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Diversified and Long-term Cropping Systems Alters the System Sustainability and Energy Use Efficiency in Soils of Indo-Gangetic Plains

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ABSTRACT

The cereal-based intensive cropping practices have posed the yield at a plateau and reduced the energy use efficiency (EUE) of the cropping systems in the Indo-genetic plains (IGPs). The long-term cropping systems experimentations with 4 diversified legumes and cereal cropping systems and a grassland fallow system were studied for >10 years representing different agro-ecological regions at the agricultural research farm, IAS, BHU-Varanasi, Uttar Pradesh of IGPs to assess their impacts on system productivity and energy use efficiency. Out of 4 cropping systems *viz*, Pigeon pea-Pigeon pea (PP-PP) and Rice-Maize (R-M) systems were managed as conventional cultivation running under the breeding project, however; Dryland Rice-Lentil (R-L) and Zero-till Rice-Wheat (R-W) systems were running under agronomy project. The grassland fallow system was maintained in the agronomy block. The maximum system productivity was seen in the zero till rice-wheat (8185 kg ha^{-1}) system and the lowestpigeon peanpea-pigeonpea system (1615 kg ha^{-1}). However, the maximum EUE was found in pigeonpea system (13.23 MJ ha^{-1}) and the lowest in the zero till rice-wheat system (8.88 MJ ha^{-1}). The study suggests that the inclusion of legumes in the cropping system is vital in enhancing the system productivity and energy use efficiency than the long-term cereal-based system in long-run to the alluvial soils of IGPs.

Keywords: Agro-ecological regions, energy use efficiency, intensive cropping systems, sustainability

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INTRODUCTION

Rice, wheat, and maize are the major cereal crops grown in the world as well as in South Asia. The cereal-based systems of Indo-Gangatic plain regions (IGPRs) with intensive conventional tillage have posed serious challenges to system productivity and future food security of the regions (Parihar et al 2017). The continuous practice of the rice-wheat (R-W) system in most areas of IGPRs has led to the decline in system productivity and recorded low energy use efficiency (Amgain et al 2019, 2020). Adoption of alternate tillage practices in integration with legumes in the R-W system could be the one option for sustainability, while the diversification of rice with maize is another alternative efficient crop and cropping system (Aulakh and Grant 2008). The reason behind the popularity of the inclusion of legumes in the rice-wheat system in the entire Indo-Gangetic alluvium belt is the compatibility of the two crops with respect to their transplanting/sowing times (Singh et al 2011).

The performance of the cropping systems is also affected by the energy. Energy is one of the most important variables affecting crop productivity (Singh et al 2008). It has been reported that the adoption of the best management practices (BMPs) can reduce energy use, in rice-based cropping systems. Tillage, irrigation, and fertilization are the primary consumers of energy and contributors of GHG emissions because these farm operations use heavy fossil fuel and electricity (Pratibha et al 2015; Soni et al 2013). Thus, reducing fossil fuel consumption by reducing or eliminating tillage operations is a promising option for reducing GHG emissions (Lal 2003; Soni et al 2013). Therefore, the choice of diversified crops and cropping systems with no-till (NT) and a low rate of irrigation and fertilizers can save the energy haphazardly used in cropping systems. The level of fertility in the IGPS shows a reverse trend with productivity and energy use efficiency (Bilore et al 2005) and suggests the scientific use of the cropping systems. Hence, the energy use efficiency of diversified cropping systems needs further improvement to reduce the reliance on non-renewable energy sources. In this regard, scientific crop rotations and precise crop management practices can be equally important in determining sustainable productivity and energy use efficiency (Francesco et al 2011). Any intensification process requires an increase in energy demands (Maraseni et al 2015) and this should be minimized to some extent by selecting the legumes in the cropping systems. In the present situation, energy consumption is higher than it was before the Green Revolution, due to irrigation, fertilizers, pesticides, fuels, machinery, etc. (Conforti and Giampietro 1997; Woods et al 2010). The two main ways to improve energy use and system yields are reducing energy inputs (EI) or increasing energy equivalent produced (EP) with the goal of improving the energy return on investment (EROI), or increasing the ratio between EP and EI (Macedo et al 2021).

Environmentally and economically sustainable cropping systems or crop management practices are needed to improve the systems productivity and energy use efficiency of cereal-based cropping systems in the IGPs (Babu et al 2014). For this, a proper understanding of the relationship between energy requirements as per the selection of crops is important in achieving the intensification of cropping systems (Tuti et al 2012). Energy consumption and productivity have a close relationship but reverse relation with EUE (Meena et al 2017). Due to the lack of ample studies on the numeric investigation on this line, the present study was intended and executed in the alluvial soils of Varanasi, IGPs to develop more productive and energy-efficient cropping systems for maintaining sustainable yields and to secure the food and nutritional security with improvement in the environment health.

MATERIALS AND METHODS

Experimental site, soil, and climate

The long-term field trials were initiated under different projects at the Banaras Hindu University's Agricultural Research Farm in Varanasi, India (25°18' N, 83°30' E and 76.22 masl.). However, the data for 10 years (2010-19) were only compiled for the research. The experimental site falls under the middle Gangetic plain zone of IGPs region. The soil at this location was sandy loam, with a pH of 7.4 and 0.37 % organic carbon (OC) with homogeneous fertility and uniform textural makeup (Bohara et al 2007). In the research plots, the initial total nitrogen was 192 kg N ha^{-1}, while soil available phosphorus was 21.4 kg P ha^{-1}) and potassium was 224 kg K ha^{-1} (Singh et al 2013). The climate of the experimental site was sub-tropical, semi-arid to sub-humid, with a moisture deficit index of 20-40. The average annual rainfall in this region was around 1100 mm, with a mean relative humidity of 68% that reaches 82% during the rainy season and drops to 30% during the dry season. The maximum and minimum temperature ranges from 37- 40 ^{o}C and 6-12 ^{o}C, respectively.

Experiment details

This study was done on long-term experiments (LTE) based on the field trials which were already established at Agricultural Research Farm, BHU (Table 1 and Figure 1).

Table 1. Experimental details

Practices	Cropping systems				
	Pigeon pea - pigeon pea	**Dryland rice-lentil**	**Rice-maize**	**Zero-till lowland rice-wheat**	**Permanent grassland**
Duration (years)	10	34	20	2	-
Tillage	Conventional	Conventional	Conventional	Zero- till	-
Fertilizers- N-P-K (kg ha^{-1})	60-100-60	90-45-30	210-90-80	270-90-80	-
Crop rotation	Pigeon pea- pigeon pea	Dryland rice- lentil	Rice-maize	Rice-wheat	-
Soil type	Sandy loam	Sandy loam	Sandy loam	Sandy loam	Sandy loam

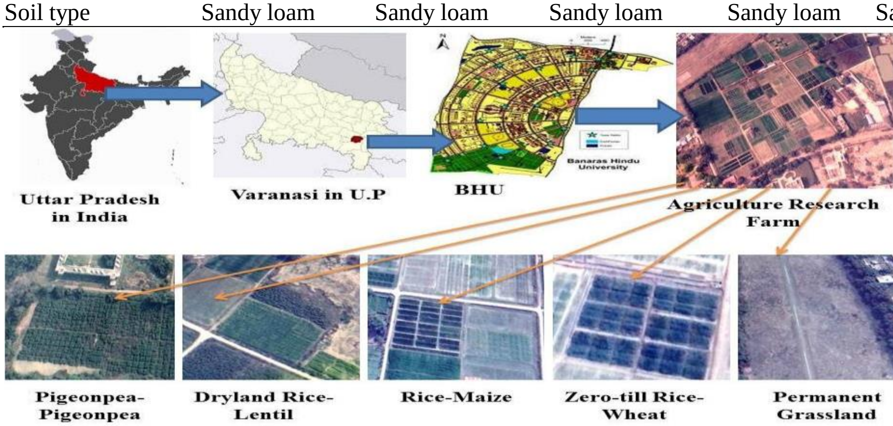

Figure 1. Location and an aerial view of experimental site with different cropping systems

Assessments of system yields and rice equivalent yield (REY)

The system yield of the 4 diversified cropping systems adopted in the study was calculated as per the seasonal crop yields of the respective crops and expressed in grain, straw/stalk, and biological yields. The rice-equivalent yield (REY) of the system was estimated by multiplying the minimum support price (MSP) of pigeon pea, lentil, wheat and maize by the ratio of their economic yield and MSP of rice using the following equation: The minimum support prices of the different crop commodities and the system yields over the diversified cropping systems have been shown in Table 2.

REY = [Yield of Rice + {(Yield of pigeon pea, maize, lentil and wheat × price of pigeon pea, maize, lentil and wheat) ÷ Price of rice}]

Table 2. Average yield of cropping systems from 2010-1019 and the prevailing market price of grain during experimentation [Indian Rupees (INRs kg^{-1} grain]

Cropping Systems	Average yield (Mt ha^{-1})	Price of grain (INRs kg^{-1})
Pigeon pea- pigeon pea	9.056	100-100
Dryland rice-lentil	15.422 - 9.689	25-80
Rice-maize	48.33 - 55.44	25-25
Zero-till lowland rice-wheat	35.00 - 40.50	25-25

Energy analysis

Crop inputs and outputs were converted to energy-unit equivalents using conversion coefficients from the published literature (Choudhary et al 2017, Singh et al 2007, Esengun et al 2007, Ozkan et al 2004, Helsel 1992 and Green et al 1987) to facilitate comparisons among treatments. Energy outputs were calculated for both economic yield (e.g. sellable harvested product) and straw/stover yield which is used as animal feed on-farms. The total energy use (TEU) total energy required to produce a crop, energy output (EO) energy produced in grain and straw products, and EUE were calculated using the following equations (Gathala et al 2016). The values given in Table 3 were used while calculating the various empirical investigations of energy analysis.

$$TEU = [Em + Ef + Ei]$$

Where, TEU = total energy use (MJ ha^{-1}); Em = manual energy uses from labor (in person-hours); Ef = the energy used for fuel; and Ei = the energy derived from all inputs (i.e., seed, fertilizer, agro-chemicals, and crop residues)

$$EO = [(\text{grain} \times \text{energy}) + (\text{straw} \times \text{energy})]$$

Where, EO = energy output (MJ ha^{-1}); grain = crop grain yield (kg ha^{-1}); Energy = specific conversion factor for grain or straw (MJ kg^{-1}); and straw = crop straw or stover yield (kg ha^{-1}).

$$EUE = EO / TEU$$

Where, EUE = energy-use efficiency (a dimensionless term); EO = energy output (MJ ha^{-1}); and TEU = total energy use (MJ ha^{-1}). The energy inputs included both renewable (e.g., labor, seed, and crop residues) and non-renewable (e.g., chemical fertilizers, tractor, diesel, machinery, and agro-chemicals) sources of energy.

Table 3. Energy equivalent of the inputs and outputs used in the estimation of various efficiencies of diversified cropping systems

Particulars		Unit	Equivalent energy (MJ unit^{-1})	References
A. Inputs				
Human labor	Man	Hour	1.96	Choudhary et al (2017)
	Nitrogen	kg	60.60	Singh (2002)
Chemical	Phosphorus	kg	11.10	Singh (2002)
fertilizers	Potash	kg	6.70	Singh (2002)
Farm machinery	Diesel	Liter	56.31	Singh et al (2007)
	Machinery	Hour	62.70	Ozkan et al (2004)
Irrigation	Water for irrigation	M^3	1.02	Esengun et al (2007)
Seed	Seed (Pigeon pea, rice, wheat lentil, maize)	kg	14.70	Choudhary et al (2017)
Chemical	Insecticide	Litre	92	Helsel (1992)
	Herbicide	Litre	238	Esengun et al (2007)
	Bio-regulator	Litre	85	Green (1987)
Electricity		KW-h	3.60	Singh (2002)
B.Outputs				
Grain (Pigeon pea, rice, wheat lentil, maize)		kg	14.70	Choudhary et al (2017)
Straw		kg	12.50	Yadav et al (2017)
Stalks		kg (dry mass)	18.0	Devasenapathy et al (2009)

Treatment details and statistical analysis of the recorded data

The experimentation was studied in a randomized complete block design (RCBD) with four replications and five treatment levels *viz,* i. T_{1-} Conventional Pigeon pea - Pigeon pea cropping system, ii. T_{2-} Dryland Rice-Lentil cropping system, iii. T_3- Conventional Rice-Maize cropping system, iv. T_4- Zero-till Rice-Wheat cropping system, and v. T_5- Permanent Grassland system. The data collected for the numerous characters under investigation were evaluated using the method of analysis of variance (Gomez and Gomez 1984). Standard error and critical values were obtained to compare the mean value of therapy.

RESULTS AND DISCUSSION

Effect of differently managed diversified cropping systems on system productivity

The data presented in Table 4 showed that the zero till lowland rice-wheat cropping system had higher grain yield than all other cropping systems. However, the rice-maize system had higher straw yield, which showed the significant result with all other systems except zero till lowland rice-wheat cropping system.

Table 4. Effect of differently managed cropping systems on grain, straw, biological and rice equivalent yield of systems

Treatments	Grain/seed yield (kg ha^{-1})	Straw/ stalk yield (kg ha^{-1})	Biological yield (kg ha^{-1})	Rice equivalent yield of system (kg ha^{-1} yr^{-1})
Pigeon pea-pigeon pea system	1615.00	7880.75	9495.75	8455.4
Dryland rice-lentil system	4639.00	7274.75	11913.75	4642.68
Rice-maize system	7725.00	11737.25	19462.25	10,377
Zero-till lowland rice-wheat system	8185.00	11130.75	19315.75	7550
Permanent grassland system	0.00	456.50	456.50	0.00
CD ($p<0.05$)	440.61	645.14	366.13	959.98

Likewise, rice-maize cropping system had significant biological yield but had insignificant biological yield in zero till lowland cropping system. The grain yield of the zero-till low rice-wheat system was high because of more energy investments in this system (Tuti et al 2012). The low yield of the rice-maize system than zero till lowland rice-wheat system was probably due to the continuous cultivation of more than one cereal crop (Islam et al 2014) and the practicing of the conventional agriculture system. However, the rice-maize system produced the maximum biological yield (19.462 Mt ha^{-1}) than other cropping systems as alike as reported by Yadav et al (2017). The data from Table 4 further showed that higher rice equivalent yield (10.377 kg ha^{-1} yr^{-1}) was obtained with a rice-maize cropping system. The increased rice equivalent yield of the rice-maize system was due to improved varieties of the crops because this system was practiced una der breeding project. The physiology of cereals is distinct from legumes and therefore the cereal-cereal system yields are also higher (Amgain and Dhakal 2019).

Effect of differently managed diversified cropping systems on energy use efficiency

The cropping systems-wise energy use patterns were computed for all systems viz energy use efficiency (EUE), energy productivity (EP), net energy production (NE), and specific energy production (SP) (Tables 5 and 6).

Table 5. Effect of differently managed diversified cropping systems on energy use efficiency (EUE) and energy productivity (EP) at Varanasi, IGPs

Treatments	EUE (MJ ha^{-1})			EP (kg MJ^{-1})		
	Grain/seed yield	Straw/stalk yield	Biological yield	Grain/seed yield	Straw/stalk yield	Biological yield
Pigeon pea-Pigeon pea	1.87	11.33	13.23	0.129	0.630	0.759
Dryland rice-lentil	4.67	6.58	11.51	0.336	0.526	0.862
Rice-Maize	5.03	6.58	11.68	0.347	0.527	0.873
Zero-till rice-wheat	4.05	4.76	8.88	0.280	0.381	0.661
Permanent grassland	0.00	9.10	9.10	0.000	0.728	0.728
CD (p<0.05)	0.34	0.70	0.49	0.025	0.055	0.038

Energy consumptions (both renewable and non-renewable) varied across various cropping system management practices. The data presented in Table 5 showed that the rice-maize cropping system has significantly increased the EUE of grain yield. However, Pigeon pea-pigeon pea cropping system has significantly increased the EUE of straw as well as the biological yield. Furthermore, the rice-maize and dryland rice-lentil cropping systems showed insignificant EUE with each other with respect to the straw/ stalk and biological yield. The control field, permanent grassland had significant EUE of straw/stalk yield with other cropping systems except pigeonpea cropping system. The operations of machines while tillage and diesel consumption for the operations were the major energy-requiring components of any production systems (Yadav et al 2017) and the same has been implied in this treatment. From the above statement, it was concluded that the zero-till rice- wheat system has higher energy use efficiency because of the exclusion of tillage operations. However, in the present study, rice-maize cropping systems have recorded a higher EUE (5.03 MJ ha^{-1}), EP (0.347 kg MJ^{-1}), NE (91267 vs. 0 MJ kg^{-1}) for grain/ seed yield than zero-till rice-wheat. Similar results were reported by Barut et al (2011). The overall EUE of the pigeon pea-based cropping system resulted more because of less energy consumption such as manures and fertilizers (47%), tillage operations (21%) and diesel consumption (19%) (O Di Nasso et al 2011; Yadav et al 2017).

Table 6. Effect of differently managed cropping systems on specific energy (SE) production and net energy (NE) production

Treatments	SE production (MJ kg^{-1})			NE production (MJ ha^{-1})		
	Grain/seed yield	**Straw/stalk yield**	**Biological yield**	**Grain/seed yield**	**Straw/stalk yield**	**Biological yield**
Pigeon pea-Pigeon pea	7.81	1.59	1.32	11223	129336	153076
Dryland rice-lentil	3.00	1.91	1.16	54368	77109	145303
Rice-Maize	2.90	1.91	1.15	91267	124425	237982
Zero-till rice-wheat	3.57	2.63	1.51	91105	109920	230239
Permanent grassland	0.00	1.38	1.38	0	5079	5079
CD ($p<0.05$)	0.55	0.17	0.07	6477	8186	4922

CONCLUSIONS

From this study, it was concluded that the system productivity and EUE significantly vary among cropping systems. The study assessed the efficient cropping system based on system productivity and energy use efficiency for enhancing food security and efficient utilization of inputs for the sustainability of cropping systems. The practices of DSR and zero-till were associated with lower energy inputs relative to conventional tillage systems. So, cropping systems managed under conservation cultivation result in low energy use. Low input application in cropping systems is not only related to low energy use. Results confirmed that the adoption of recommended crop management practices such as zero tillage and residue retention enhance soil health thereby increasing the cropping system productivity.

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AUTHORS' CONTRIBUTION

The main author Laxmi Bhandari carried out the experiment, collected data, prepared ANOVA and manuscript, and the rest of the authors guided and helped in the entire process of the experimentation to the write-up of the manuscript.

CONFLICTS OF INTEREST

The authors have no any conflict of interest to disclose.

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