ ha^{-1} in conventional tillage (CT), reduced tillage (RT) and zero tillage (ZT), respectively. CT recorded 30 and 12% higher energy input over zero and reduced tillage, respectively (Fig. 1). Higher energy input in CT was due to increased number and depth of tillage operations which accounted for higher machinery use and increased fossil fuel consumption. The present study results agree with the finding of Houshyar et al. (2015) and Rathke et al. (2007). But some studies (Zentner et al., 2004) reported that there is no significant difference between conservation tillage and conventional tillage since the savings in fuel in zero tillage is compensated for by higher herbicide and N fertilizer requirements. However Cantero-Martínez et al. (2003) differed with additional N fertilizer requirement under mediterranean semi arid rainfed conditions. Besides fossil fuel consumption intercultural operations and manual weeding also contributed to higher energy use in CT. In this study human labor is considered since in CT human labor is used for weed control unlike in studies of Moreno et al. (2011) and Rathke et al. (2007) of

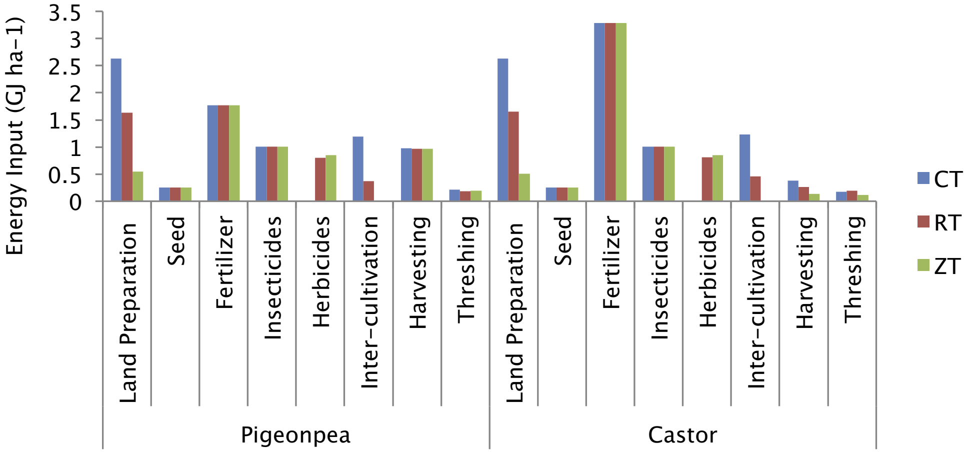

Fig. 3. Operation-wise energy consumption (GJ ha^{-1}) in different tillage treatments in pigeonpea–castor cropping systems. CT – conventional tillage; RT – reduced tillage; ZT – zero tillage.

developed countries. Soltani et al. (2013) and Kustermann et al. (2013) also indicated lower energy input in RT and ZT.

Averaged across crops, conventional tillage recorded 12% higher direct energy than indirect energy whereas RT and ZT recorded 41 and 72% higher indirect energy than CT, respectively. The fossil fuel share in CT (34%) and RT (26%) was highest where as in zero tillage it was only 16% this higher fossil fuel consumption in CT and RT was due to land preparation and sowing. The fossil fuel consumption for land preparation and sowing was less as compared to other studies like Houshyar et al. (2015) was due to use of CRIDA precision planter for sowing and the advantage of this implement is sowing, fertilizer and pre-emergence application of herbicide is done simultaneously in a single operation. The decrease in number of tillage operations saved 32 and 68% fossil fuel in RT and ZT, respectively as compared to CT. The share of fertilizers was highest in ZT (34%) but in CT and RT the fossil fuel share of energy was followed by fertilizers. Energy use of fossil fuel consumption and fertilizers were followed by insecticide application. Herbicides share was 10 and 13% in RT and ZT, respectively. The share of fertilizers and insecticides energy in different tillage systems was similar in all the treatments within the crop as in different studies. This was purposefully kept similar to study the influence of tillage systems and residue levels on the output of the crop. However, the higher fossil energy use in pigeonpea and manual labor use in castor was due to differential harvesting and threshing methods. In developing countries like India, under rainfed conditions usually combine harvester and manual threshing was done. But the detailed analysis revealed that major human energy is used in harvesting of castor. Castor is currently harvested in 2 to 3 picking manually. The challenging issue for the use of pluckers in castor harvesting is that the varieties available in castor do not mature at the same time hence the use of machine cuts the plant in the first round and may also pluck immature capsules leading to yield reduction by around 35–40%. Hence use of castor harvester may become reasonable on the condition of harvester or crop variety improvements; i.e., a crop variety that leads to simultaneous castor maturity, or a flexible harvester to harvest the yield several times economically. Whereas threshing was done with sheller. Renewable energy share to total energy input was 22, 14, and 10% in CT, RT and ZT, respectively. The higher renewable energy use in CT and RT is due to manual weeding and intercultural operations. Whereas in zero tillage herbicides were used for weed control. In both the crops when averaged across residue treatments, CT recorded higher non renewable energy as compared to ZT. This differential non renewable energy consumption in both the crops was due to use of fossil fuel for land preparation and sowing (Fig. 2).

Operation wise energy consumption is presented in Fig. 3. In CT highest share of energy input was in land preparation and sowing (33% of total energy input) while fertilizer application has recorded highest energy use in RT (26% of total energy input) and ZT (32% of total energy input) practices in pigeonpea. However, in castor fertilizer application was the highest energy consumer and it accounted to 37, 41 and 53% of total energy input in CT, RT and ZT, respectively. Weed control through herbicide application reduced the energy use in RT and ZT as compared to manual weeding in CT. Similar observations were reported by Singh et al. (2008) in ZT in soybean based cropping systems under rainfed conditions. The energy use for harvesting and threshing operations were lower in ZT as compared to conventional and RT as they are directly related to grain and biomass yields and these yields were comparatively lower in ZT.

Grain Energy Output (EO$_g$) was directly related to the yield, hence the highest energy output was observed in the treatment with highest yield. EO$_g$ was significantly influenced by the crop, tillage practices, height of harvested residues and year. Variation in grain yield contributed to the variation in energy output in different years. This variation in yield was due to difference in both quantity and distribution of rainfall in different years during the crop growth period. Averaged across years, tillage and residue level, castor recorded highest EO$_g$ than pigeonpea. This differential EO$_g$ in different crops is due to difference in the yield. Energy output was significantly ($P < 0.05$) influenced by tillage practices in both the crops. In pigeonpea and castor highest EO$_g$ was observed in CT (29.77 GJ ha^{-1}, 50.69 GJ ha^{-1}, respectively), followed by RT (28.99 GJ ha^{-1}, 49.37 GJ ha^{-1}, respectively) and ZT (24.08 GJ ha^{-1}, 40.61 GJ ha^{-1}, respectively). CT and RT were on par with each other but were significantly higher than ZT in both the crops. These results are in agreement with Borin et al. (1997). Different residue heights have significant ($P < 0.05$) influence on EO$_g$. In both the crops 30 and 10 cm anchored residue recorded highest energy output and was significantly superior to 0 cm anchored residue, in agreement with Goglio et al. (2014). Interaction between tillage and anchored residue height were non significant in pigeonpea but significant in castor. In castor 30 cm anchored residue (53.50 GJ ha^{-1}) had maximum EO$_g$ and was on par with 10 cm (51.71 GJ ha^{-1}) and 0 cm (46.84 GJ ha^{-1}) anchored residues in CT, 10 (51.12 GJ ha^{-1}) and 30 cm (50.95 GJ ha^{-1}) anchored residues in RT. But this was significantly superior to RT 0 cm and all anchored residue heights in ZT. 6 and 14% higher output was observed in ZT 10 cm anchored residue over ZT 0 and ZT 30 cm anchored residue. Furthermore, the energy output in 0 and 30 cm were statistically on par with each

Table 3
Energy (GJ ha^{-1}) balance in different tillage and residue height treatments in pigeonpea–castor cropping systems.

Tillage	Residue (cm)	EI (GJ ha^{-1})	EO_g (GJ ha^{-1})	EO_t (GJ ha^{-1})	EUE_g	EUE_t	NE_g (GJ ha^{-1})	NE_t (GJ ha^{-1})	EP_g (kg MJ^{-1})	EP_t (kg MJ^{-1})
Pigeonpea										
CT	0	8.04^{Aa}	26.41^{Aa}	53.69^{Aa}	3.29^{Aa}	6.69^{Aa}	15.59^{Aa}	41.65^{Aa}	0.13^{Aa}	0.47^{Aa}
	10	8.04^{Aa}	31.62^{Ab}	59.37^{Aab}	3.94^{Ab}	7.39^{Aab}	21.95^{Ab}	47.32^{Aab}	0.16^{Ab}	0.50^{Aab}
	30	8.04^{Aa}	31.28^{Ab}	60.25^{Ab}	3.89^{Ab}	7.5^{Ab}	18.86^{Aab}	48.20^{Ab}	0.16^{Ab}	0.52^{Ab}
RT	0	6.98^{Ba}	26.51^{Aa}	56.37^{Aa}	3.82^{Aa}	8.1^{Ba}	15.41^{Aa}	45.87^{Aa}	0.15^{Aa}	0.57^{Ba}
	10	6.98^{Ba}	29.08^{Ab}	55.15^{Aab}	4.18^{Ab}	7.93^{Aab}	16.69^{Ab}	44.66^{Aab}	0.17^{Ab}	0.55^{Aab}
	30	6.98^{Ba}	31.36^{Ab}	61.91^{Ab}	4.52^{Ab}	8.91^{Bb}	18.88^{Aab}	51.41^{Ab}	0.18^{Ab}	0.62^{Bb}
ZT	0	5.59^{Ca}	21.35^{Ba}	46.53^{Aa}	3.86^{Aa}	8.39^{Ba}	10.47^{Aa}	38.12^{Aa}	0.15^{Aa}	0.60^{Ba}
	10	5.59^{Ca}	25.97^{Bb}	50.64^{Bab}	4.67^{Bb}	9.12^{Bab}	16.32^{Ab}	42.23^{Aab}	0.19^{Bb}	0.63^{Bab}
	30	5.59^{Ca}	24.91^{Bb}	49.81^{Bb}	4.49^{Ab}	8.98^{Bb}	13.71^{Aab}	41.40^{Ab}	0.18^{Ab}	0.63^{Bb}
Castor										
CT	0	8.96^{Aa}	46.84^{Ab}	72.98^{Aa}	5.3^{Aa}	8.14^{Aa}	38.59^{Aa}	64.03^{Aa}	0.21^{Aa}	0.49^{Aa}
	10	8.96^{Aa}	51.71^{Aa}	78.77^{Ab}	5.77^{Ab}	8.78^{Ab}	42.76^{Ab}	69.81^{Ab}	0.23^{Ab}	0.53^{Ab}
	30	8.96^{Aa}	53.51^{Aa}	79.73^{Ab}	5.97^{Aab}	8.9^{Ac}	44.55^{Ab}	70.77^{Ab}	0.24^{Aab}	0.53^{Ac}
RT	0	7.93^{Ba}	46.02^{Ab}	70.03^{Aa}	5.8^{Ba}	8.83^{Aa}	38.09^{Aa}	62.11^{Aa}	0.23^{Aa}	0.54^{Aa}
	10	7.93^{Ba}	51.12^{Aa}	77.56^{Ab}	6.44^{Ab}	9.77^{Bb}	43.19^{Ab}	69.63^{Ab}	0.26^{Ab}	0.59^{Ab}
	30	7.93^{Ba}	50.95^{Aa}	78.63^{Ab}	6.42^{Aab}	9.91^{Bc}	43.03^{Ab}	70.70^{Ab}	0.26^{Aab}	0.61^{Bc}
ZT	0	6.16^{Ca}	40.67^{Ab}	60.70^{Ba}	6.61^{Ba}	9.85^{Ba}	34.53^{Ba}	54.54^{Ba}	0.26^{Ba}	0.59^{Ba}
	10	6.16^{Ca}	43.14^{Aa}	68.48^{Bb}	7^{Bb}	11.11^{Cb}	36.98^{Bb}	62.33^{Bb}	0.28^{Bb}	0.69^{Bb}
	30	6.16^{Ca}	37.99^{Aa}	59.03^{Bb}	6.16^{Aab}	9.57^{Bc}	31.84^{Bb}	52.87^{Bb}	0.25^{Aab}	0.59^{Bc}

Due to significant interaction between tillage and residue levels, the effect of tillage has been analysed at the same level of residue and the effect of residue at the same level of tillage; capital letters in the superscript indicate the effect of tillage, whereas lower case letters the effect of residue levels; means followed by the same letter are not significantly different at $P = 0.05$; CT – conventional tillage; RT – reduced tillage; ZT – zero tillage; 0 cm, 10 cm and 30 cm are harvesting heights from soil; other abbreviation details as in Table 2.

other (Table 3). Similar results were observed in total energy output (EO_t), which included energy output of grain and crop residue harvested and removed from the field. Crop residue left over in the field was not included in calculation of total energy output since they were returned to the land at the end of crop season (Moreno et al., 2011).

Energy use efficiency (EUE) was influenced by different tillage treatments and anchored residue height in both pigeonpea and castor (Table 3). Averaged over treatments castor recorded higher EUE (6.16 EUE_g and 9.43 EUE_t) as compared to pigeonpea (4.07 EUE_g and 8.11 EUE_t). ZT (4.34, 6.59 in pigeonpea and castor, respectively) and RT (4.17, 6.22 in pigeonpea and castor, respectively) recorded significantly higher EUE_g than CT but in RT and ZT they were statistically similar in both the crops. Similar observations were recorded in EUE_t. Barut et al. (2011) reported higher energy use efficiency in minimum tillage as compared to CT. Irrespective of tillage treatments anchored residue heights influenced the EUE significantly in both the crops. In general, with increase in anchored residue height EUE_g and EUE_t also increased. Anchored residue height of 30 and 10 cm registered highest EUE_g and EUE_t and were on par with each other but they were statistically superior to 0 cm anchored residue. In pigeonpea no significant interaction was observed between tillage and residue heights in both EUE_g and EUE_t, but in castor the interaction was significant. In pigeonpea maximum EUE_g was observed in ZT 10 cm anchored residue and this was significantly higher than all the residue heights and tillage treatments. In castor significant interaction in tillage and residue height was observed and it is of the order 10 cm anchored residue height in ZT > RT 30 cm > ZT 0 cm > RT 10 cm > ZT30 cm.

In general, Grain Net Energy gain (NE_g), Total Net Energy gain (NE_t), Grain Energy Productivity (EP_g) and Total Energy Productivity (EP_t) was higher in castor. In both the crops NE_g and NE_t was significantly influenced by the tillage treatments (Table 3). CT has higher NE_g and NE_t and was significantly superior to ZT in both the crops and RT in pigeonpea but in castor CT and RT were on par with each other. Different anchored residue height significantly influenced NE_g and NE_t in both the crops. Highest NE_g and NE_t was observed in 30 and 10 cm anchored residue and these were significantly higher than 0 cm in both the crops. In pigeonpea there was no significant interaction between tillage and residue height, whereas in castor significant interaction between tillage and residue height was observed. ZT 10 cm anchored residue recorded highest NE_g and this was followed by ZT 30 cm.

Castor recorded higher grain energy productivity (EP_g) and total energy productivity (EP_t) as compared to pigeonpea (Table 3). In pigeonpea, RT (0.174 kg MJ^{-1}) and ZT (0.167 kg MJ^{-1}) have higher EP_g than CT (0.148 kg MJ^{-1}), but EP_t was higher in ZT (0.621 kg MJ^{-1}) followed by RT (0.581 kg MJ^{-1}) and CT (0.496 kg MJ^{-1}). While, in castor ZT has higher EP_g and EP_t over RT and CT. In both the crops EP_g and EP_t was significantly influenced by anchored residue heights. 10 and 30 cm anchored residue have higher EP_g and EP_t over 0 cm in both the crops. Significant interaction between tillage and anchored residues was not observed in pigeonpea unlike in castor. In castor ZT 10 cm recorded significantly higher EP_g and EP_t over other tillage and residue heights.

3.2. Greenhouse gas emissions and Global warming potential

In general castor grown on pigeonpea residue had 20 and 26% higher CO_2 emissions and N_2O based CO_2 emissions (Table 4). The data averaged over years and treatments in different crops revealed that castor grown on pigeonpea residues (castor) have 22% higher GWP (757 kg CO_2 eq. ha^{-1}) over pigeonpea grown on castor residues (pigeonpea) (619 kg CO_2 eq. ha^{-1}). The differential GWP in pigeonpea and castor was due to difference in the quantity of N fertilizer applied, quantity and N content of crop residue (root and aboveground) recycled in the field (Gan et al., 2011; Janzen et al., 2003). Haas et al. (2007) and Isaksson (2005) in Germany and Sweden field conditions, respectively, observed lower energy and GHG emissions in the crop cultivation without N fertilizers over crop production with fertilizer application.

N_2O emission from agricultural soils is one of the chief source with the biggest uncertainty in GHG emissions These uncertainties are due to uncertainties related to the emission factors, natural variability, activity data, lack of coverage of measurements, spatial aggregation, and lack of information on specific on-farm practices (Lesschen et al., 2011) and moreover the emission factors also depends on the crop, soil moisture conditions, rainfall and temperature. In the IPCC (2006) guidelines globally the uncertainty range of the 1% EF is 0.3–11.0% (Smith et al., 1998; Flessa et al., 1995; Kaiser

Table 4

CO_2 equivalent (kg CO_2 eq. ha^{-1}) emission from various sources in different tillage and residue height treatments in pigeonpea–castor cropping systems.

	CT			RT			ZT		
Emission source	0	10	30	0	10	30	0	10	30
Pigeonpea									
Primary tillage and sowing	163.3	163.3	163.3	102.1	102.1	102.1	32.2	32.2	32.2
Inter-cultivation	6.2	6.2	6.2	1.6	1.6	1.6	0.0	0.0	0.0
Harvesting	61.7	61.7	61.7	61.7	61.7	61.7	61.7	61.7	61.7
Threshing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Application of fertilizers	135.7	135.7	135.7	135.7	135.7	135.7	135.7	135.7	135.7
Application of pesticides	6.7	6.7	6.7	8.9	8.9	8.9	8.9	8.9	8.9
Pesticides	127.9	127.9	127.9	127.9	127.9	127.9	127.9	127.9	127.9
Herbicides	0.0	0.0	0.0	17.6	17.6	17.6	17.6	17.6	17.6
CH_4 based CO_2 eq. emissions	0	0	0	0	0	0	0	0	0
N_2O based CO_2 eq. emissions									
Direct emissions	126.5	139.7	170.0	119.4	133.4	159.6	110.6	126.2	147.1
Indirect emissions	34.0	35.6	39.4	33.1	34.8	38.1	32.0	33.9	36.5
Total GWP	661.9	676.8	710.8	607.9	623.7	653.1	526.5	544.1	567.5
Castor									
Primary tillage and sowing	163.3	163.3	163.3	102.1	102.1	102.1	32.2	32.2	32.2
Inter-cultivation	6.2	6.2	6.2	1.0	1.0	1.0	0.0	0.0	0.0
Harvesting	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Threshing	5.3	5.3	5.3	5.0	5.0	5.0	4.0	4.0	4.0
Application of fertilizers	284.2	284.2	284.2	284.2	284.2	284.2	284.2	284.2	284.2
Application of pesticides	6.7	6.7	6.7	8.9	8.9	8.9	8.9	8.9	8.9
Pesticides	127.9	127.9	127.9	127.9	127.9	127.9	127.9	127.9	127.9
Herbicides	0.0	0.0	0.0	18.4	18.4	18.4	18.4	18.4	18.4
CH_4 based CO_2 eq. emissions	0	0	0	0	0	0	0	0	0
N_2O based CO_2 eq. emissions									
Direct emissions	169.4	185.4	262.6	168.9	181.3	193.1	130.8	137.0	159.0
Indirect emissions	40.5	42.7	52.8	40.5	42.2	43.8	35.4	36.2	39.1
Total GWP	803.4	821.6	908.9	756.8	770.9	784.4	641.8	648.7	673.6

CT – conventional tillage, RT – reduced tillage, ZT – zero tillage; 0 cm, 10 cm and 30 cm are harvesting heights from soil; GWP – global warming potential.

et al., 1998; Veldkamp et al., 1998) where as in Asian and Indian conditions the values ranged from 0.14 to 12.8% (Ghosh et al., 2003; Babu et al., 2006). consequently, the methodology exclude factors that are crucial in determining current emissions, and has no means to assess the potential impact of future climate and land-use change (Flynn et al., 2005). Additionally, this IPCC default approach does not provide incentives to mitigation measures, since the effect is not expressed in the national GHG emissions inventory. IPCC also encourages countries to use a Tier 2 approach, in which N2O EFs are disaggregated based on environmental and crop management related factors Few countries already developed Tier 2 approaches for N_2O soil emissions for specific sources, e.g. Canada (Rochette et al., 2008) and New Zealand (De Klein and Ledgard, 2005). Hence in the present study Rochette et al. (2008) method which is a function of precipitation and PET is used to estimate the emission factors. The direct and indirect emission factors used in this study is lower than the IPCC default factor and hence the emissions are much lower than that of IPCC default factors. Similar observations were made under Indian conditions by Bhatia et al. (2004). This is in agreement with some studies but differed with some other studies.

Contribution analysis of different subsystems to the GHG emissions was done to assess the influence of different factors on GHG emissions in pigeonpea and castor in conventional and conservation agriculture systems. It was observed that in both the crops CT recorded maximum CO_2 emissions from fossil fuel and this was followed by fertilizer application and pesticides, whereas in RT and ZT fertilizer application, pesticides had highest CO_2 emissions. The contribution of CO_2 emission from different tillage system is 32, 22 and 8.3% in CT, RT and ZT, respectively. In both the crops the direct N_2O based CO_2 emissions are higher in CT as compared to RT and ZT. The increase in height of anchored residues has increased both the direct and indirect N_2O based CO_2 emissions. In pigeonpea and castor direct and indirect N_2O emissions from crop residues was an important source of GHG emissions in all the tillage systems except in CT 0 cm anchored residues followed by fossil fuel, fertilizers and pesticides in CT. Whereas in RT and ZT highest share of CO_2 eq. emissions was from fertilizer application and this was followed by pesticides and fossil fuel. The fossil fuel share was 24, 16 and 6% in CT, RT and ZT, respectively. This difference in share of fossil fuel to GHG emissions in different tillage treatments was due to reduced number and depth of tillage operations in RT and ZT. While in castor in all the tillage treatments fertilizer application was the principal source of CO_2 equivalent emissions which is followed by N_2O, fossil fuel and pesticides in CT and N_2O, pesticides and fossil fuel in RT and ZT, respectively.

Among the different tillage practices in pigeonpea and castor CT had highest GWP (kg CO_2 eq. ha^{-1}) which was 9 and 10% higher than RT, while ZT have 20 and 22% lower GWP (kg CO_2 eq. ha^{-1}) as compared to CT in pigeonpea and castor, respectively. GWP of CT and RT were significantly higher than ZT in both the crops. Lowest GWP in ZT was due to savings on fossil fuel from reduced number of passes and also emissions associated with energy consumed in manufacture, transport, repair and use of machines (Mohammadi et al., 2014). GWP of 10 and 30 cm anchored residue height in both crops was higher than 0 cm. This increase in GWP was due to addition of higher quantity of residues in 30 and 10 cm anchored residue. Gan et al. (2009) and Goglio et al. (2014) observed similar increase with increase in quantity of residues. In pigeonpea 30 cm anchored residue had highest GWP (CO_2 eq. ha^{-1}) as compared to 10 and 0 cm anchored residue in all the three tillage systems, whereas 0 cm and 10 cm were on par with each other except in RT where they were significantly different.

Carbon output was higher in castor as compared to pigeonpea (Table 5). The pooled data revealed that carbon output was significantly influenced by tillage treatments and anchored residue height. Among the tillage treatments in both the crops, CT recorded higher carbon output (1963 kg C ha^{-1} in pigeonpea and 3456 kg C ha^{-1} in castor) and this was on par with RT and both

Table 5
Carbon input (kg $C_{eq.}$ ha^{-1}), output(kg $C_{eq.}$ ha^{-1}), sustainability index and carbon efficiency in different tillage and residue height treatments in pigeonpea–castor systems.

		Pigeonpea				Castor			
Tillage	Residue (cm)	Cinput	Coutput	CSI	CE	Cinput	Coutput	CSI	CE
CT	0	163^{Aa}	1862^{Ab}	10.39^{Aa}	11.39^{Aa}	212^{Aa}	3275^{Aa}	14.5^{Aa}	15.57^{Ab}
	10	163^{Ab}	1987^{Aab}	11.18^{Aa}	12.18^{Aa}	217^{Ab}	3531^{Ab}	15.67^{Ab}	16.67^{Aa}
	30	177^{Ac}	2041^{Aa}	10.43^{Aa}	11.43^{Aa}	242^{Ac}	3562^{Ac}	13.83^{Aa}	14.83^{Ab}
RT	0	147^{Ba}	1906^{Ab}	11.85^{Aa}	12.85^{Aa}	200^{Ba}	3187^{Aa}	15.19^{Aa}	16.19^{Ab}
	10	150^{Bb}	1846^{Aab}	11.33^{Aa}	12.31^{Aa}	204^{Bb}	3528^{Ab}	16.69^{Bb}	17.69^{Ba}
	30	161^{Bc}	2068^{Aa}	11.8^{Aa}	12.8^{Aa}	207^{Bc}	3586^{Ac}	16.58^{Ba}	17.58^{Bb}
ZT	0	126^{Ca}	1593^{Bb}	11.59^{Aa}	12.59^{Aa}	167^{Ca}	2733^{Ba}	15.43^{Aa}	16.43^{Ab}
	10	130^{Cb}	1669^{Bab}	11.86^{Aa}	12.86^{Aa}	169^{Cb}	3113^{Ab}	17.55^{Bb}	18.55^{Ca}
	30	138^{Cc}	1660^{Aa}	10.96^{Aa}	11.96^{Aa}	176^{Cc}	2764^{Bc}	14.35^{Aa}	15.35^{Ab}

Due to significant interaction between tillage and residue levels, the effect of tillage has been analyzed at the same level of residue and the effect of residue at the same level of tillage; capital letters in the superscript indicate the effect of tillage, whereas lower case letters the effect of residue levels; means followed by the same letter are not significantly different at $P = 0.05$; CT – conventional tillage, RT – reduced tillage, ZT – zero tillage; 0 cm, 10 cm and 30 cm are harvesting heights from soil; other abbreviation details as in Table 2.

were significantly superior to ZT (1641 kg C ha^{-1} in pigeonpea and 2870 kg C ha^{-1} in castor). This increase in C output is due to higher grain yields of pigeonpea and castor under CT as compared to ZT. Wilhelm et al. (1987) also reported lower yields in ZT. Among different anchored residue heights, 30 cm anchored residue had highest carbon output as compared to 0 and 10 cm height in pigeonpea. Further significant interaction between tillage and residue height was observed in pigeonpea, whereas in castor no significant interaction was observed. In all the three tillage systems 10 and 30 cm anchored residue recorded significantly higher carbon output as compared to 0 cm anchored residue.

In the context of the global climate change and anthropogenic emissions of GHGs into the atmosphere, sustainability of a production system increases with increased use efficiency of carbon based inputs (Lal, 2004). Averaged across years, Carbon Sustainability Index (CSI) and carbon efficiency (CE) were higher in castor as compared to pigeonpea (Table 5). The data revealed that CSI and CE were higher under RT (11.66, 12.66) and this was followed by ZT (11.47, 12.47) and CT (10.67, 11.67), however they were statistically on par with each other in pigeonpea. While in castor CSI and CE were higher in RT and ZT and were on par with each other and significantly superior over CT. Dubey and Lal (2009) reported significant effect of tillage practices on CSI and CE. This higher CSI and CE in RT was due to higher carbon output with lower carbon input whereas in ZT the carbon input was lower. The CSI and CE in different anchored residue heights did not significantly differ with each other in pigeonpea but in castor 10 cm anchored residue recorded significantly higher CSI and CE as compared to 0 and 30 cm anchored residue. In pigeonpea significant interaction between tillage and residue height was not observed. Whereas in castor ZT 10 cm anchored residue had higher CSI closely followed by RT 10 and RT 30 cm anchored residue and these treatments were on par with each other but were significantly superior to all residue heights in CT and RT 0 cm and ZT 0 and 30 cm anchored residue. ZT 10 cm anchored residue had highest CE followed by 10 and 30 cm anchored residue in RT and was significantly higher than all residue height in CT, RT 0 cm residue height, 0 and 30 cm residue height in ZT. Higher CE indicates more efficient use of carbon.

4. Conclusions

Fossil fuel based carbon dioxide emissions are well known as a major contributor to energy input and GWP in the crop production. Hence the present study aims to reduce the GWP and energy input of agriculture by adopting conservation agriculture in pigeonpea and castor one year rotation under rainfed conditions. The results indicated that the energy input was higher in CT as compared to RT and ZT, however, no difference was observed in different anchored residue height. In both the crops CT and RT have highest EO_g with 10 and 30 cm anchored residue. But ZT with 10 and 30 cm anchored residue recorded highest EUE. CT had highest GHG emissions as compared to RT and ZT in both the crops. Furthermore, the contribution of fossil fuel to total energy input and CO_2 emissions is the highest. Hence, reduction in tillage operation reduced the energy input and CO_2 emission. In both the crops 30 cm anchored residue emitted higher GHG as compared to 0 and 10 cm. The results of this study revealed that yields in CT are higher under rainfed conditions but these yields were on par with RT. However, the yield gap between the tillage treatments is narrowing down over years. Hence, it may take time for the ZT to out yield CT and RT. But from the environmental point there is energy saving, higher EUE and lower GHG emissions from ZT followed by RT. Keeping in view, yield and environmental impacts, RT with 10 cm anchored residue may be recommended. Further, the harvesting height at 10 cm adds residue to the soil which improves the soil quality and also helps to overcome the competing use of residue.

Acknowledgements

Authors are thankful to Dr. M. Maheswari, PI, National Initiative on Climate Resilient Agriculture (NICRA) for the support and encouragement. This study was financially supported by NICRA project. We are grateful to the two anonymous reviewers and the editor for comments and suggestions for improvement of the manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.eja.2015.02.001.

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