

Review Article

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## Energy Auditing and Carbon Footprint with Diverse Organic and Inorganic Fertilizer Management Options in Cereal based Cropping Systems under Conservation Agriculture: A Review

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### ABSTRACT

Soil is a key compartment for climate regulation as a source of greenhouse gases (GHGs) emissions and as a sink of carbon. Thus, soil carbon sequestration strategies should be considered alongside reduction strategies for other greenhouse gas emissions. Practicing conservation tillage, residue retention and diverse organic and inorganic fertilizer management options were advocated because of their multiple benefits. Hence we explored the energy requirement and carbon footprint of conservation agriculture (CA) based maize production systems. ZT and PB plots consumed lower energy in land preparation (49.7-51.5%) and irrigation (16.8-22.9%) compared to CT. Significantly higher system output (10.6-14.5%) and net energy (14.8-18.9%) returns, biomass productivity (9.9-14.1%), energy use-efficiency (13.4-17.1%), and bio-energetic based adult equivalent yield (17.3-19.8%) was recorded in ZT and PB than the CT. Among the crop rotation plots the pooled net energy-output (35, 3346 MJ ha<sup>-1</sup>), biomass yield (11.87 Mg ha<sup>-1</sup>), energy use efficiency (4.16), and bio-energetic based adult equivalent yield (46 adults ha<sup>-1</sup> year<sup>-1</sup>) was recorded significantly higher in MWMB plots. The carbon footprint for durum wheat grown after a pulse was 0.25 kg CO<sub>2</sub>e per kg of the grain and 0.28 kg CO<sub>2</sub>e per kg of the grain when grown after an oilseed: a reduction in the carbon footprint of 24% to 32% than when grown after a cereal. The application of chemical fertilizer + FYM at 6 t/ha to rice-wheat system produced significantly higher yield attributes, economic yield, energy output of the system and higher carbon efficiency CE and net return over control and sole application of FYM at 6 t/ha. The application of INM with ridge furrow sowing increased available N and P contents in the soil. The adoption of NT-RR significantly reduced the energy use (16,727 MJ/ha) compared with those under CT-RI (27,630MJ/ha). Thus, NT-RR also increased the energy use efficiency (EUE), energy productivity (EP), and reduced carbon footprint (CF) of the system compared with those under CT-RI. Use of different mulches also increased the energy use efficiency and system productivity compared with those under NM. The total CO<sub>2</sub>-e emission (CF) was higher under CT-RI (2307 kg CO<sub>2</sub>-e/ha) as compared to those under NT-RR (2013 kg CO<sub>2</sub>-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 based cropping system in India and similar agro-eco-regions elsewhere in the rice based cropping system in the world.

#### Keywords

Carbon footprint, Carbon sequestration, Input energy use, Output energy, Net energy

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## Introduction

Soil is involved in the biogeochemical cycles of carbon (C) and nitrogen (N), and thus is a key compartment for climate regulation either by emitting greenhouse gases (GHGs) or by sequestering C (Fig.1). Soil stores vast amounts of C: the first meters of mineral soils contain between 1,500 and 2,400 Pg of organic C (Ciais *et al.*, 2013; Stockmann *et al.*, 2013). This is about three to four times the amount of C in vegetation (450–650 PgC) and twice to three times the amount in the atmosphere (~829 GtC). Moreover, peat soils and permafrost account for more than 1,500 Pg of C. Concerning emissions; CO<sub>2</sub> is released from soils due to biological decay of plant litter and soil organic matter (Smith, 2004). Together with the respiration of vegetation it represents a flux of 118.7 PgC a year, which is less than the photosynthesis flux (123 PgC yr<sup>-1</sup>) actually turning land into a sink. Methane (CH<sub>4</sub>) is produced when organic materials decompose in oxygen-depleted conditions, such as in rice paddies or under flooded conditions (Mosier *et al.*, 1998). Rice cultivation is responsible for 24–30 Pg C a year that is nearly half of the emissions originating from livestock. Nitrous oxide (N<sub>2</sub>O) is part of the global N cycle and is linked with other forms of N (e.g., organic, ammonia, nitrate). In soil, N<sub>2</sub>O is generated by the microbial transformation of organic and mineral N, and is often enhanced under wet conditions (Oenema *et al.*, 2005). Emissions from soil, linked to cultivation are estimated between 1.7 and 4.8 Tg N<sub>2</sub>O a year and are the main anthropic source.

Emissions in agriculture also include those from the inputs of fertilizers, manures, plant litter, and those from the interwoven flows of N among several pools. Farming also removes CH<sub>4</sub> from the ecosystem by the oxidative activity of soil microbes, but such removals are small compared with emissions (Janzen *et*

*al.*, 2006). In general, carbon footprint stands for a certain amount of gaseous emissions that are relevant to climate change and associated with human production or consumption activities. With regards to crop production and other agricultural services, a larger portion of the total GHG emission occurs as N<sub>2</sub>O, rather than CO<sub>2</sub> (Janzen *et al.*, 2006). Therefore, in our discussion, the carbon footprint relevant to agricultural products and processes is defined as the total amount of greenhouse gas emission associated with a food product or a service, expressed in carbon dioxide equivalence (CO<sub>2</sub>e). The focus is on two components: (1) the total emission per unit area per year expressed as kilograms CO<sub>2</sub>e per hectare per year, and (2) the emission per unit (kilograms) of product produced expressed as kilograms CO<sub>2</sub>e per kilogram of product. These two components parallel the approaches with which the efficiency of agricultural productivity is evaluated, i.e., (1) the net production per unit area such as grain yield per hectare per year and (2) the costs associated with the production of a unit of product such as input costs per kilograms of grain produced.

Most consumers and citizens are willing to pay for measures leading to drastic reductions in GHG emissions. A growing number of consumers want to know the carbon footprint of the food products they buy in grocery stores. In response, some multinational food companies have proposed that suppliers identify on product labels the CO<sub>2</sub>e emissions released in the production of that particular food item. Farmers are eager to adopt improved mitigation practices on their farms. Therefore, it is critical that integrated strategies and practices are developed for farming systems so as to maximize agriculture's productivity while minimizing the greenhouse gas emissions in the production of grains, fibers, feedstock's, and other agricultural products. Energy is one of

the most valuable inputs in production agriculture. It is invested in various forms such as mechanical (farm machines, human labour, animal draft), chemical fertilizer, pesticides, herbicides), electrical, etc. The amount of energy used in agricultural production, processing and distribution should be significantly high in order to feed the expanding population and to meet other social and economic goals. Sufficient availability of the right energy and its effective and efficient use are prerequisites for improved agricultural production. It was realized that crop yields and food supplies are directly linked to energy (Stout, 1990). Bridges and Smith (1979) developed a method for determining the total energy input for agricultural practices. Lal *et al.*, (2003), in their study on energy use and output assessment of food-forage production systems, reported sorghum (single cut) – berseem + mustard – maize + cowpea as most energy efficient and remunerative system among the five forage systems. The cropping systems were evaluated in terms of energy use, biomass production and gross income etc. The benefit-to-cost (B: C) ratio for the most energy efficient forage production was 1.37:1. The fertility of the soil could also be maintained by increasing organic carbon.

Rice in general is grown using transplanting of seedlings under puddled field conditions. It requires huge amount of the input energy for the growing the seedlings, transplanting, puddling, irrigation etc. With the advancement in the technology and general agricultural developments, the use of the energy resources has increased markedly. Traditional, low energy farming is being replaced by modern one which requires more energy use. The energy-agriculture relationship is therefore becoming more and more important with the intensification of the cropping systems, which is considered to be the only means of raising agricultural output in land scarce situations. In India, about 28 to

30 Mt of nutrients (N, P, K) are removed from the soil whereas, 18 to 20 Mt are added through all sources, leaving a deficit of about 10 Mt yearly (Singh and Singh, 2003). Therefore, management of organic and mineral fertilizers is, advocated to meet the nutrient needs, improve soil quality, and to obtain sustainable and higher yields. Application of adequate amount and judicious combination of organic and inorganic fertilizers commensurations with the crop needs is considered imperative for realizing sustainable yields of these crops when grown in sequence under limited irrigated (Satyajeet *et al.*, 2007). To optimize the use of organic and mineral sources, information is needed on the rate and pattern of N and P mineralization in the soil from organic source (Hadas and Portnoy, 1994). Application of organic source with wide C: N ratio may increase the immobilization of fertilizer N, thereby influencing crop availability and N losses. On the other hand, combining with fertilizer N lowers the C: N ratio of the organic source, leading to an enhanced N mineralization (Singh *et al.*, 2003). Judicious and efficient nutrient management in cropping system depends on understanding complex interactions between soil and experimental site properties, crop characteristics, climate, and biological processes influencing nutrient dynamics. Preceding and succeeding crop history and other management practices also affect nutrient management strategies. The complexity of the interacting factors indicates that site specific knowledge may be needed for best nutrient management. The in situ soil core technique can be helpful in evaluating management effects on nutrient availability and provide site-specific information needed for improved nutrient management (Kolberg *et al.*, 1997). Crop establishment is also most important concern in this cropping sequence conservation agriculture based ridge-furrow method plays a vital role (Jat *et al.*, 2008, Naresh *et al.*, 2018). Because moisture is the

principle growing factor for crop production under irrigated conditions, which needs to be conserved for optimization of nutrient use and maximizing the yield advantages of this cropping system (Naresh *et al.*, 2018). Agricultural productivity is closely linked with the carbon and energy efficiency.

Tillage is an energy-intensive farm operation 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. Experimental confirmations from 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 (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). Further, reducing fossil fuel consumption and dependency on agro-chemicals may reduce energy input, decrease GHG emissions, reduce the cost of cultivation and enhance the nutrient use efficiency (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 (Lu and Liao, 2016).The present review study was undertaken to find out the best conservation agriculture based crop establishment and efficient nutrient management practices for cereal based cropping system to achieve sustainable and high productivity, carbon and energy efficiencies and sustainable soil health and quality. We also used some examples from subtropical India and summarized key agronomic strategies for reducing the carbon footprint in cereal based system with diverse organic and inorganic fertilizer management options in subtropical environments and to identify energy efficient cereal cropping systems.

### **Strategies and practices for lowering carbon footprints**

Yadav *et al.*, (2018) also found that 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 those under 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.2). 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. Thus, efficient utilization of resources (i.e., energy, water, human labor) through NT-RR and mulch application are feasible 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.

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. The NT-RR reduced the energy requirement from 27,630 MJ/ha under CT-RI to 16,727 MJ/ha. 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).

Gan *et al.*, (2003) also found that diversified cropping systems compared with monoculture systems significantly reduced the production inputs and increased the grain and straw yields of durum wheat. Thus, compared with monoculture systems, durum wheat grown in diversified cropping systems had a lower carbon footprint. Durum wheat preceded by a pulse crop produced grain with a carbon footprint of 0.200 kg CO<sub>2</sub>e kg<sup>-1</sup> of product, 46% lower than when preceded by a cereal crop. Furthermore, durum wheat had a carbon footprint of 0.301 kg CO<sub>2</sub>e kg<sup>-1</sup> of grain when grown after an oilseed crop 19% lower than when grown after a cereal (Fig. 3).

Gan *et al.*, (2011) revealed that synthetic N fertilizers used in the production of a cereal crop contributed the greatest percentage of the

carbon footprint, averaging 65 % of the total emissions. The total emission included direct and indirect emissions through volatilization of NH<sub>3</sub> and NO<sub>x</sub>, leaching of nitrate from the application of N fertilizers on farm fields (27 % of the total emissions), and emissions associated with the production, transportation, storage, and delivery of N fertilizers to the farm gate (38 %). The intensity of the emissions associated with N fertilization depends on the ratio of precipitation to potential evapo-transpiration during the period when the N fertilizer is applied (Gregorich *et al.*, 2005).

Zhang and Zhang, (2016) reported that the carbon emissions from grain crop production consist of the following four components: (1) emissions from the upstream production and transport of agricultural inputs, (2) direct or indirect emissions induced by various agricultural management processes, (3) emissions from the burning of crop residues and (4) the soil carbon sequestration associated with various production methods (i.e., minimum and no-till practices, straw returning and fertilization) implemented during crop growth. According to LCA theory, the field production carbon footprint includes carbon emissions and carbon sequestration at two points in the production life cycle: the upstream links are associated with the creation of inputs used in agricultural production and processing (i.e., seeds, fertilizer, pesticides, machinery and agricultural film) and the in-field emissions and sequestration are associated with field cultivation (i.e., tillage, sowing, plant protection, harvesting and straw treatment) (Fig. 4a).

Liu *et al.*, (2016) reported that the carbon footprint (CF) of rice production was assessed by considering fertilizer and pesticide consumption, farm-work (plowing, seedling transplantation, fertilizer and pesticide



spraying, irrigation, and harvest), soil N<sub>2</sub>O and CH<sub>4</sub> emissions, soil carbon increment, and energy budget of bio-char production. Carbon cost from straw or bio-char transportation was ignored based on the assumption that the pyrolysis unit for producing bio-char was fed by a local straw supply (Fig.4b).

Yadav *et al.*, (2018) reported that the adoption of NT-RR saved 10,903 MJ/ha energy (~39%) over that used under CT-RI (Fig. 5). 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. 5). Similarly, diesel energy use was also reduced by 94% (5462 MJ/ha) under NTRR 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. 5).

Chen *et al.*, (2014) included carbon emissions from fertilizer production and nitrogen fertilization, but they did not include emissions from manure, pesticides or agricultural films. Zhang *et al.*, (2017) observed that the carbon footprint (emission minus soil carbon sequestration), we found that the three crops emitted more carbon than they sequestered. Of the three main crops in 2013, maize had the lowest carbon footprint, i.e., 4052 kg ce/ha of carbon per unit area or 0.48 kg ce/kg per unit yield. The carbon

footprint of wheat was 5455 kg ce/ha per unit area or 0.75 kg ce/kg per unit yield, while rice had the highest carbon footprint, i.e., 11881 kg ce/ha per unit area or 1.60 kg ce/kg per unit yield. The factors contributing to these emissions varied markedly between crops. Rice yielded the greatest emissions (maximum: 15679 kg ce/ha) with 45% consisting of CH<sub>4</sub> derived from paddy fields, 21% from straw burning, 14% from nitrogen fertilizer, 13% from fossil fuels for agricultural machinery and 4% from electricity consumption for irrigation. Wheat exhibited a high carbon emission value of 9119 kg ce/ha, of which 37% came from electricity consumption for irrigation, 28% from nitrogen fertilizers, 25% from fuel consumption by agricultural machinery and 6% from straw burning. Maize emitted 7900 kg ce/ha with 39% coming from nitrogen fertilizer, 20% from fuel consumption by agricultural machinery, 18% from electricity consumption for irrigation and 18% from straw burning (Fig.6a). However, the carbon footprint of maize production varied substantially among the eight regions in China, ranging from 1192 kg ce/ha to 9282 kg ce/ha (Fig. 5b) (the carbon footprint per unit yield ranged from 0.25 kg ce/kg to 0.73 kg ce/kg so that the regions could be divided into four groups.

The greatest carbon footprint was found in V, where the carbon per unit area reached 9282 kg ce/ha. This result likely stemmed from the high overall carbon emissions (12967 kg ce/ha) and low carbon sequestration (3685 kg ce/ha), which can be explained as follows (Fig.6b). (1) The general use of deep ploughing required fossil energy that resulted in high carbon emissions (46%), particularly when compared to no-till operations; in addition, electricity consumption for irrigation was relatively high. (2) Nitrogen fertilizer inputs were also much greater in this region, averaging 328 kg N/ha. (3) Low temperatures

and drought conditions reduced the efficiency of soil organic carbon transformation after straw returning.

Yadav *et al.*, (2018) reported that the influence of different factors on GHGs emissions under different tillage and mulch systems indicated that CO<sub>2</sub>-emissions from N<sub>2</sub>O based estimation contributed the maximum followed by that by the fertilizer use in both the tillage systems. 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<sub>2</sub>-e/ha indicated that NTRR emitted 328 kg (~74%) less GHGs from diesel than those emitted under the CT-RI. However, CO<sub>2</sub>-e emission was slightly increased with the application of plant protection chemicals under NT-RR as compared to those under CT-RI (Fig.7). Pratibha *et al.*, (2015) also reported that NT has low GHGs emissions as compared to those under CT. CO<sub>2</sub>-e emission from N<sub>2</sub>O (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.7). 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<sub>2</sub>-e emission was higher under CT-RI (2307 kg CO<sub>2</sub>-e/ha) as compared to those under NT-RR (2013 kg CO<sub>2</sub>-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).

### **Energy in rice-wheat cultivation**

Rautaray *et al.*, (2017) observed that the energy input was less by 20.6% and 28.4 % in SCA in the year 2010 and 2011, respectively, as compared to the CNV (10.2 GJ ha<sup>-1</sup>). Low energy input for the SCA was associated with the low input of chemical fertilizers (43.3 kg N, 6.9 kg P<sub>2</sub>O<sub>5</sub> and 13.8 kg K<sub>2</sub>O ha<sup>-1</sup>). It was especially important for the nutrient nitrogen with maximum amount saved (43.3 kg ha<sup>-1</sup>) and highest energy equivalent (60.6 MJ per kg nitrogen) as compared to phosphorus and potash. Also, there was save in energy (447 MJ) due to less labour requirement for hand weeding possibly due to allelopathic effects of *Sesbania* on weed population. Energy required for growing rainfed *Sesbania* with the existing practice of summer ploughing was very low (294 MJ towards seed and 23.5 MJ ha<sup>-1</sup> as human energy for seeding) as compared to energy saved through chemical fertilizers (2793 MJ) and less weeding (447 MJ). Ramchandra and Nagarathna (2001) reported that energy input for rice cultivation in the coastal zone of Uttara Kannada district was 22.2 GJ ha<sup>-1</sup>, out of which 13.59 GJ ha<sup>-1</sup> was due to addition of FYM alone. Thus, energy input in their study was 8.61 GJ ha<sup>-1</sup> without considering the energy input through FYM. Net energy in the SCA (135.4 and 138.8 GJ ha<sup>-1</sup> in the first and second year, respectively) was higher as compared to CNV. Also, the energy output: input ratio and energy productivity were higher for the SCA. These parameters indicate higher energy efficiency in case of SCA as compared to CNV. Saikia *et al.*, (2004) reported energy output: input ratio of 13.5 which is close to the value for the treatment CNV (14.0). Higher ratio (17.7 and 20.0 in the first and second year, respectively) for SCA in this experiment is mainly due to saving in chemical fertilizers and less labour requirement in weeding.

Rajesh *et al.*, (2018) revealed that the source wise energy consumption with percentage share for rice is presented in Fig. 8a. It is clear from these figures, electricity (34%) was a highest input followed by fertilizer (33%), diesel (19%), farmyard manure (4%), human (4%), machinery (including tractor) (3%), seed (1%) and chemical (2%). Total input energy involved for rice was 23773.84 MJ/ha. The component of commercial energy was found to be highest (93%) and rest was non-commercial energy. The energy from direct, indirect, renewable and non-renewable sources was 57, 43, 9 and 91%, respectively. Moreover, the percentage source wise energy share for raising wheat is presented in Fig. 8b. It is clearly shown that fertilizer (36%) was a major source of energy followed by diesel (28%) electricity (19%) and seed (8%). The remaining was chemical (4%), farmyard manure (3%), machinery (including tractor) (1%) and human (1%).

Parihar *et al.*, (2018) also found that tillage practices the mean total energy of 119764 MJ ha<sup>-1</sup> was consumed in zero tillage flat planting (ZT) followed by in permanent bed planting (116294 MJ ha<sup>-1</sup>) and the least in conventional tillage (CT, 115787 MJ ha<sup>-1</sup>) (Fig. 9a). Maximum renewable energy and non-renewable input energy (132957MJ ha<sup>-1</sup>) was recorded under MMS rotation followed by MWMB as compared to other cropping systems (MMuMb and MMS). Overall, renewable energy through crop residues biomass contributed maximum input energy followed by non-renewable resources viz., diesel, fertilizers, chemicals and machineries. The percentage share of these input energy resources followed the order with the highest by crop residues (72.6%), followed by fertilizers (14.8%), diesel (6.8%), water (1.6%), seeds (1.3%), human labors (1.3%) plant protection chemicals (1.1%), and the least by machineries (0.5%) (Fig. 9b). Further, the trend of operation-wise input

energy utilization showed that the highest energy was consumed in residue application (71.9%) followed by fertilizer (15.3%), irrigation (5.8%), land preparation and sowing (3.7%), harvesting and threshing (1.8%), herbicide application (0.8%), and the least by plant protection (0.3%) (Fig. 9c). These energy utilization patterns of either source-wise or operation-wise may be due to less mechanization and more use of human/animal power in Indian agriculture (Fig. 9b and 9c). This might be due to carbon inputs and outputs were remarkably influenced by the tillage and nutrient management practices. The increment in total energy was 32.4, 13.9 and 13.3% over control and sole application of FYM at 6t/ha while the energy efficiency (12.78 MJ/ha) and energy productivity (0.98 MJ/ha) was maximum with sole application of FYM at 6t/ha while the energy efficiency energy productivity and energy intensity were shown reverse trend with increasing fertility levels and observed highest with control and lowest with highest fertility level.

Soni *et al.*, (2018) revealed that direct energy contributed 30.81% and 24.84% of the total energy input in the paddy-wheat (PW) and paddy-potato (PP) cropping systems, respectively. Renewable energy use was higher in PP systems, with a contribution of 21.66% compared to 9.59% in the PW system. The higher renewable energy input in the PP system can be explained by the higher human and animal energy input in the system. Fig. 10a and 10b illustrate the share of direct and indirect energy inputs and the output energy in the two systems. India is an important agricultural country, producing 22.3%, 11.78%, and 2% of global rice, wheat, and maize grains, respectively (FAO, 2017). India is also the largest emitter of agricultural GHG emissions, accounting for 13.0% of global total agricultural emissions (FAO, 2017). In recent decades, India's agricultural output has increased due to high input rates of



pesticides and fertilizers but with the little adoption of conservation agriculture (CA). India has announced that by 2020 it will reduce carbon dioxide emissions per unit of GDP by 20 to 25% and by 30-35% in 2030, compared to the 2005 level.

Parihar *et al.*, (2018) reported that tillage practices residue plus fertilizer application consumed major (76-81%) input energy, of which residue application consumed about 43.7-49.8% and fertilizer application consumed about 31.2-32.4%. CA based (ZT and PB) planted cereal crop consumed 3-5% less energy, compare to conventionally tilled (Fig. 11a). However, fertilizer use was the second most important energy contributor with 29-36% share in total input energy, and rest all other operations consumed about 17-22% of input energy (Fig. 11b). Energy consumed in the residue application varied due to retention/ incorporation of differential amount of residue biomass in different tillage (ZT, PB and CT) and diversified crop rotations (MWMb, MCS, MMuMb and MMS) treatments. Retention/ incorporation of crop residue have several advantages like better soil health, higher crop productivity and improved environmental quality. Further, the crop residue is a renewable energy source and can also supplement plant nutrients without any negative impact on crop productivity. This might be due to less consumption of water, labour, and fuel for irrigating in the PB plots than to CT plots and also the surface retention of crop residue in CA based PB and ZT systems helped in lowering down the evaporation losses and hence conserving more soil moisture (Parihar *et al.*, 2016; Jat *et al.*, 2013; Aggarwal and Goswami, 2003).

Irrespective of tillage and crop establishment in winter season crops, residue application contributed maximum (61-87%) to the total input energy. While, the next energy consuming operation was fertilizer

application (5-21%) followed by irrigation (3-11%) and land preparation and sowing (1.2-6.6%). However, herbicide application and inter-culture operation adopted to control the weeds in CT plots consumed 98-101% less input energy than CA based ZT and PB plots. Liu *et al.*, (2016) also found that the wheat in the continuous wheat system produced the highest grain yield and gained highest soil organic carbon over the years, leading to the smallest footprint value at  $-0.441 \text{ kg CO}_2\text{eq kg}^{-1}$  of grain, significantly lower than the footprint for the other three systems which ranged between  $-0.102$  to  $-0.116 \text{ kg CO}_2\text{eq kg}^{-1}$  of grain.

Jat *et al.*, (2019) also found that the cropping systems (MMuMb and MWMb) remained at par with respect to yield within same tillage and residue management practices. However, crops planted on PB with residue registered 11.7% increase in system productivity compared to PB-R. Highest PEY (1.91 Mg/ha) and APE (87.4 adult/ha/year) were registered in MWMb under PB+R and N through NCU (Fig. 12a). Among N management treatments, highest system productivity was recorded in N through NCU in PB+R and PB-R being at par with N through PU under PB-R and N through SCU under PB+R. N management through Neem coated urea (NCU) recorded 2.3 and 10.9% higher system productivity compared with non-coated prilled urea plot under PB-R and PB+R, respectively. In general, the superiority of coated urea materials over PU is due to the slow release of nitrogen through the coating, synchronized with the nitrogen need of the growing plants.

Nitrogen is released slowly and is absorbed and utilized by the plants effectively, hence with minimization of losses; crop use increases and simultaneously the system productivity. Neem oil extracted from seed kernels contains various kind of bitter,

especially the meliacins that have been identified in retarding the process of nitrification of Urea. The bio-molecules having antibacterial action against Gram negative and Gram-positive microorganisms act as an active Nitrification Inhibitors. In this way, NCU maintained superiority over other coated materials due to its nitrification inhibiting character which suppressed the rate

of formation and leaching loss of N as  $\text{NO}_3^-$ . Neem cake has acidic properties which also retarded the volatilization loss of  $\text{NH}_3$  through reducing the alkalinity of the medium in the immediate vicinity of urea prills. Gagnon *et al.*, (2012) and Sanjay-Kumar *et al.*, (2015) had also similar finding for the effectiveness of coated fertilizer towards a higher yield of ZT maize..

Fig.1 Soil and GHGs fluxes (adapted from Ciaia *et al.*, 2013)

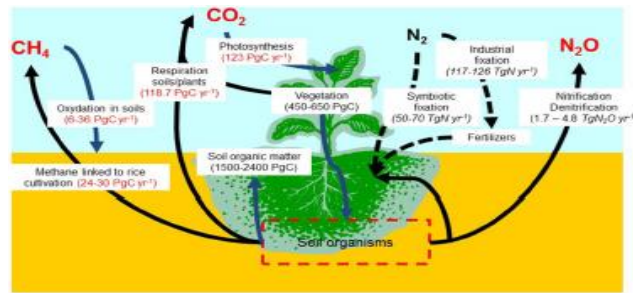


Fig.2 Share of different component of cost of cultivation and cost saving over respective component under different tillage practices (CT-Conventional tillage; NT-No-till; RI-100% residue incorporation; RR-100% residue retention)

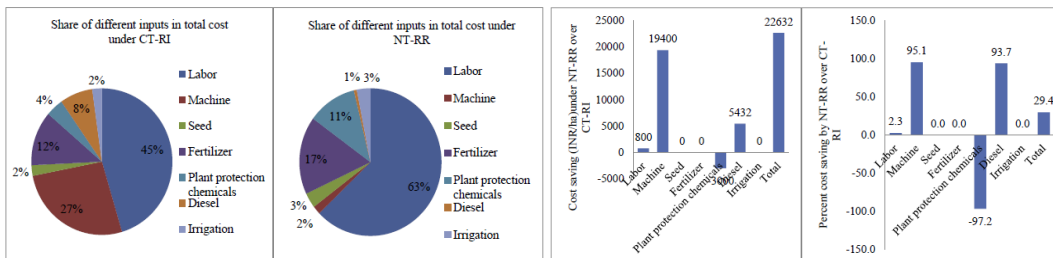
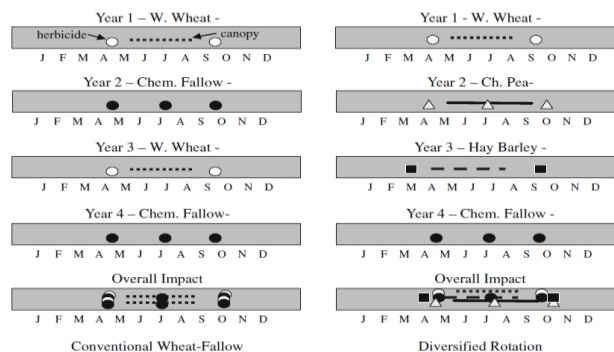
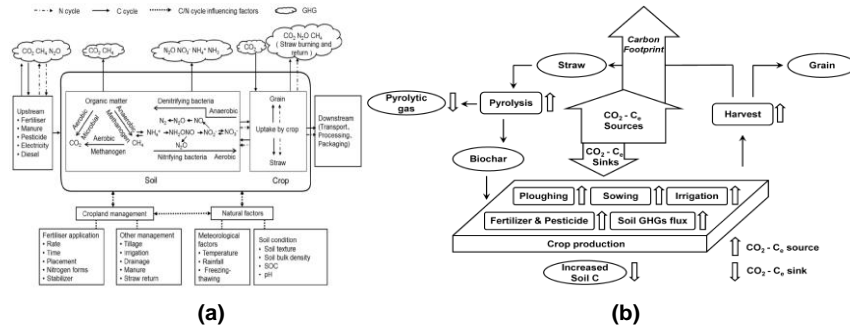


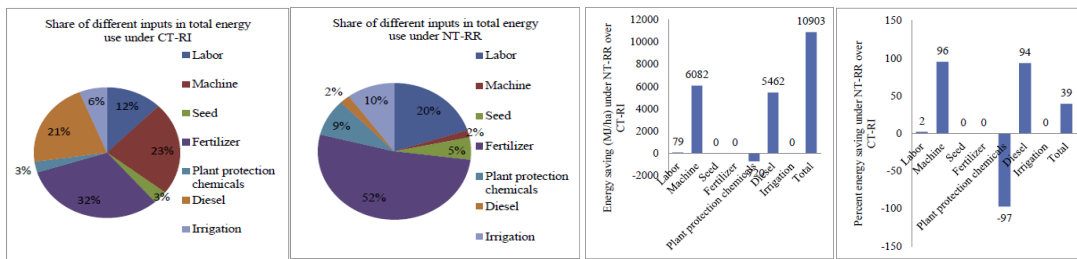
Fig.3 Conventional and diversified rotations differ in the type and timing of weed management practices, seeding dates, and canopy characteristics (adopted from Gan *et al.*, 2010)



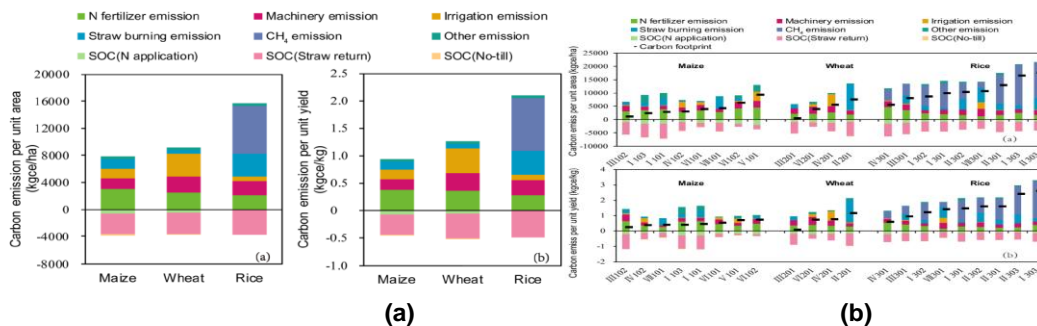
**Fig.4 (a)** A theoretical model of the carbon footprint of crop production (adopted from Zhang and Zhang, 2016); **(b)** Carbon footprint budget in one life cycle of crop production under bio-char amendment. Carbon footprint = CO<sub>2</sub>-Ce sources – CO<sub>2</sub>-Ce sinks. CO<sub>2</sub>-Ce sources involve plowing, sowing, irrigation, fertilizer and pesticide input, harvest, soil N<sub>2</sub>O and CH<sub>4</sub> emissions and total electric energy cost for pyrolysis process (adopted from Liu et al., 2016)



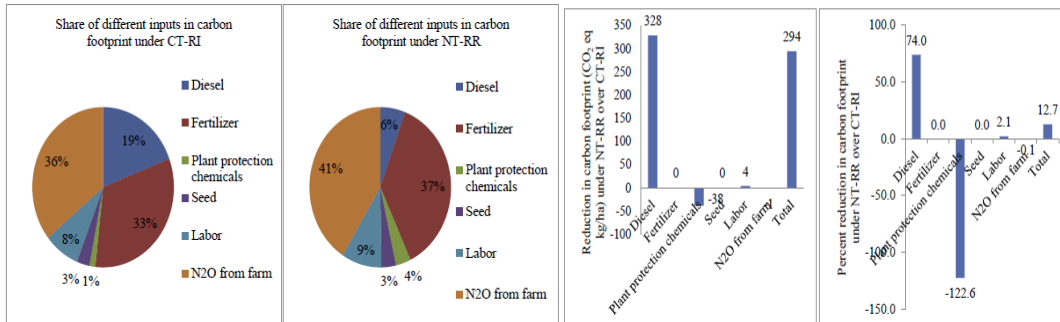
**Fig.5** Share of different component of energy and energy saving over respective component under different tillage (CT- Conventional tillage; NT-No-till; RI- 100% residue incorporation; RR-100% residue retention)



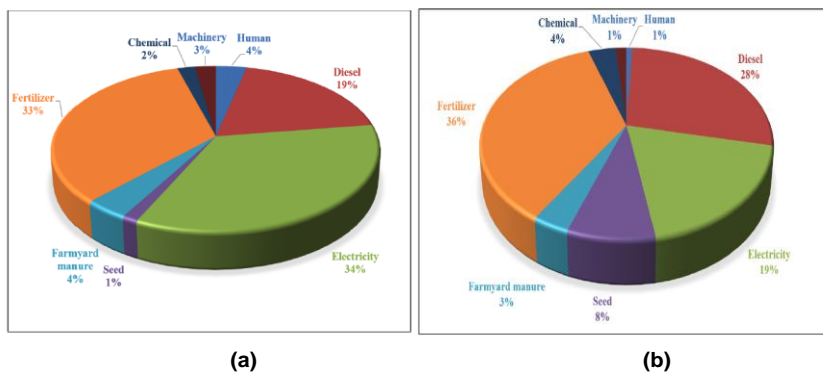
**Fig.6 (a)** Carbon emission and carbon sequestration components per unit area/yield for the three primary grain crops; **(b)** Distribution of carbon emissions and carbon sequestration among the three main crops in different areas “Other emission” includes emissions from the upstream production and transport of agricultural inputs (such as chemical fertilizer, agricultural film, pesticides and manure)



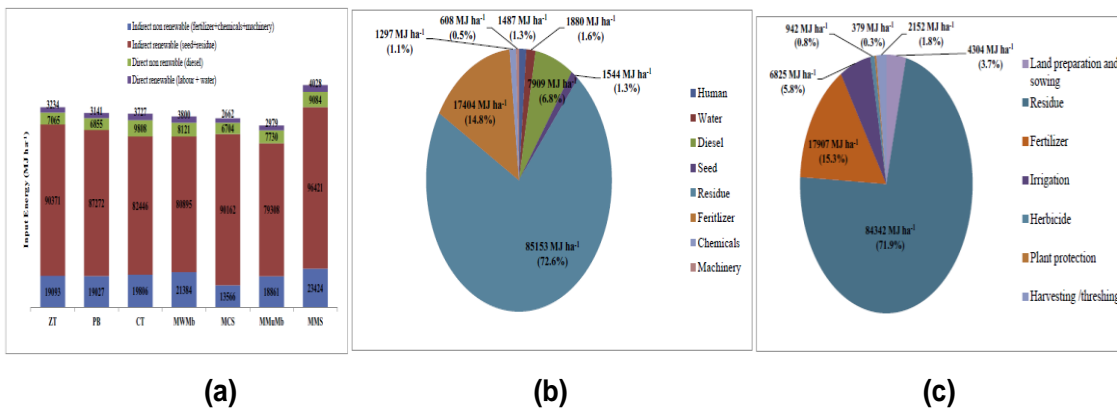
**Fig.7** Share of different inputs of component carbon footprint and reduction in carbon footprint under different inputs (CT- Conventional tillage; NT-No-till; RI- 100% residue incorporation; RR-100% residue retention



**Fig.8 (a)** Source Wise Energy Consumption for Raising Rice; **(b)** Source Wise Energy Consumption Percentage Share for Wheat

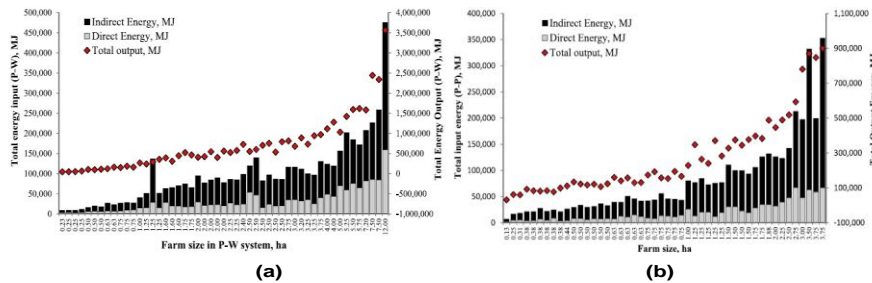


**Fig.9 (a)** Renewable and non-renewable input energy (MJ ha<sup>-1</sup>) under different tillage practices **(b)** Source-wise input energy in contrasting tillage and cereal based cropping system **(c)** Operation-wise input energy in contrasting tillage and cereal based cropping systems



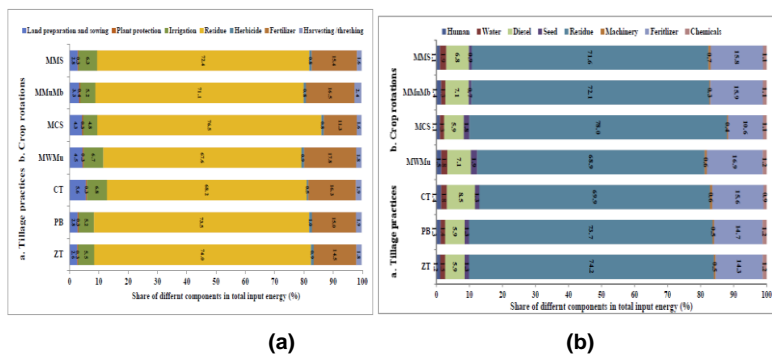


**Fig.10 (a)** Share of direct and indirect energy sources to total input energy, and output energy of paddy–wheat system; **(b)** Share of direct and indirect energy sources to total input energy, and output energy of paddy–potato system

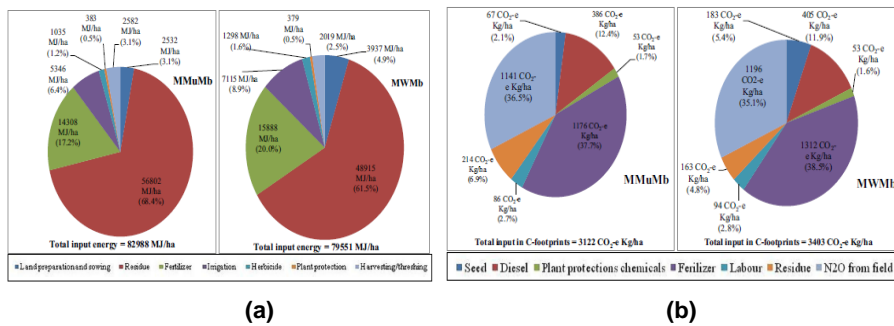


**Fig.11 (a)** Operation-wise input energy-use (%) under contrasting tillage practices (a) cropping systems (b)

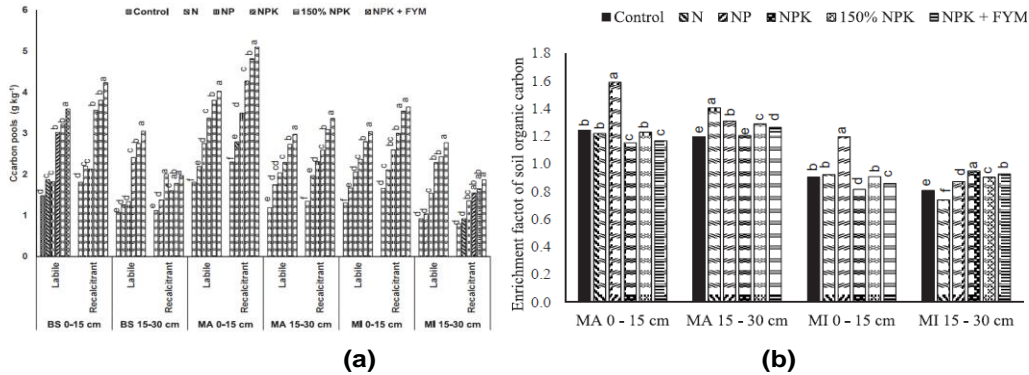
**Fig.11 (b)** Source-wise input energy-use (%) under contrasting tillage practices (a) cropping systems (b)



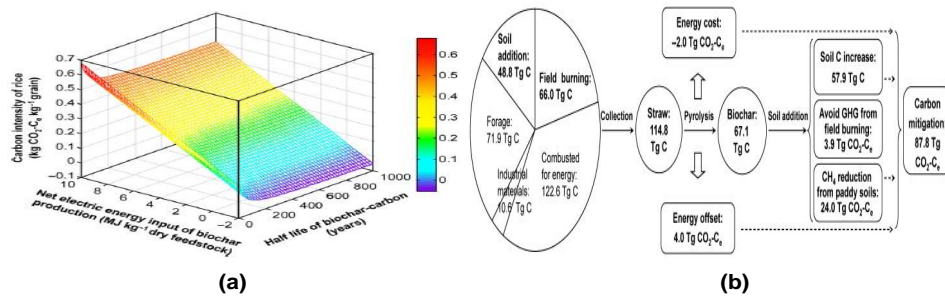
**Fig.12 (a)** Share of different farming operations in energy input of maize-mustard-mungbean (MMuMb) and maize-wheat-mungbean (MWMb) cropping systems under tillage, residue and nitrogen management practices; **(b)** Share of different inputs towards carbon footprints of maize-mustard-mungbean (MMuMb) and maize-wheat-mungbean (MWMb) cropping systems under various tillage, residue and nitrogen management practices



**Fig.13 (a)** Labile and recalcitrant carbon pools in bulk soils and aggregates as affected by long-term fertilization in the 0–15 and 15–30 cm soil layers under a wheat based cropping system in an Inceptisol; **(b)** Enrichment factor of soil organic C (SOC) in aggregates as affected by 44 years of fertilization under wheat based cropping system in an Inceptisol



**Fig.14 (a)** Carbon intensity (CI) of rice production under bio-char amendment in response to net electric energy input of bio-char production ( $E_{net}$ ) and half-life of bio-char-carbon ( $T_{1/2}$ ); **(b)** Estimation of annual carbon mitigation potential via transformation of straw into bio-char



Jat *et al.*, (2019) observed that Irrespective of residue retention the mean total energy of 82,988 and 79,551 MJ/ha was used in the MMuMb and MWMB rotations, respectively (Fig.12b). Largely, crop residues contributed highest energy input 68.4 and 61.5% in MMuMb and MWMB cropping system, respectively. Next to it, the major energy demanding operation is fertilizer application, it accounts for about 17.2% of total energy in MMuMb and 20.0% in MWMB.

Parihar *et al.*, (2017a) described crop residue management as most energy demanding operation (71–89%) in maize-based cropping system. MWMB required 1405 MJ/ha more energy for land preparation and sowing

compared to MMuMb. Similarly, irrigation operation in MWMB consumed about 1769 MJ/ha more energy than MMuMb. This was mainly because, wheat cultivation in MWMB cropping system required more irrigations than mustard. Among various N management practices total energy requirement was highest in plots under N application through NCU (149,068 MJ/ha), followed by N through SCU (146,512 MJ/ha) >N through PU (141,887 MJ/ha) N unfertilized (98,527 MJ/ha) in PB+R practice.

Ghosh *et al.*, (2018) also found that the plots with NPK+FYM had significantly higher labile C within macro-aggregates compared with NPK and control plots (Fig. 13a).

However, labile C concentrations within macro-aggregates of 150% NPK and NPK+FYM were similar. Labile: recalcitrant C in macro-aggregates of NPK+FYM was 1.38:1. There was a gradual decrease in labile C within macro-aggregates in NP, N and control plots. Similarly, recalcitrant C closely followed the trend of labile C within macro-aggregates, except under NP plots, which had significantly less labile C within macro-aggregates than all other plots. However, macro-aggregates of NPK+FYM had 19% and 46% higher recalcitrant C than NPK and NP plots. Like labile C within macro-aggregates, 150% NPK and NPK+FYM plots had similar recalcitrant C pools. Similar trend of C concentration was observed within micro-aggregates, as was observed within macro-aggregates. Moreover, labile recalcitrant C in bulk soils and micro-aggregates of NPK, 150% NPK and NPK+FYM plots were similar and significantly higher than control, N and NP plots, and signifying higher rate of C sequestration in the former treatments than the latter ones in sub-surface layer. Labile: recalcitrant C ratios within macro-aggregates were similar for all treatments. When expressed on a total soil basis, macro-aggregates accounted larger part of total SOC in surface and subsurface soil layers. Interestingly, macro-aggregates of NP plots in soil surface had 1.36 and 1.38 times greater SOC enrichment than NPK+FYM and NPK treated plots. Whereas, macro-aggregates from N plots had 1.12 and 1.18 times greater C enrichment than NPK+FYM and NPK plots, respectively, in sub-surface soil. Carbon enrichment factor of soil micro-aggregates from all plots were <1, indicating net C depletion (Fig. 13b). The increased labile C content with application of fertilizers and manure could be because of the priming effect of applied nutrients on fresh organic materials in the soils. All these amendments stimulate the microbial activity helping SOC

decomposition due to rapid excretion of the labile C (Tripathi *et al.*, 2014).

Petersen *et al.*, (2006) tracked N<sub>2</sub>O emissions from five rotation sequences and found N<sub>2</sub>O emissions were lower from the organic than conventional crop rotations, ranging from 4.0 kg N<sub>2</sub>O-N ha<sup>-1</sup> to 8.0 kg N<sub>2</sub>O-N ha<sup>-1</sup> across all crops as total N inputs increased from 100 to 300 kg N ha<sup>-1</sup> yr<sup>-1</sup>. Robertson *et al.*, (2000) compared the net global warming potential (GWP) of conventional tillage, no-till, low input and organic management of a corn soybean-wheat system over 8 yrs. After converting the combined effects of measured N<sub>2</sub>O production, CH<sub>4</sub> oxidation and C sequestration, plus the CO<sub>2</sub> costs of agronomic inputs to CO<sub>2</sub> equivalents (g CO<sub>2</sub> m<sup>-2</sup> yr<sup>-1</sup>) none of the systems provided net mitigation, and N<sub>2</sub>O production was the single greatest source of GWP. The no-till system had the lowest GWP (14), followed by organic (41), low input (63) and conventional (114). Cavigelli *et al.*, (2009) also calculated the greenhouse gas intensity (GHGI = GWP per unit of grain yield). The contribution of energy use to GWP was 807, 862, and 344 in NT, CT, and Org3, respectively. The contribution of N<sub>2</sub>O flux to GWP was 303, 406, and 540 kg CO<sub>2</sub>e ha<sup>-1</sup> y<sup>-1</sup> in NT, CT and Org3, respectively. The contribution of change in soil C to GWP was 0, 1080, and -1953 kg CO<sub>2</sub>e ha<sup>-1</sup> y<sup>-1</sup> in NT, CT and Org3, respectively. GWP (kg CO<sub>2</sub>e ha<sup>-1</sup> y<sup>-1</sup>) was positive in NT (1110) and CT (2348) and negative in Org3 (-1069), primarily due to differences in soil C and secondarily to differences in energy use among systems. Despite relatively low crop yields in Org3, GHGI (kg CO<sub>2</sub>e Mg grain<sup>-1</sup>) for Org3 was also negative (-207) and significantly lower than for NT (330) and CT (153). Org3 was thus a net sink, while NT and CT were net sources of CO<sub>2</sub>e. The authors concluded that common practices in organic systems including soil incorporation of

legume cover crops and animal manures can result in mitigation of GWP and GHGI relative to NT and CT systems, primarily by increasing soil C.

Dyer and Desjardins (2005) reported that GHG emissions for secondary tillage operations, such as discing that would require more draft power than finger weeders, as low ( $\sim 28 \text{ kg CO}_2 \text{ ha}^{-1}$ ) compared to plowing ( $90\sim 28 \text{ kg CO}_2 \text{ ha}^{-1}$ ) and between two to three times that for spraying ( $\sim 10 \text{ kg CO}_2 \text{ ha}^{-1}$ ). Manure spreading is also a relatively low E requiring practice. Bos *et al.*, (2010) also found that the energy requirements for imported organic manures were restricted to those for transport and application only and a 'zero energy' price for organic manures themselves was assumed. Consequently, E use was lower for a crop fertilized mainly with organic fertilizers than for a crop fertilized mainly with mineral fertilizers. On farms, manure (or compost) application is a relatively low fuel and E cost ( $< 10 \text{ kg CO}_2 \text{ ha}^{-1}$ ) when compared with tillage operations ( $> 80 \text{ kg CO}_2 \text{ ha}^{-1}$  and  $> 28 \text{ kg CO}_2 \text{ ha}^{-1}$  for plowing and discing respectively) and harvesting ( $> 33 \text{ kg CO}_2 \text{ ha}^{-1}$ ).

Liu *et al.*, (2016) revealed that bio-char was applied into soil, net electric energy input of bio-char production ( $E_{\text{net}}$ ) and half-life of bio-char- carbon ( $T_{1/2}$ ) are two of the most critical factors in influencing carbon footprint value in agricultural activities. CI of rice production under bio-char amendment has a positive and negative relationship with  $E_{\text{net}}$  and  $T_{1/2}$ , respectively (Fig.14a). However, based on the lowest energy consumption pattern of bio-char production in current study, a rough estimation on net carbon mitigation under bio-char strategy was about  $87.8 \text{ Tg CO}_2\text{-Ce yr}^{-1}$  by considering available straw source, soil carbon sequestration, avoided straw field-burning, and soil  $\text{CH}_4$

reduction from paddy soils (Fig.14b). This value is higher than a previous estimate of  $20.5\text{--}55.9 \text{ Tg CO}_2\text{-Ce yr}^{-1}$  reported by Dickie *et al.*, (2014).

In conclusions the intensive agricultural production systems rely on fossil fuel burning for energy management and having a lion share in the energy input and GHGs emissions. The fossil fuel based  $\text{CO}_2$  emissions are major contributors to energy input and GWP in agro-ecosystems. Hence, high water and fertilizer inputs as well as the operation of machinery for agricultural purposes not only induced soil  $\text{N}_2\text{O}$  and  $\text{CH}_4$  emissions but resulted in considerable consumption of energy from fossil fuels. Straw burning further increased the carbon emissions of these grain crops. It is recommended that intermittent irrigation be optimized to reduce the emission of  $\text{CH}_4$  from rice paddies and that the irrigation of wheat, nitrogen fertilizer management for maize and straw returning for rice and maize be optimized to reduce the carbon footprint of these crops. The carbon balance can be an indicator of agricultural production efficiency, soil fertility and environmental pollution. So identifying the carbon footprint of a crop is an important component of sustainable agriculture. In aspects of carbon and energy efficiency the scope of diverse organic has immense importance, as it has the potential to replace a part of chemical fertilizer and then farming will be more dependent on renewable sources.

Clear and significant differences exist in energy and GHG emission performance between organic and conventional operations. Organic generally has lower energy use and GHG emissions  $\text{ha}^{-1}$ , better energy input/output ratios per unit of product, but variable results for energy use and GHG emissions per unit of product. With some variability in results for field crops with



organic systems are consistently more energy efficient, beyond a 20% threshold, than conventional systems. Life cycle assessment on carbon footprint of crop production in bio-char-managed agro-ecosystem provided an insight into bio-char's role in the contribution of each process to carbon equivalent emissions. Based on pyrolytic gas-recycled pyrolysis technique with low energy cost, bio-char amendment could reduce carbon footprint of rice production compared with conventional straw return management, benefiting from significant soil carbon sequestration and reduced CH<sub>4</sub> emissions. In CA systems, crop residues contributed the maximum (~76%) in total energy input (167,995 MJ ha<sup>-1</sup>); however, fertilizer application (nonrenewable energy source) contributed the maximum (43%) in total energy input (47,760 MJ ha<sup>-1</sup>) in CT-based systems. CA-based cereal (rice/maize) systems recorded higher net energy and energy-intensiveness (EI) levels of 251% and 300%, respectively, compared with those of the CT-based rice-wheat system (RW/CT). There are huge gaps between the development of new cropping technologies and the implementation of the technologies in farming operations. Therefore in future, the synergistic combinations of the more diverse organic and inorganic fertilizer management options suitable for particular crop and cropping systems must be explored under CA to achieve the sustainable development growth

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