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Long-Term Tillage and Irrigation Management Practices: Impact on Carbon Budgeting and Energy Dynamics under Rice–Wheat Rotation of Indian Mid-Himalayan Region

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Abstract: In modern agriculture, reducing the carbon footprint and emission of greenhouse gases with greater energy efficiency are major issues for achieving the sustainability of agricultural production systems. To address this issue, a long-term field experiment was established from 2001 through 2016 with two contrasting tillage practices (ZT: zero tillage; CT: conventional tillage) and four irrigation schedules {I-1: pre-sowing (PS), I-2: PS + crown root initiation (CRI), I-3: PS + CRI + panicle initiation (PI)/flowering (FL), and I-4: PS + CRI + PI/FL + grain filling (GF)}. The grain yield of rice, wheat and the rice–wheat system was increased significantly by 23.6, 39.5 and 32.8%, respectively, with irrigation at four stages (I-4) compared to a single stage (I-1). Energy appraisal results exhibited that 17.2% higher energy was consumed under CT as compared to ZT (25,894 MJ ha^{-1}). Fertilizer application consumed the highest energy (46.5–54.5%), followed by irrigation (8.83–19.5%), and the lowest energy consumption was associated with winnowing, packing and transport (2.07–2.43%) operations. The total energy output of the rice–wheat system did not change significantly among contrast tillage, but higher energy was obtained under CT (214,603 MJ ha^{-1}) as compared to ZT (209,728 MJ ha^{-1}). ZT practice improved the energy use efficiency (EUE), energy productivity (Ep) and energy profitability (Eprof) by 16.6, 21.0 and 16.6%, respectively, over CT. The EUE, SE (specific energy), Ep, net energy return (NER) and Eprof were enhanced by 17.1, 16.6, 21.0, 36.5 and 20.6%, respectively, with irrigation at four stages (I-4) compared to a single stage (I-1). Zero tillage plots reflected a 8.24% higher carbon use efficiency (CUE) and a 9.0% lower carbon footprint than CT plots. Among irrigation schedules, application of I-4 showed a 8.13% higher CUE and a 9.0% lower carbon footprint over single irrigation (I-1). This investigation indicated that ZT with irrigation at four stages (I-4) was the most sustainable option for improving the EUE and CUE with minimal GHGs emissions from the rice–wheat cropping system of Indian mid-Himalayan regions.

Keywords: irrigation; tillage; carbon use efficiency; net energy return; GHGs emissions; carbon footprint

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Citation: Choudhary, M.; Panday, S.C.; Meena, V.S.; Yadav, R.P.; Singh, S.; Parihar, M.; Mishra, P.K.; Bisht, J.K.; Pattanayak, A. Long-Term Tillage and Irrigation Management Practices: Impact on Carbon Budgeting and Energy Dynamics under Rice–Wheat Rotation of Indian Mid-Himalayan Region. *Conservation* **2022**, 2, 388–401. https://doi.org/10.3390/conservation2020026

Academic Editor: Svein Øivind Solberg

Received: 15 March 2022
Accepted: 13 June 2022
Published: 17 June 2022

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1. Introduction

In order to achieve the self-sufficiency in food production level, intensive utilization of agricultural inputs such as seeds of improved varieties, fertilizers, pesticides, irrigation, farm machinery and implements is increasing markedly. This intensified use of agricultural inputs had led to carbon exhaustion, which, through the emission of greenhouse gases (GHGs), has a detrimental effect on the environment [1], such as rising temperatures due to global warming [2,3]. Therefore, the efficient utilization of energy and carbon are the keys for sustainable crop production, and these help in increasing farm profitability and productivity with minimal GHG emissions [4], which reduces the potential of global warming. To resolve the aforesaid issues, conservation management practices (CMPs) are considered a suitable approach for the accomplishment of sustainable production and increased farmers' income while conserving the natural resources [5]. Zero tillage (ZT) is the main component of CMPs, which includes the minimum soil disturbance with efficient utilization of inputs and energy and leads to higher crop productivity and soil fertility through recycling of nutrients [6,7]. The combined effect of tillage and irrigation practices provides a suitable option for efficient water utilization in the rice–wheat production system [8]. Adoption of conservation-based interventions is an urgent concern in the Indian mid-Himalayas regions where undulating topography with water and soil runoff leads to heavy soil and nutrient losses during the rainy season [9]. However, along with CMPs, efficient utilization of irrigation water is also needed hourly under the present situation of diminishing water resources. Therefore, to understand the soil-moisture relationship across the soil profile, these irrigation practices are necessary and viable for enhancing the overall sustainability of water and crops [10].

To address these problems, conservation of natural resources will help in achieving agroecosystem sustainability. Several studies reported reduction in 50–60 L ha^{-1} diesel through adoption of CMPs based ZT practice in Indo-Gangetic Plains, which provides a saving of ~3000 MJ ha^{-1} energy. This study further confirmed that lower consumption of fuel and water due to precision irrigation management saves ~20–30% moisture in rice–wheat rotation. Conversely, continuous use of conventional tillage (CT) has been found to increase the energy requirement vis-à-vis harmful effects on the soil health [11]. Globally, India is the third major emitter of GHGs, and its agricultural sector emits a large proportion (~71%) of total GHGs emission. In recent years, the intensive use of farm machinery and agrochemicals for higher crop production has been a major threat to sustainable crop production [7]. Proper water management in rice cultivation with suitable sowing methods significantly reduced the CH4 emissions more than that of traditional methods of cultivation [12].

Till now, few studies have been conducted to assess the effect of irrigation and tillage management on crop productivity and soil chemical properties of rice–wheat cropping system in mid-Himalaya [8,13]. Similarly, research investigations on energy dynamics, carbon efficiency and GHGs emission under different tillage and irrigation practices of rice–wheat rotation in the mid-Himalayan regions is completely missing. Such investigations are vital for developing or identifying carbon and energy efficient tillage and irrigation practices for reducing the carbon and energy footprint and subsequently the adverse impacts on the environment along with conserving the natural resources.

Therefore, a hypothesis was postulated that combined the use of tillage and irrigation practices to enhance soil sustainability and rice–wheat system productivity in long-term field experiments. To deal with this assumption, the present study was framed to examine the effect of contrasting tillage and irrigation schedules on carbon use efficiency, energy dynamics and GHGs emissions.

2. Materials and Methods

2.1. Site Details, Experiment Design and Crop Management

The long-term (16-years-old, 2001–2016) field research was performed at the Hawalbagh experimental farm of ICAR-VPKAS, Almora, situated in the mid-Himalaya of India (Figure 1). Mechanical analysis indicated that experimental soil belonged to the sandy clay loam textural class. The region is characterized by a sub-temperate climate with a dry summer (March–June), rainy monsoon season (June–September) and a cool winter (October–February) season. The mean annual maximum and minimum air temperature during study period were 26 °C and 10 °C, respectively. The average annual rainfall was 921 mm during experimentation period (2001–2016), of which ~73% was received during the monsoon season [14].

The permanent plots were used to assign treatments, i.e., main plot (ZT: zero tillage and CT: conventional tillage) and sub-plots consisted of four irrigation schedules to determine their impact on carbon, energy budgeting and GHG emission in rice–wheat cropping system. The treatment details are provided in Table 1. During the essential growth phases of both crops, irrigation water (50 mm depth) was applied as per the treatment. In order to maintain the treatment uniformity, both crops were irrigated seven days after a rainfall event (if fall out during the critical stage of crop growth). During the experimental study, fertilizer and crop management practices were carried out as per recommendations. Rice and wheat crops were harvested in the month of October-November and April-May of each year, respectively.

Table 1. Experimental setup and management practices.

Treatment	Treatment Description
Tillage management (Scenario—I)	
CT	Conventional tillage
ZT	Zero tillage
Irrigation management (Scenario—II)	
I-1	Pre-sowing (PS) irrigation
I-2	Pre-sowing (PS) irrigation + active tillering (AT)/crown root initiation (CRI) stage
I-3	Pre-sowing (PS) irrigation + active tillering (AT)/crown root initiation (CRI) stage + panicle initiation (PI)/flowering (FL), stage
I-4	Pre-sowing (PS) irrigation + active tillering (AT)/crown root initiation (CRI) stage + panicle initiation (PI)/flowering (FL), stage + grain filling (GF) stage
Cropping system and experimental details	
Experimentation period	2001 to 2016
Cropping system	Rice (*Oryza sativa* L.)—Wheat (*Triticum aestivum* L.)
Experimental design	Split plot design
Crop varieties used	Rice (*VL Dhan* 82) Wheat (*VL Wheat* 804)
Replication	4
Sowing time	Rice (First to second week of June) Wheat (Last of week of October to first week of November)
Fertilizer applied (N-P_2O_5-K_2O kg ha^{-1})	For both crops (100–60–40)
Fertilizer type	Nitrogen (urea) = 46% N Nitrogen and Phosphorous (diammonium phosphate) = 18% Nitrogen and 46% Phosphorus (P_2O_5) Potassium (muriate of potash) = 60% K_2O
Irrigation application rate	50 mm per irrigation
Harvesting time	Rice (Last week of October) Wheat (Last week of April/May)

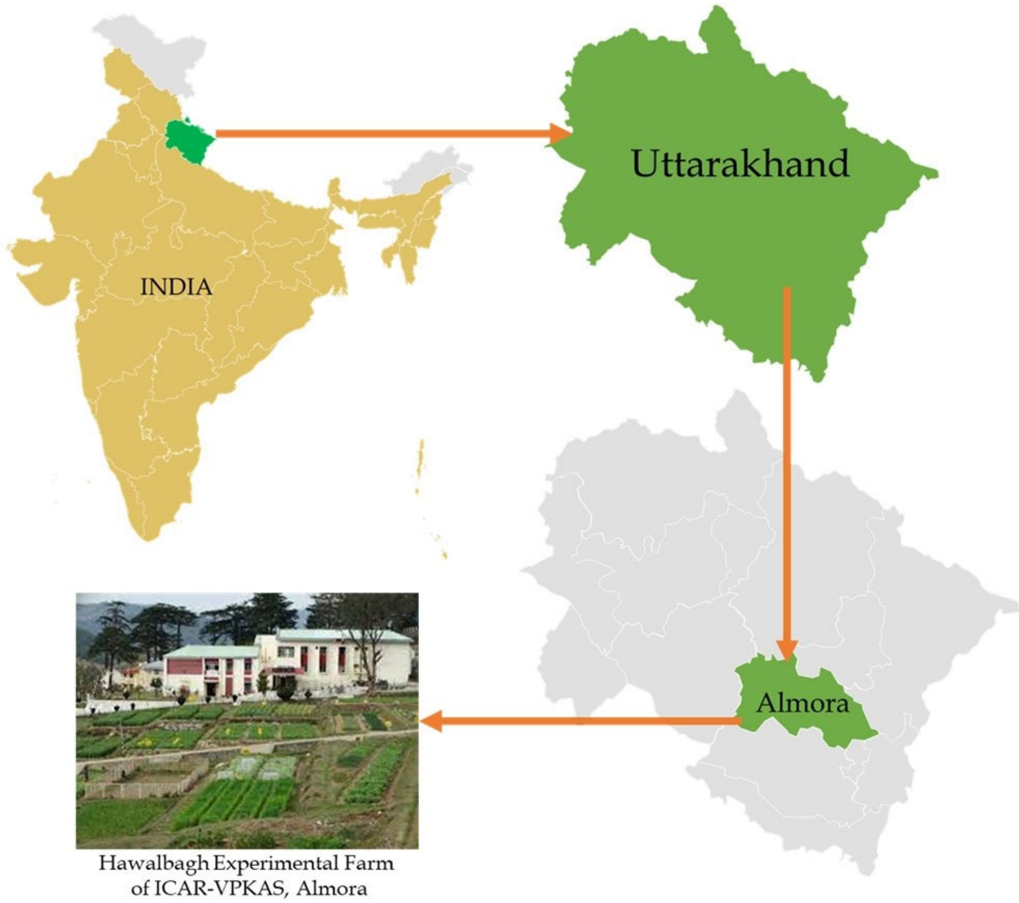

Figure 1. Long-term experimental site of rice–wheat cropping system.

2.2. Energy and Carbon Use Indices

Energy consumption was computed based on primary data of assorted inputs for irrigation and tillage management. Energy output from the product (grain and straw) was calculated by multiplying the amount of production and its corresponding energy equivalent as given in Table 2. Energy use indices (energy use efficiency, specific energy, energy productivity, energy profitability and net energy return) were calculated according to specific procedures as described in Table 3. Carbon equivalent (CE) was computed by multiplying the inputs (diesel, chemical fertilizers and pesticides) with the corresponding emission coefficients given by Lal [15] and West and Marland [16] as presented in Table 3.

Table 2. Energy equivalents coefficients of inputs and outputs in crop production.

Particulars		Unit	Energy Equivalents (MJ Unit^{-1})	References
Inputs				
Human power		Man-hr	1.96	[17]
		Women-hr	1.56	
Diesel		Litre	56.31	[17]
Farm machinery		kg	62.70	[17]
Seed	Rice	kg	15.2	[17–19]
	Wheat		15.2	
Chemical fertilizers	N	kg	60.60	[17]
	P_2O_5		11.10	
	K_2O		6.70	
Water for irrigation		m^3	1.02	[20]
Electricity		kWh	11.93	
Chemicals	Herbicides	kg	238	[21]
	Insecticides		199	
	Fungicides		92	
Outputs				
Grain yield	Rice	kg	14.70	[17]
	Wheat		15.70	
Straw/leaves/roots/stubbles yield	Rice		12.50	
	Wheat		12.50	

Table 3. Energy equivalents of inputs and outputs in agricultural production.

Parameters	Formulas/Equations	References
Energy use indices	Energy use efficiency (EUE) = Energy output (MJ ha^{-1})/Energy input (MJ ha^{-1}) Specific energy (S_E) (MJ kg^{-1}) = Total energy input (MJ ha^{-1})/Grain + straw yield (kg ha^{-1}) Energy productivity (E_P) (kg MJ^{-1}) = Economic yield (kg ha^{-1})/Energy input (MJ ha^{-1}) Energy profitability (P_E) = Net energy return (MJ ha^{-1})/Energy input (MJ ha^{-1}) Net energy return (NER) (MJ ha^{-1}) = Energy output (MJ ha^{-1})—Energy input (MJ ha^{-1})	[17]
Carbon use indices	Carbon output (kg CE ha^{-1}) = Total biomass (economic yield + by product yield) × 0.44 * Carbon input (kg CE ha^{-1}) = (Sum of total GHG emissions in CO_2 eq.) × 12/44 Carbon use efficiency = Carbon output/carbon input Carbon footprint (kg CE kg^{-1} grain) = Total carbon emission or input (kg CE ha^{-1})/System grain yield (kg ha^{-1})	[15,22]
GHGs emissions	GHG_{CO_2} emissions $= \sum_{i=1}^{n} AIi \times EFi$; Where GHG emissions are the total carbon emissions; *AIi* is the agricultural input factors applied, e.g., Diesel, electricity, fertilizer and pesticide and *EFi* is the appropriate carbon emission conversion coefficient for each factor of *AIi.* GHG_{N2O} emission = FN × E_F × [44/28]; Where GHG_{N2O} represents direct N_2O emissions from the application of N fertilizer (C eq. per unit); F_N is the quantity of N fertilizer (kg) applied for crop production; E_F is the emission factor of N_2O emissions induced by N fertilizer application; 44/28 presents the molecular weight of N_2 in relation to N_2O. GHG_{CH4} emissions = E_F × T Where CH_4 is the methane emissions from rice cultivation (kg CH_4 ha^{-1}), E_F is the adjusted daily emission factor (kg CH_4 ha^{-1} day^{-1}), and T is the cultivation period of rice (days).	[23,24]
GWP	GWP = (CO_2 emission × 1) + (CH_4 emission × 25) + (N_2O emission × 298)	[25]

* Plant biomass contains on an average 44% carbon content as given by Lal [15].

2.3. Greenhouse Gas (GHGs) Emission

Emissions of three core GHGs, i.e., methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O), were accounted for in the present long-term field investigation and expressed in carbon dioxide (CO_2) equivalent basis. Emissions of those gases were estimated by multiplying the inputs (diesel fuel, electricity, farm machinery, mineral fertilizers, pesticide) with their corresponding emission coefficients [26] that were further used for the estimation of global warming potential (GWP) (Table 3). The coefficients of CO_2 emission were used to evaluate the sum of GHG emissions from inputs (Table 4).

Table 4. Greenhouse gas (GHGs) emission coefficients of inputs in rice–wheat production.

Particulars	Unit	GHG Coefficients (kg CO_2 eq. Unit^{-1})	References
Diesel	Litre	2.68	[27]
Electricity	kWh	0.994	
Machinery	MJ	0.074	[28]
Nitrogen (N)		4.96	
Phosphorus (P_2O_5)	kg	0.73	[29]
Potassium (K_2O)		0.54	
Herbicides		6.30	
Insecticides	kg	5.10	[15]
Fungicides		3.90	
Emission factor for N_2O emissions for rice	kg N_2O-N kg^{-1} N input	0.51	[30]
Emission factor for N_2O emissions for wheat		0.33	
CH_4 emissions	kg CH4 ha^{-1} day^{-1}	3.12	[31]

2.4. Data Processing and Statistical Analyses

The immunity, if any were noted, *vis-à-vis* time intervals were measured at the time of sampling in the field. The analysis of variance (ANOVA) [32] was performed using the SPSS statistical package 20 (SPSS, Inc., Chicago, IL, USA) to determine the effect of treatments.

3. Results

3.1. Biomass Yield

Tillage practices did not significantly affect the biomass yield of rice, wheat and rice–wheat systems (Table 2). However, the average biomass yields of rice, wheat and system biomass were increased significantly ($p < 0.05$) under various irrigation schedules (Table 5). The results showed that for rice, wheat and rice–wheat systems, I-4 provided substantial higher crop yield, i.e., 6896, 10,721 and 17,618 kg ha^{-1}, respectively, while the lowest was recorded in I-1 i.e., 5579, 7684 and 13,264 kg ha^{-1}, respectively. The I-4 improved the biomass yield of rice, wheat and system significantly by ~24, 40 and 33%, respectively, as compared to I-1.

Table 5. Biomass yield of rice and wheat as influenced by different management practices.

Treatments †	Total Biomass Yield (kg ha^{-1})		
	Rice	Wheat	Rice–Wheat System
Tillage			
CT	6352 ± 444 ^{a}	9470 ± 611 ^{a}	15,822 ± 840 ^{a}
ZT	6143 ± 509 ^{a}	9299 ± 698 ^{a}	15,442 ± 699 ^{a}
Irrigation			
I-1	5579 ± 504 ^{c}	7684 ± 387 ^{c}	13,264 ± 540 ^{d}
I-2	6098 ± 332 ^{bc}	9191 ± 835 ^{b}	15,288 ± 705 ^{c}
I-3	6416 ± 652 ^{ab}	9943 ± 829 ^{ab}	16,359 ± 942 ^{b}
I-4	6896 ± 417 ^{a}	10,721 ± 574 ^{a}	17,618 ± 891 ^{a}

† Refer to Table 1 for treatment details. Mean (± values are standard deviations from means) followed by different superscript letter within each column indicate significant difference among the treatments (at $p < 0.05$) according to Duncan Multiple Range Test.

3.2. Energy Consumption Pattern and Indices

The results revealed that the rice–wheat cropping system consumed an average total energy of 30,368 MJ ha^{-1} (Figure 2). The highest input energy was consumed by indirect non-renewable (agrochemicals and farm machinery) energy sources followed by direct renewable resources (labour and water) and direct non-renewable resources (diesel and electricity) while the lowest was consumed by indirect renewable sources of energy (seed). It was observed that the sources of renewable and non-renewable energy in the rice–wheat system contributed ~30% and 70%, respectively, of the total energy consumption. Electricity and fuel alone contributed ~20% of the total energy in the rice–wheat system. Apart from the source-wise distribution of energy, the operation-wise consumption of energy by different components under contrasting tillage and irrigation practices is presented in Table 3.

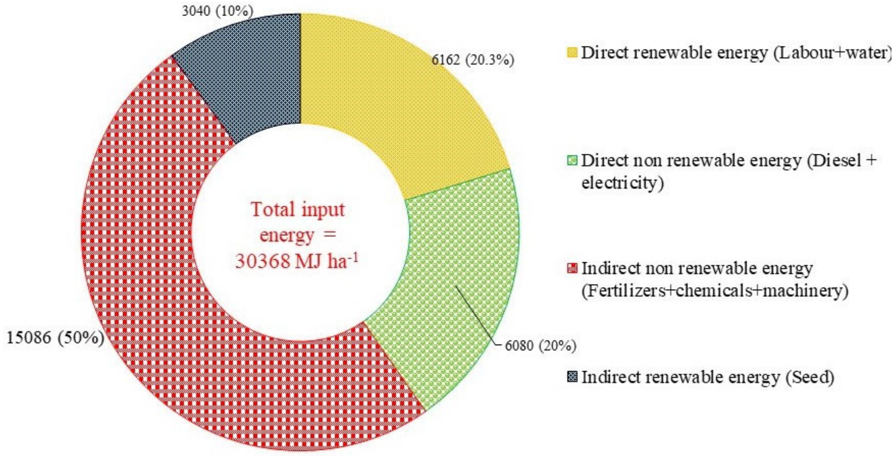

Figure 2. Input and output of energy under different management practices.

Data revealed that the fertilizer addition consumed a large portion (46–54%) of the total energy as compared to the rest of the operations in the rice–wheat cropping system. Additionally, the second major energy consuming input was irrigation that accounted for about 9.0–21% of the total energy in rice–wheat system. Seed sowing and land preparation correspondingly consumed a substantial amount of energy (Figure 3). It was observed that land preparation under CT treatments consumed 4080 MJ ha^{-1} energy. In contrast with CT, no-energy was consumed in ZT plots for land preparation (Figure 4). Data showed that the average annual energy input was ~11% lower in ZT as compared to CT system (Table 6). The total energy consumption pattern under contrast tillage and different irrigation schedules followed the order of CT > ZT, and I-4 > I-3 > I-2 > I-1.

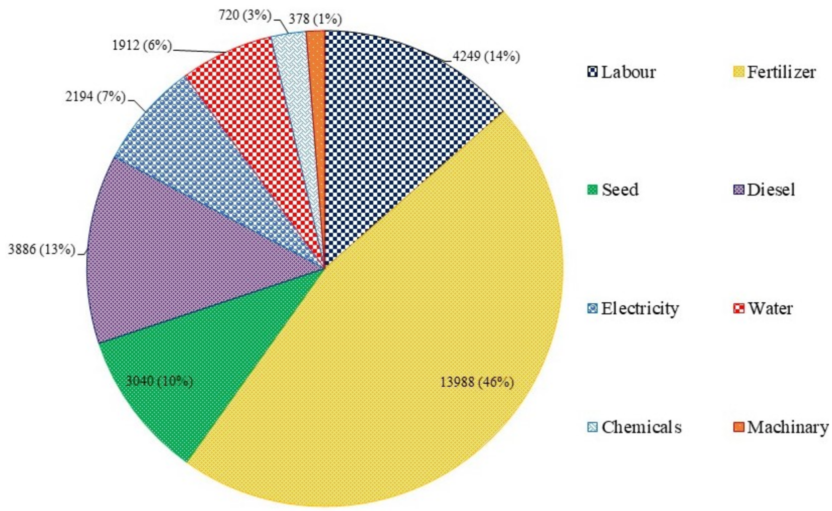

Figure 3. Source-wise energy input under different tillage and irrigation management practices.

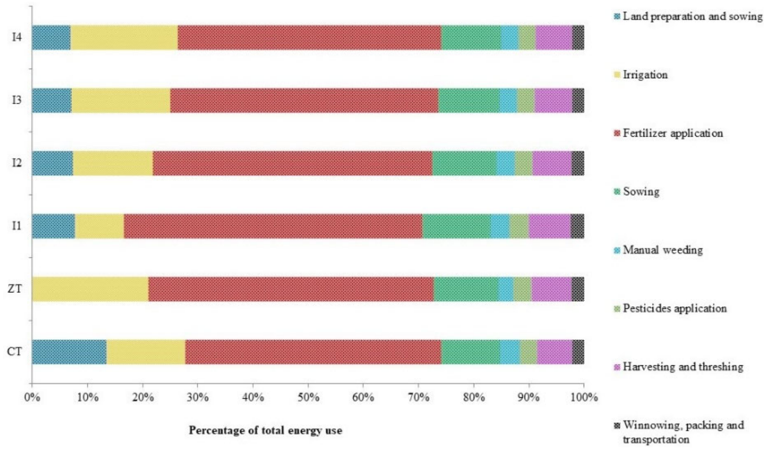

Figure 4. Operation-wise energy input under different tillage and irrigation management practices.

Table 6. Energy (MJ ha^{-1}) consumption pattern of different management practices.

Treatments †	Land Preparation	Irrigation	Fertilizer Application	Seed and Sowing	Manual Weeding	Pesticides Application	Harvesting and Threshing	Winnowing, Packing and Transportation	Total Input Energy
Tillage									
CT	4080 (13.4) [a]	4325 (14.2)	14,114 (46.5)	3228 (10.6)	1098 (3.60)	919 (3.62)	1974 (6.50)	628 (2.07)	30,366
ZT	0	4325 (16.7)	14,114 (54.5)	3228 (12.5)	706 (2.61)	919 (3.55)	1974 (7.62)	628 (2.43)	25,894
Irrigation									
I-1	2040 (7.81)	2306 (8.83)	14,114 (54.1)	3228 (12.4)	902 (3.52)	919 (3.52)	1974 (7.56)	628 (2.41)	26,111
I-2	2040 (7.33)	4037 (14.5)	14,114 (50.7)	3228 (11.6)	902 (3.24)	919 (3.30)	1974 (7.09)	628 (2.26)	27,842
I-3	2040 (7.04)	5190 (17.9)	14,114 (48.7)	3228 (11.1)	902 (3.11)	919 (3.17)	1974 (6.81)	628 (2.17)	28,995
I-4	2040 (6.90)	5766 (19.5)	14,114 (47.7)	3228 (10.9)	902 (3.13)	919 (3.11)	1974 (6.68)	628 (2.12)	29,571

† Refer to Table 1 for treatment details. [a] Figures in the parentheses are the percentage contribution of input energy for each management practices.

On an average, the total quantity of energy accumulated from the biomass of wheat was 128,947 MJ ha^{-1}, and its 44 and 56% portion was contributed by grain and straw, respectively. Total energy accumulated in the case of rice was 83,219 MJ ha^{-1} out of which grain and straw accounted for around 41 and 59%, respectively. The total rice–wheat rotation systems energy output was higher under CT (214,603 MJ ha^{-1}) as compared to ZT (209,728 MJ ha^{-1}) (Table 7). However, energy output indices, i.e., EUE, Ep and Eprof were found significantly higher under ZT than CT. Plots under the application of four irrigations (I-4) were provided ~33, 17, 16.6, 21, 36 and 21% higher system energy output, EUE, SE, Ep, NER and Eprof, respectively, than that of single irrigation (I-1) plots (179,833 MJ ha^{-1}, 6.92, 1.68 MJ kg^{-1}, 0.19 kg MJ^{-1}, 153,722 MJ ha^{-1} and 5.92 kg MJ^{-1}).

Table 7. Energy dynamics influenced by different management practices of rice–wheat rotation.

Treatments †	Energy Input (MJ ha^{-1})	Energy Output (MJ ha^{-1})	Energy Use Efficiency	Specific Energy (MJ kg^{-1})	Energy Productivity (kg MJ^{-1})	Net Energy Return (MJ ha^{-1})	Energy Profitability
Tillage							
CT	30,366	214,603 ± 10,454 ^{a}	7.05 ± 0.34 ^{b}	1.93 ± 0.01 ^{a}	0.19 ± 0.004 ^{b}	184,237 ± 10,454 ^{a}	6.06 ± 0.35 ^{b}
ZT	25,894	209,728 ± 8895 ^{a}	8.08 ± 0.36 ^{a}	1.69 ± 0.08 ^{b}	0.23 ± 0.006 ^{a}	183,834 ± 8895 ^{a}	7.07 ± 0.34 ^{a}
Irrigation							
I-1	26,111	179,833 ± 6649 ^{d}	6.92 ± 0.25 ^{c}	1.68 ± 0.08 ^{c}	0.19 ± 0.007 ^{d}	153,722 ± 6649 ^{d}	5.92 ± 0.25 ^{c}
I-2	27,842	207,321 ± 8967 ^{c}	7.47 ± 0.32 ^{b}	1.77 ± 0.08 ^{bc}	0.21 ± 0.005 ^{c}	179,479 ± 8967 ^{c}	6.48 ± 0.32 ^{b}
I-3	28,995	222,151 ± 11,951 ^{b}	7.68 ± 0.40 ^{b}	1.83 ± 0.11 ^{b}	0.22 ± 0.005 ^{b}	193,157 ± 11,951 ^{b}	6.70 ± 0.40 ^{b}
I-4	29,571	239,356 ± 11,130 ^{a}	8.11 ± 0.39 ^{a}	1.96 ± 0.09 ^{a}	0.23 ± 0.004 ^{a}	209,785 ± 11,130 ^{a}	7.14 ± 0.39 ^{a}

† Refer to Table 1 for treatment details. Mean (± values are standard deviations from means) followed by different superscript letters within each column indicate a significant difference among the treatments (at $p < 0.05$) according to the Duncan Multiple Range Test.

3.3. Greenhouse Gasses (GHGs) Emission and Carbon Budgeting

The appraisals of GHGs emissions for different management practices are presented in Table 8. Results showed that the average emission of CO_2, CH_4, and N_2O across the tillage and irrigation practices was 2010, 359, and 132 kg ha^{-1}, respectively, in the rice–wheat cropping system. The CO_2 emission consisted of > 80% of GHGs emissions and the share of remaining two gases (CH_4 and N_2O) was < 20%. However, in terms of GWP, the most significant gas was N_2O (78%), followed by CH_4 (18%) and CO_2 (4%) (Figure 5). The average value of total CO_2 emitted was 2501 kg CO_2 eq. ha^{-1} for rice–wheat cropping system. It was also noted that source wise, fertilizer (49.8–67.4%) had highest share in GHGs emission followed by electricity (23.4–43.3%), diesel fuel (1.24–8.81%), pesticides (1.51–2.07%), and farm machinery (0.77–1.28%) under contrast tillage and irrigation practices (Figure 6).

Table 8. Greenhouse gas (GHGs) emissions as influenced by different management practices.

Treatments	Diesel	Electricity	Fertilizer	Machinery	Pesticides	GHGs Emission			Total CO_2 eq. Emissions
						CO_2	N_2O	CH_4	
	kg CO_2 Equivalent ha^{-1}								
Tillage									
CT	185	731	1122	27	34	2099	132	359	2590
ZT	24	731	1122	22	34	1933	132	359	2424
Irrigation									
I-1	105	390	1122	15	34	1665	132	359	2156
I-2	105	682	1122	16	34	1959	132	359	2450
I-3	105	877	1122	17	34	2155	132	359	2646
I-4	105	974	1122	17	34	2252	132	359	2743

Refer to Table 1 for treatment details.

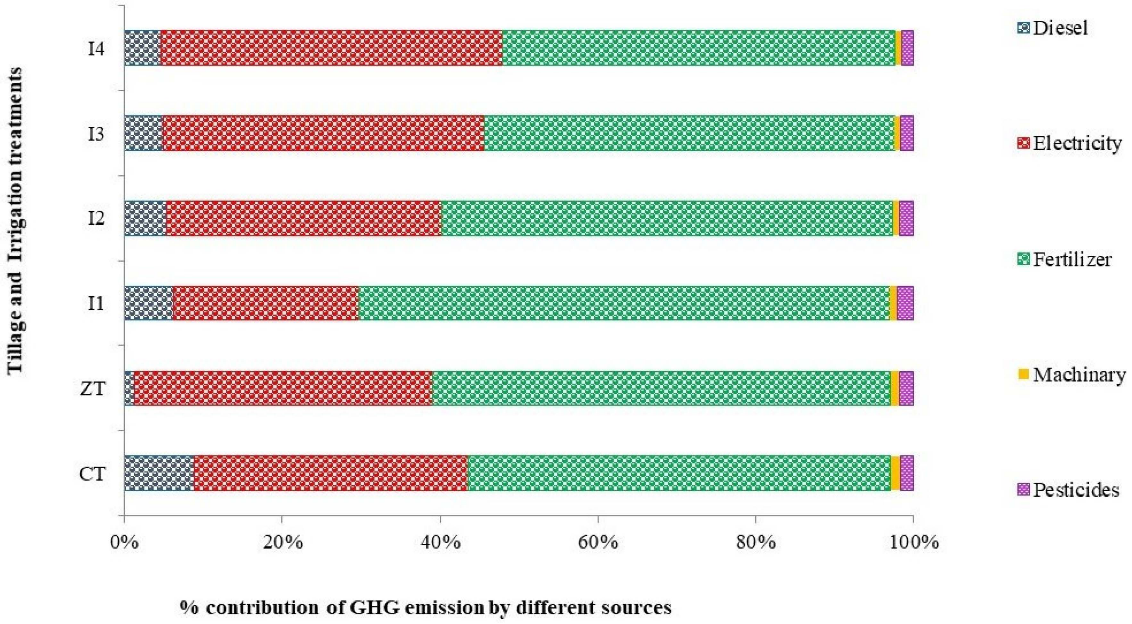

Figure 5. Percent share of GHGs emitted from different management practices.

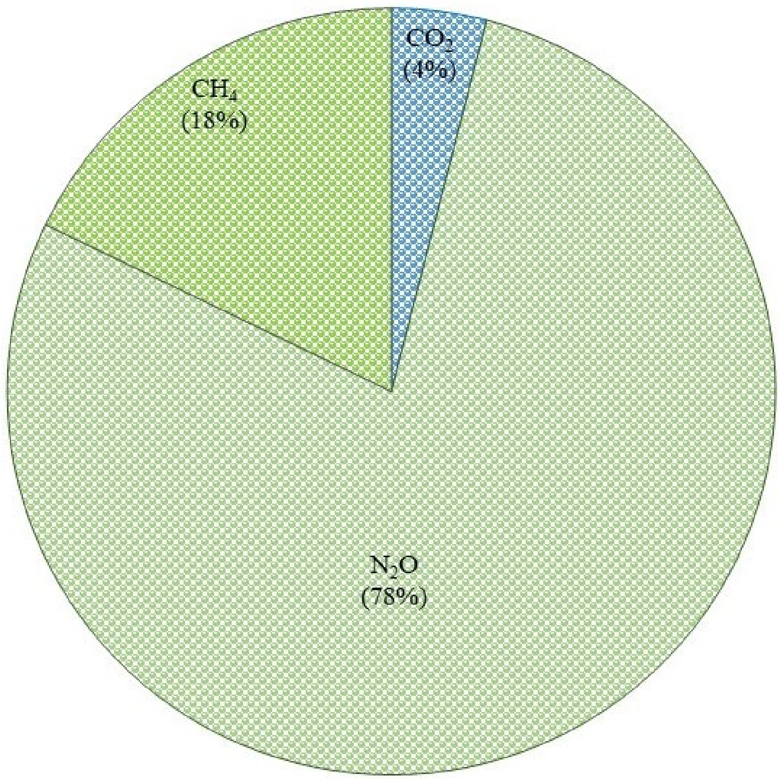

Figure 6. Percent contribution in global warming potential (GWP) originated from different GHGs under contrast tillage and irrigation practices.

4. Discussion

The results from the present long-term investigation revealed that rice and wheat biomass yield was found higher in CT plots than that of yield obtained under ZT plots (Table 2). It was observed that wheat yield increased after eight years after experimentation in ZT as compared to CT plots. In the case of rice, productivity was the same in ZT as well as CT plots. Low yield under ZT might be due to comparatively more weed, pest, and especially increased white grub populations [33], and disease infestation in the rainy season caused decline in biomass yield [34]. The optimum yield is influenced by the availability of moisture as stored water in the soil profile. As the present investigation was conducted under different irrigation regimes, moisture may thus be limiting factor here. Results showed that the significant higher biomass yield was recorded under I-4 plots as compared to I-1, I-2 and I-3, which might be explained by higher exchange/mobility of nutrients in soil under I-4, which ultimately enhanced the nutrient availability in root rhizosphere and resulted in a higher biomass yield.

4.1. Energy Dynamics

In the rice–wheat cropping system, various management activities under CT consumed 30,366 MJ ha^{-1} energy in terms of total energy input, which was 17.2% higher than that of ZT (Figure 4). The ZT system curtailed the energy necessity due to exchangeable energy during land preparation and crop management [35]; nevertheless, irrigation consumed slightly higher energy than ZT [6]. More than 70% of energy was required by fertilizer and irrigation application. Agha-Alikhani et al. [36] and Jat et al. (2020b) also reported that the highest energy was consumed in the application of fertilizers (43%), but these findings differed with Chaudhary et al. [37] and Alimagham et al. [38], who showed that higher energy was associated with irrigation application over fertilizers. CT yielded higher biomass productivity, which eventually helped to retain higher EO, SE, and NER. However, EUE and Eprof were higher in ZT as compared to CT. This might be ascribed to the fact that the ZT utilized lower energy due to the absence of field preparation. Plot under I-4 recorded the highest biomass yield, which facilitated to sustain higher EO, EUE, SE, NER, Epro and Eprof in comparison to rest of the irrigation practices, i.e., I-3, I-2, and I-1 [39].

4.2. GHGs Emissions and Carbon Sustainability

Data related to GHGs emissions (CO_2, CH_4 and N_2O) indicated that CO_2 accounted for ~80% of the total emissions under contrast tillage and irrigation practices in rice–wheat cropping system, largely due to field operations, harvesting and management practices. Methane (CH_4) covered ~14% emission due to rice cultivation, and N_2O-based CO_2 equivalent contributed merely ~5.0% emission due to fertilizer application [11]. Among tillage and irrigation practices, share of equivalent CO_2 emission was recorded highest from fertilizers, followed by electricity (electricity consumption for pumping of water with electrically operated pumps) and diesel fuel consumption [40] (Table 5).

Results revealed that lower consumption of fuel in ZT reduced the emission of GHGs by 8.64% as compared to CT in rice–wheat cropping system [2]. Carbon output was observed higher in CT as compared to ZT (Table 6). This increment in carbon output is attributed to higher biomass yields of rice and wheat. The higher carbon use efficiency in ZT (10.50) was due to lower carbon consumption in ZT that is also majorly in the form of fuel. A significantly higher value of carbon footprint was noted in CT (0.12 kg CE kg^{-1} grain yield) as compared to ZT (0.11 kg CE kg^{-1} grain yield). It might be explained by lower carbon emission in the form of fossil fuel in ZT over CT. Carbon indices significantly varied under various irrigation regimes. Plots under I-4 recorded higher carbon output, carbon use efficiency and lower carbon footprint as compared to rest of the irrigation practices, which might be due to the reason that the optimum moisture condition favors the production of higher biomass yield [6,41].

5. Conclusions

Results obtained from the present long-term study revealed that rice, wheat and rice–wheat system recorded higher biomass yield in CT than that of the yield of ZT. Plots with four irrigations (I-4) had provided ~24, 40 and 33% higher productivity of rice, wheat and rice–wheat rotation as compared to that of single irrigation (I-1). Results confirmed that energy input in the rice–wheat production system varied from 25,894 to 30,366 MJ ha^{-1}, whereas energy output varied from 179,833 to 239,356 MJ ha^{-1} under contrast tillage and irrigation practices in the Indian mid-Himalayas.

Overall, numerous factors were responsible for emissions of GHGs under different management practices in the current investigation. These consisted of inherent properties of the soil, the type of tillage and the different irrigation practices, which influenced GHGs production through their impact on soil. We conclude that ZT along with the four irrigations (I-4) improved the energy use efficiency (EUE), the carbon use efficiency (CUE) in addition to a higher crop productivity while lowering the carbon footprint, as compared to CT and the rest of the irrigation practices. In sum, ZT helps to reduce the emission of GHGs and maintain the sustainability of agriculture production in order to strengthen the global/regional food security.

Author Contributions: Conceptualization, S.C.P., V.S.M., S.S., P.K.M., J.K.B. and A.P.; Data curation, M.C., R.P.Y. and M.P.; Formal analysis, M.C., V.S.M., S.S., M.P., P.K.M. and A.P.; Investigation, S.C.P., R.P.Y., M.P., P.K.M., J.K.B. and A.P.; Methodology, R.P.Y., S.S., M.P. and P.K.M.; Project administration, S.C.P., P.K.M., J.K.B. and A.P.; Resources, M.C. and J.K.B.; Supervision, S.C.P., V.S.M. and A.P.; Validation, V.S.M.; Visualization, V.S.M.; Writing—original draft, M.C. and V.S.M.; Writing—review & editing, M.C., V.S.M., R.P.Y. and S.S. All authors have read and agreed to the published version of the manuscript.

Funding: We thank the ICAR-VPKAS, under project IXX08505 for funding this research.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: We thank the ICAR-VPKAS. We also thank the field staff of the institute for maintaining this long-term field experiment.

Conflicts of Interest: The authors declare no conflict of interest.

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