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Soil Organic Carbon and System Environmental Footprint in Sugarcane-Based Cropping Systems Are Improved by Precision Land Leveling

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Abstract: A six-year experiment (2009 to 2015) was conducted on sugarcane-based cropping systems in farmers' fields to examine the effects of precision land leveling (PLL) compared to traditional land leveling (TLL) in terms of soil organic carbon (SOC), greenhouse gas emissions, irrigation water requirements, and system productivity and profitability. Twelve treatments compared different sugarcane sowing regimes and crops in rotation under both PLL and TLL. Spring-sown sugarcane grown in rotation with rice, potato, and wheat under PLL had the highest production (89.7 kg ha^{-1} day^{-1}) and required 142 cm irrigation water, which was 35.1% less water than a commonly practiced cropping system with late-sown sugarcane grown in rotation with rice and wheat only under TLL). Cropping systems established under PLL had higher land use efficiency (ranging between 64.9 and 86.2%), higher energy productivity (90.7 to 198.6 GJ ha^{-1}), and lower greenhouse gas emissions (5249.33 to 944.19 kg CO_2 eq ha^{-1} year^{-1}) than those under TLL. As well, treatments under PLL had increased levels of SOC, particularly in the upper soil layers, relative to SOC in treatments under TLL. Combining PLL with diversification of crops in sugarcane cropping systems has the potential to sustainably increase farmers' land productivity and profitability while improving soil health and reducing irrigation requirements. These benefits are likely to have applications in other sugarcane-based cropping systems in similar agro-ecologies.

Keywords: precision land leveling; soil organic carbon; crop diversification; energy use pattern; environmental footprint

1. Introduction

Sugarcane is an important food crop, from which jaggery, cane sugar, and refined sugar are produced [1]. The Indian state of Uttar Pradesh, which is the epicenter of the country's sugarcane production, produces 135 m tons of sugar on over 2.2 Mha of land, and has 119 operational sugar processing factories. Sugarcane farming is the state's most important source of revenue and industrial development [2–5]. By 2030 sugarcane demand is expected to increase, and the amount recovered after cane processing will need to increase by 10.75% to meet this demand [3]. Sugarcane can be planted either in autumn (October to November) or spring (February to March). Optimal cane germination occurs when average air temperatures range between 20 °C and 32 °C [6]. In western Uttar Pradesh's Indo-Gangetic Plains, average air temperature of 30.6 °C has been reported as good for cane germination [7]. Excessive temperatures in both summer and winter adversely affect sugarcane production. Compared with sugarcane grown in other Indian agro-climatic zones, that grown in the western plain zone (WPZ) has higher fluctuations in air temperature and rainfall, potentially negatively affecting crop yields [7]. Sugarcane planted in the autumn generally experiences less heat stress at key plant development stages than that planted in spring, leading to improved germination, growth, and productivity in the autumn crop. However, an autumn-planted sugarcane crop has opportunity costs: a winter wheat crop cannot be cultivated, as it can prior to a spring-sown sugarcane crop. Soil organic matter (SOM) plays a significant role in the development of soil aggregates and soil improvement in any agricultural soil, hence increasing soil health [8]. Increasing SOM encourages soil aggregation and slows the rate of organic matter breakdown. Soil aggregates act as nuclei for soil stabilization with time. Because of physical barriers in the aggregate, SOM is better retained in bigger soil aggregates than in smaller ones [9].

Aggregate stability is determined by the characteristics and amount of humic chemicals in the soil, as well as their level of interaction with clay particles. [10]. Many factors affect SOC levels within the soil, including aggregate type [11], aggregate physico-chemical characteristics, and aggregate organic carbon stability [12]. SOC storage and soil-nutrient turnover are affected by structural stability, soil aggregation, and the preference of some microbial groups for some soil micro-resources [13]. Soil structural stability is greatly influenced by land use change uses [14] and cultivation practice [15]. Leveling an uneven soil surface is a necessary precursor to efficient soil, water and crop management. Soil leveling improves crop germination, establishment and yield as it facilitates more even distribution across the field of rain and/or irrigation water and thus soil moisture [16]. Increased cost and time to prepare the soil before crop establishment are major limitations in traditional soil leveling methods. These vary depending on the environmental factors, topography, soil volume and type, and the leveling equipment available [17]. Precision laser land leveling has emerged as an effective method to speedily level fields with a high degree of accuracy ($\pm$2 cm). Under similar soil fertility levels and land configurations, laser land leveling increased water productivity by 37 to 39% and water-use efficiency by 25 to 34% in a wheat-rice cropping system in Uttar Pradesh, compared to an unleveled field [18–20]. Laser land leveling (LLL) improves soil microclimatic conditions [21], reduces irrigation water requirements by 20 to 30% [22], and more evenly distributes salts within saline soils, extending the amount of land cultivatable by 3 to 5% [18]. In sugarcane cultivation, the application of laser land leveling is highly likely for improving yield and quality. In this research we investigated the effects of precision laser land levelling in sugarcane cultivation on farmers' fields in terms of soil heath, carbon budgets, irrigation efficiency, crop yields, and quality.

2. Materials and Methods

2.1. Field Experiments

The experiment was directed over ten successive *kharif* (monsoon, July to October), *rabi* (winter, November to February), and spring (March to June) seasons between 2009 and 2015 at eight randomly selected farmers' fields from Meerut and Muzaffarnager districts in western Uttar Pradesh, India. The climate at all sites falls into the Western Uttar Pradesh Zone (UP-6; Farmech.dac.gov.in/UP; accessed on 28 May 2021), and soils were subtropical sandy loams. The inherent soil properties of the experimental site are available in Table 1.

2.2. Comparing Traditional and Precision Laser Land Leveling

In traditional land levelling, a simple wooden or iron scraper is dragged across the field every year, generally after wheat harvesting. As TLL is not an effective levelling tool, it requires approximately 3–4.5 h ha^{-1} to scrape a field, and 2–3 laborers plus a tractor driver. After traditional levelling the field is not completely levelled and many small ditches and dykes remain. Consequently, irrigation water does not distribute uniformly and accumulates in lower-lying patches. It will take around 8.75–10 h to irrigate one hectare of a traditionally levelled field, depending on the soil texture.

In contrast, under precision laser levelling, laser-equipped drag-buckets are used to smooth the soil (Figure 1). PLL is generally conducted every 2–3 years. PLL generally takes about the same time as TLL (3–4 h ha^{-1}), but the land is better levelled, with all ditches and dykes removed. Only one tractor driver is required under PLL. After PLL irrigation water is distributed uniformly over the field and it requires approximately 5.0–7.5 h to irrigate one hectare (depending on soil texture), thus reducing the amount of electricity or diesel required to pump water.

Table 1. Inherent soil properties of the experimental site.

Soil Parameters	Status/Value	Methods Employed
Mechanical Separates		
I. Sand	63.0	Modified hydrometer [23]
II. Silt	16.2	
III. Clay	20.4	
Texture	Sandy loam	
density on bulk basis(Mg m^{-3})	1.40 (0–15 cm) 1.46 (15–30 cm)	Core sampler
Water stable aggregates (>0.25 mm)	48.5	Wet sieving [24]
Field capacity moisture (%)	15.5	
Chemical properties		
I. pH	7.5	1:2.5 soil and water suspension [25]
II. Organic carbon (%)	0.36	Rapid titration method [26]
III. Major nutrients (kg ha^{-1})		
Nitrogen	165.8	Alkaline permanganate method [27]
Phosphorus	12.5	0.5 M $NaHCO_3$, pH 8.5 [28]
Potash	193.2	Ammonium acetate [29]

2.3. Experimental Treatments and Procedure

Each experimental site had two adjacent plots: a treatment plot which was precision laser levelled and a control plot which was cultivated according to the farmer's current practice and was thus leveled using traditional practices. Each plot was 0.40 ha. Prior to the experiment, land slope was measured at between 0.5 and 2.0%; the average slope was 1.2%. Each treatment plot was laser levelled to a slope of 0 to 0.2% at the start of the experiment, employing huge power machines and soil movers equipped with laser-guided instrumentation to move the dirt either by cutting or filling to establish the required slope/level.

Six crop rotations were imposed on both the laser leveled and control plots: two treatments were based on an autumn-planted sugarcane, three on a spring-planted sugarcane, and one on a late-planted sugarcane. For each rotation both precision laser land leveling (PLL) and traditional laser leveling (TLL) were examined. In each rotation a monsoon rice or maize crop was grown. In the first four treatments (T_1 to T_4) this was followed by an autumn-sown sugarcane which was ratooned once and then followed by a wheat crop. In treatments T_5 to T_{10} monsoon rice was followed by a short-duration winter crop, then spring-planted sugarcane which was ratooned once and then followed by a wheat crop. In the final two treatments (T_{11} and T_{12}) monsoon rice was followed by a wheat crop and then a late-planted spring sugarcane which was ratooned once and then followed by a wheat crop. All crop rotations are commonly observed in western Uttar Pradesh. The twelve treatments are summarized in Table 2.

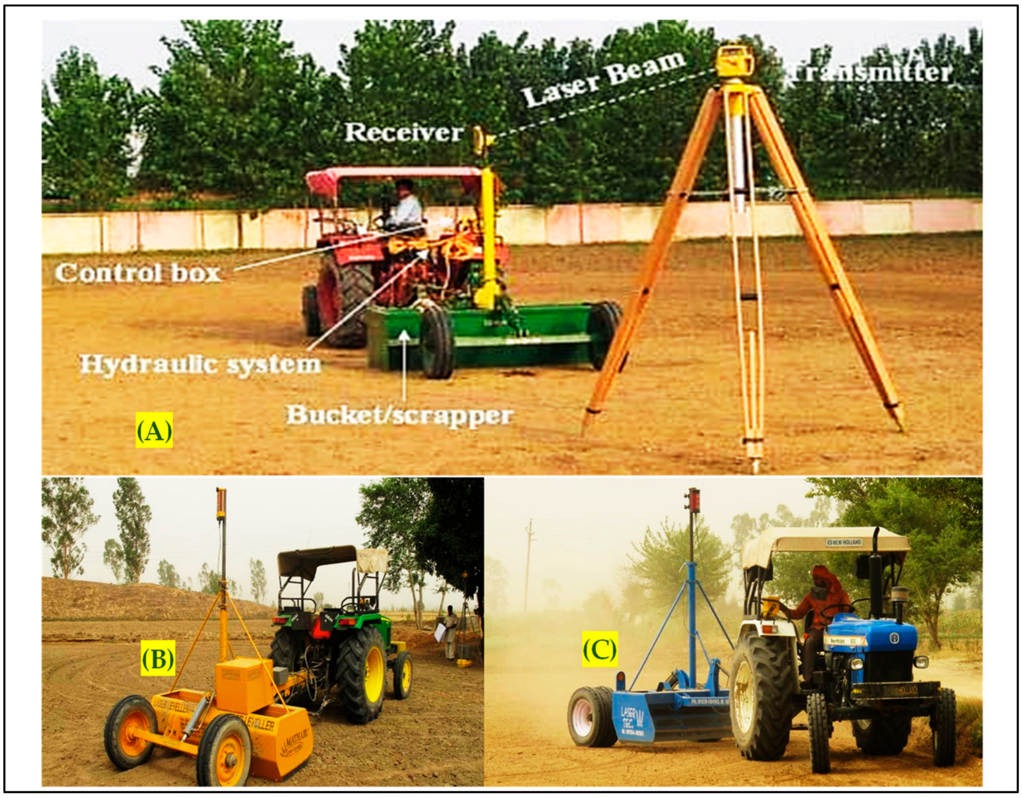

Figure 1. Precision laser land leveling (PLL) in field conditions, (**A**) showing the function of different components; (**B**,**C**) PLL in operation levelling a field.

The land preparation, crop establishment timing, and in-crop management followed the practices recommended by the Uttar Pradesh Department of Agriculture (than those under TLL) and are summarized in Table 3. Irrigation was applied to both PLL and TLL plots according to crop demand in the PLL plots, and soil moisture and water stress were monitored. Frequently, crops in the TLL plots were severely water stressed during their development: in these instances, an additional life-saving irrigation of 7 cm water was applied to the TLL plots.

Fertilisers including nitrogen (N), phosphorus (P), potassium (K), and zinc (Zn) were applied regularly during all crop rotations. All treatments received 150 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, 40 kg K_2O ha^{-1}, and 25 kg $ZnSO_4$ ha^{-1} in the first trial year (2009–10). The remaining N was disseminated in two equal splits at two vegetative development periods, with 0.33% of the N and all other fertilizers applied as a basal application. At maturity, all crops were hand harvested, with a seed yield of 14% moisture content. The average crop water requirement (ETc) during each crop growing period was estimated using the CROPWAT model (version 8.0, FAO, Rome, Italy) with weather data from a ten-year period from the agro-meteorological observatory at Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, U.P., India.

Table 2. Summary of experimental treatments.

No	Crop Rotation	Leveling	Abbreviation
T2	Rice-black gram-autumn sugarcane-ratoon sugarcane-wheat	TLL	R-B-S-R-WTLL
T3	Maize-autumn sugarcane-ratoon sugarcane-wheat	PLL	M-S-R-WPLL
T4	Maize-autumn sugarcane-ratoon sugarcane-wheat	TLL	M-S-R-WTLL
T5	Rice-potato-spring sugarcane-ratoon sugarcane-wheat	PLL	R-P-S-R-WPLL
T6	Rice-potato-spring sugarcane-ratoon sugarcane-wheat	TLL	R-P-S-R-WTLL
T7	Rice-mustard-spring sugarcane-ratoon sugarcane-wheat	PLL	R-M-S-R-WPLL
T8	Rice-mustard-spring sugarcane-ratoon sugarcane-wheat	TLL	R-M-S-R-WTLL
T9	Rice-pea-spring sugarcane-ratoon sugarcane-wheat	PLL	R-P-S-R-WPLL
T10	Rice-pea-spring sugarcane-ratoon sugarcane-wheat	TLL	R-P-S-R-WTLL
T11	Rice-wheat-late spring sugarcane-ratoon sugarcane-wheat	PLL	R-W-S-R-WPLL
T12	Rice-wheat-late spring sugarcane-ratoon sugarcane-wheat	TLL	R-W-S-R-WTLL

PLL: precision laser leveling; TLL: traditional laser leveling.

Table 3. Agronomic practices of crops in experimental rotations.

Crop in Rotation	Seed Rate qt ha^{-1}	Date of Sowing/Transplanting	Date of Harvesting
Rice (*Oryza sativa* L)	0.25	3rd week of June	October 3rd week
Wheat (*Triticum aestivum* L.)	1.00	2nd week of November	April 2nd week
Sugarcane (*Saccharum officinarum*)	35,000–45,000 3-bud set/ha (60 q/ha)	2nd Week of June	4th week of Nov to 4th of March
Sugarcane ratoon crop	n/a	n/a	January 2nd week
Maize (*Zea mays* L.)	0.20	October (Autumn) and February–March (Spring)	2nd week of October
Mustard (*Brassica juncea*)	0.04	September 3rd week to October 1st week	March 1st week
Potato (*Solanum tuberosum* L.)	20.00	October 3rd week	March 1st week
Pea (*Pisum sativum* L.)	0.70–0.80	3rd week of October to 1st week of November	October 3rd and 4th week
Black gram (*Vigna mungo* L.)	0.25	4th week of August	October 2nd week

2.4. Calculations

Production indices and the economic efficiency of each cropping system under both PLL and TLL were calculated using the methodology of Katyal and Gangwar [30]. Prices were obtained from the Meerut market each season.

2.4.1. Equivalent Cane Yield of All Crops in Rotation (ECY)

On the basis of current market prices, the yield of all crops in rotation was converted into equivalent cane yield and estimated using Bandyopadhyay's methodology [31].

2.4.2. Adjusted Cane Yield (ACY)

Adjusted cane yield was calculated by adding equivalent cane yield of all crops in rotation with the yield of sole sugarcane crop as per Equation (1).

$$\text{Adjusted cane yield (ACY)} = \text{ECY} + \text{SY} \quad (1)$$

SY represents the sugarcane yield whereas ECY represents the equivalent land productivity of all crops in rotation. Nutrient use productivity and energy calculations were calculated following the approach outlined by Mandal et al. [32].

2.5. Statistical Analysis

SPSS software was employed to analyze the effect in terms of level of significance of different imposed treatments. Further, Duncan's multiple range test (DMRT) was used for comparing the means. The probability level of 5.0 percent is considered statistically significant.

3. Results and Discussion

3.1. Production Efficiency and Land Use Efficiency

Of the twelve experimental treatments, the crop rotations with PLL combined with autumn- or spring-sown sugarcane had the highest average daily productivity, followed by their counterpart rotations under TLL (Table 4; Figure 2). The treatments with late-sown spring sugarcane had the lowest productivity under either laser leveling option. High potato and maize productivity potential, as well as higher bean yields in pea, black gram, and mustard, could explain why these systems are so efficient. Furthermore, as a result of increased output, higher reward was achieved. Potato/maize/mustard/pea/black gram-based systems reported to be productive and profitable than cereal-based systems. T_5 and T_6 showed [33] the highest production efficiency, better water and nutrient availability [34,35], and better soil microbial activities [36] due to PLL.

Table 4. Water use efficiency, employment generation efficiency, productivity, net return, and system profitability of experimental treatments.

Treatments	WUE (kg Grain m^{-3}) Water Used)	EGE (Man dayha^{-1} day^{-1})	Productivity (kg ha^{-1} day^{-1})	Net Return (INR ha^{-1})	System Profitability (INR ha^{-1} day^{-1})
T_1	2.149	0.58	49.8	55,520	174.2
T_2	0.963	0.96	45.1	48,410	163.9
T_3	1.678	1.52	83.3	126,689	346.8
T_4	0.784	1.73	55.9	59,091	176.8
T_5	2.892	1.56	89.7	154,030	388.9
T_6	1.058	1.95	80.3	123,933	346.2
T_7	1.883	1.38	88.6	141,765	376.2
T_8	0.875	1.65	79.3	119,793	328.6
T_9	2.216	0.64	84.2	138,050	361.4
T_{10}	0.986	1.21	71.8	102,142	288.8
T_{11}	1.378	1.25	81.2	131,800	359.3
T_{12}	0.635	1.41	57.4	68,600	188.7

Treatments details in Table 2; WUE, water use efficiency; EGE, employment generation efficiency, INR, Indian rupees.

3.2. Production, Monetary, and Employment Efficiencies

Maximum daily cropping system productivity (89.7 kg ha^{-1} day^{-1}), daily monetary return use efficiency (351.6 INR ha^{-1} day^{-1}), and daily cropping scheme profitability (388.9 INR ha^{-1} day^{-1}) were observed in T_5 (Table 4; Figure 2). Other treatments that performed well in terms of these metrics were T_7 and T_9; all three cropping systems included a spring-sown sugarcane and PLL. Of the cereal crops, maize has a higher economic value than rice, whereas potato, pea, and mustard are all higher-value vegetable crops: rotations with these crops (rather than those with lower-value crops) achieved higher system productivity and are thus more attractive options for smallholder famers. Thus, there is potential to replace the traditional rice and wheat crops, with which sugarcane is rotated, with other crops with both higher economic value and capacity to improve soil health.

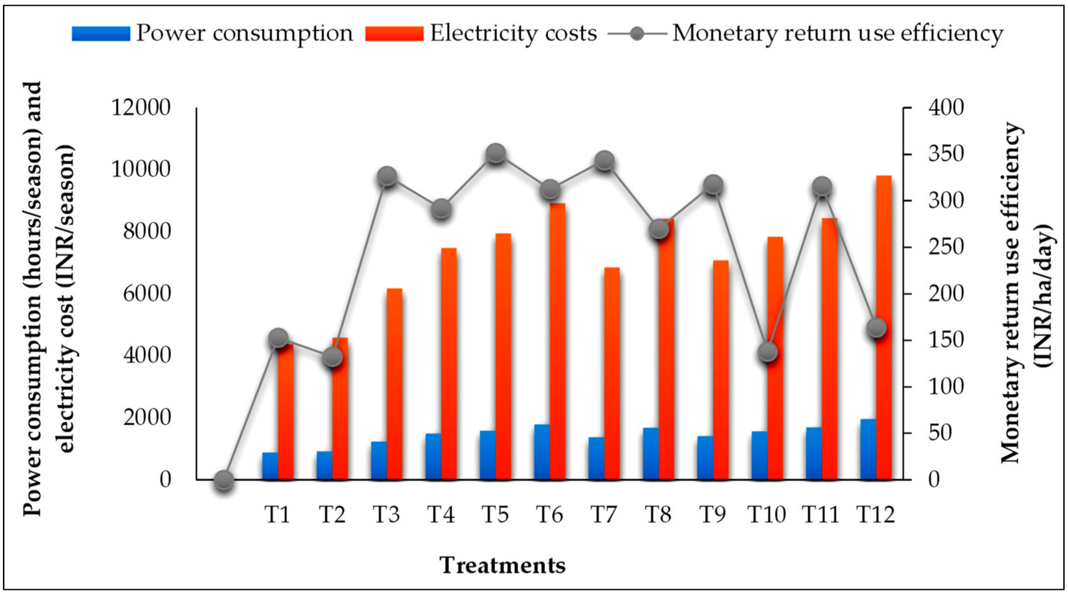

Figure 2. Power consumption, electricity cost, and monetary return use efficiency of experimental treatments.

As compared to the T_{11} system, T_5, T_7, and T_9 gave 1.29, 1.27, and 1.21 times higher productivity, saved 51–69 cm of irrigation water. The T_5 system used 51 cm less water and reported with highest productivity (89.7 kg ha^{-1} day^{-1}) and has productivity margin of 8.5 kgha^{-1} day^{-1}. The T_7 system produced 88.6 kg ha^{-1} day^{-1} with 132 cm irrigation water (Table 4), resulting in a 61 cm water savings. T_5 cropping system used 155 cm of irrigation water and produced 84.2 kgha^{-1} day^{-1}, while T_4 cropping system used 38 cm of irrigation water and produced 84.2 kgha^{-1} day^{-1} (Table 3). This could be due to the black gram pulse crop, which, when compared to the R-W-S-R-W system, reduced water loss due to evaporation, percolation, and seepage [35–38]. The highest net returns were INR 138,982 ha^{-1} annum^{-1} in the R-P-S-R-W system, which was 1.39 times greater than the R-W-S-R-W system (Table 4), followed by INR 130,779 and Rs. 120,096, respectively, in the R-M-S-R-W and R-P-S-R-W sequences. As compared to the R-W-S-R-W system, the R-P-S-R-W, R-M-S-R-W, and M-S-R-W consumed 17.9, 24.8, and 32.1% lesser irrigation water which further resulted in saving electricity consumption by 140, 300, and 460 electricity units' ha^{-1}, respectively (Table 4; Figure 2). Similar observations were also reported by Bohra et al. [39]; Rathore et al. [40].

3.3. Resource Use Efficiency

Cropping system profitability ranged from 163.9 (T2) to 388.9 (T5) INR ha^{-1} day^{-1}, with MRUE values ranging from 132.6 (T2) to 351.6 (T5) INR ha^{-1} day^{-1} (Table 4). Similar trends of high profitability under PLL and spring-sown sugarcane were reported by Singh et al. [41] and Sharma [35,42].

Labor requirements where highest in the T_6 cropping system (1.95 person days ha^{-1} day^{-1}) and lowest in T_1 (0.58 person days ha^{-1} da^{-1}). Overall, in the more profitable spring-sown PLL treatments, labor requirements varied between 0.64 (T_9) and 1.56 (T_5) person days ha^{-1} day^{-1}. Intercropping increased the labor required for weeding by 36% compared to the sole crops. T_8, T_{10}, and T_{12} only hire farmers for 1.73, 1.65, and 1.41 men days ha^{-1} day^{-1}, respectively, but >0.58 men days ha^{-1} day^{-1} engagement in any order resulted in underemployment, as documented by [43–46] (Table 4; Figure 2).

3.4. Soil Organic Carbon Patterns

The treatment T_5 had the greatest soil organic carbon concentration in the surface layer (0–15 cm) at 8.76 g kg^{-1}, followed by T_{11} (8.52 g kg^{-1}) (Table 5). Treatments with PLL achieved maximum soil organic carbon concentrations in the surface and lower soil layers than were observed in treatments with TLL. Across all treatments, the mean SOC concentration varied from 2.69 inT_8 to 6.91 g kg^{-1} in T_5 and with almost nil improvements in T_2 emphasizing the role of laser levelling [47]. The greatest improvement in SOC concentration was observed in the T_9 (8.25 g kg^{-1}) and T_3 (7.45 g kg^{-1}) treatments.

Table 5. After 6 years, changes in soil organic carbon (SOC) concentration (g kg^{-1}) under alternative agricultural systems and precision land levelling procedures.

Soil Depth (cm)	Inherent (2009)	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	Mean
0–15	6.7 ± 0.26	7.21 ± 0.74 ^{d}	4.85 ± 0.23 ^{c}	7.45 ± 1.40 ^{d}	4.92 ± 0.23 ^{a}	8.76 ± 0.21 ^{c}	5.93 ± 0.28 ^{a}	7.09 ± 1.09 ^{b}	3.96 ± 0.18 ^{b}	8.25 ± 1.16 ^{b}	5.26 ± 0.2 ^{b}	8.52 ± 1.40 ^{c}	5.53 ± 0.26 ^{a}	6.48 ± 0.62
15–30	6.2 ± 0.25	6.77 ± 0.30 ^{d}	3.64 ± 0.18 ^{c}	6.95 ± 1.16 ^{b}	4.17 ± 0.21 ^{b}	8.33 ± 1.15 ^{c}	5.52 ± 0.23 ^{a}	6.44 ± 1.84 ^{c}	3.47 ± 0.17 ^{a}	7.84 ± 1.08 ^{d}	4.83 ± 0.19 ^{b}	8.06 ± 1.30 ^{d}	5.23 ± 0.22 ^{a}	5.94 ± 0.67
30–60	5.1 ± 0.19	6.17 ± 0.12 ^{a}	2.97 ± 0.15 ^{c}	6.44 ± 1.16 ^{a}	3.65 ± 0.18 ^{c}	7.72 ± 0.34 ^{a}	5.25 ± 0.21 ^{b}	5.92 ± 0.35 ^{b}	2.75 ± 0.13 ^{a}	7.62 ± 0.33 ^{b}	3.62 ± 0.18 ^{c}	6.99 ± 0.34 ^{b}	4.76 ± 0.19 ^{b}	5.32 ± 0.31
60–90	4.3 ± 0.13	4.52 ± 0.14 ^{c}	2.18 ± 0.11 ^{a}	4.76 ± 0.21 ^{c}	2.74 ± 0.14 ^{a}	5.88 ± 0.09 ^{a}	3.61 ± 0.19 ^{c}	4.71 ± 0.22 ^{d}	1.92 ± 0.11 ^{a}	5.09 ± 0.09 ^{b}	2.98 ± 0.15 ^{c}	5.66 ± 0.12 ^{a}	2.95 ± 0.15 ^{a}	3.92 ± 0.14
90–120	3.4 ± 0.09	2.53 ± 0.18 ^{a}	1.53 ± 0.07 ^{b}	2.88 ± 0.09 ^{a}	1.66 ± 0.09 ^{b}	3.87 ± 0.12 ^{b}	2.46 ± 0.13 ^{d}	2.47 ± 0.23 ^{b}	1.36 ± 0.07 ^{d}	3.13 ± 0.23 ^{a}	1.74 ± 0.10 ^{b}	3.62 ± 0.33 ^{b}	1.92 ± 0.12 ^{b}	2.43 ± 0.15
Mean	5.14 ± 0.18	5.00 ± 0.29	3.03 ± 0.15	5.69 ± 0.80	3.43 ± 0.17	6.91 ± 0.38	4.55 ± 0.21	5.33 ± 0.75	2.69 ± 0.13	6.39 ± 0.58	3.69 ± 0.17	6.57 ± 0.69	4.08 ± 0.19	-

According to the Duncan multiple range test (DMRT) for separation of means, different letters within columns are substantially different at $p = 0.05$.

In 2012–13, SOC values were 11% higher under T_5 than T_8, and 10% higher with T_{11}. By the end of the experiment (i.e., after six years), SOC was 25% higher in T_5 than T_8 and 16% higher with T_{11} and 17% higher with T_9 than T_8, respectively. However, the SOC contents was just 7% higher under conventional leveling. Under PLL in the 20–30 cm layer, recorded SOC values were 12% and 19% higher than with T_2 and T_8 treatments, respectively (Table 5).

3.5. Changes in SOC over Time: Temporal Comparison

Average SOC stocks in the top 400 kg of soil dropped from 5.92 to 5.41 kg C m^{-2} (Table 6). Between 2009 and 2015, changes in important treatments were -1.88 ± 0.04 kg C m^{-2} in T8 (i.e., 5.41 to 4.89 kg C m^{-2}); -0.68 ± 0.2 kg C m^{-2} in T10 (i.e., 5.93 to 5.28 kg C m^{-2}); -0.82 ± 0.09 kg C m^{-2} in T4 (i.e., 5.92 to 5.22 kg C m^{-2}); and -0.700 ± 0.09 kg C m^{-2} in (i.e., 5.48 to 5.05 C m^{-2}). PLL-treated plants stored larger fractions of atmospheric carbon and, in certain circumstances, established an equilibrium of C imports and exports. SOC stocks decreased after six years in TLL therapy. Over the six-year trial, similar trends in soil C content were seen in lower soil layers (i.e., 400–800 and 800–1200 kg of soil m^{-2}): the average over all PLL treatments was -0.070 ± 0.06 and -0.020 ± 0.02 kg C m^{-2} in the 400–800 and 800–1200 kg of $soil^{-2}$ intervals, respectively. This approximates an average yearly rate of change of -6.9 and -5.6 g C m^{-2} $year^{-1}$ for the mid and lower soil layers, respectively (Table 6).

Due to associated errors during its calculation, SOC estimates in the 400–800 and 800–1200 kg m^{-2} layers were small. Over the entire 0 to 1200 kg m^{-2} soil depth, SOC stocks did not vary greatly under different land leveling treatments (Table 6), although superficial differences were observed during 2015 between rotations (Table 7).

Under T_5, SOC increased from 22.33 to 24.31 kg C m^{-2} between 2009 and 2015. Changes were also observed in T_{11} (20.89 to 21.86 kg C m^{-2}), T_7 (14.96 to 14.13 kg C m^{-2}), and T_8 (13.08 to 12.35 kg C m^{-2}). Archived samples exposed that decomposition degree of SOC under T_5, T_8, and T_7 was 1.5 times greater, and significantly higher than that of R-W-S-R-W_{PLL} with PLL (Table 7) and hence to evaluate the effect of applied treatments on SOC, previous year samples are certainly important [48].

Between 2009 and 2015, the average SOC in 0–1200 kg m^{-2} of soil (i.e., around 1 m soil depth) in T_8 treatments declined by $-1.97+0.06$ kg m^{-2}, from 13.08 to 12.35 kg C m^{-2}. SOC stocks in 0–1200 kg m^{-2} of soil grew by +1.98 kg m^{-2} (i.e., from 22.33 to 14.13 kg m^{-2}) in T_5 (i.e., from 22.33 to 24.31 kg m^{-2}) and $+0.83 \pm 0.3$ kg m^{-2} in T_7 (i.e., from 14.96

to 14.13 kg m^{-2}) in T_5 (i.e., from 22.33 to 24.31 kg m^{-2}. Between 2009 and 2015, C was removed from the soil rather than absorbed from the environment in the TLL treatments.

Table 6. Annual rate of change in multiple soil mass intervals and variations in SOC stocks from (averaged over alternative cropping systems and precision land leveling practices) 2009 and in 2015.

Crop Sequences	Soil Organic Carbon (± Standard Error)											
	0–400 kg of Soil m^{-2} (Approx. 0–30 cm)			SOC Change Rate g of Cm^{-2} $year^{-1}$	400–800 kg of Soil m^{-2} (Approx. 30–60 cm)			Annual SOC Change Rate g of C m^{-2} $year^{-1}$	800–1200 kg of Soil m^{-2} (Approx. 60–90 cm)			SOC Change Rate g of Cm^{-2} $year^{-1}$
	2009	2015	Difference		2009	2015	Difference		2009	2015	Difference	
	kg m^{-2}				kg m^{-2}				kg m^{-2}			
T_1	8.12	9.11 *	0.99 ± 0.2	46.2	5.47	5.57	0.10 ± 0.09	7.1	3.38	3.47	0.01 ± 0.11	4.4
T_2	5.48	5.05	−0.70 ± 0.09	−23.3	3.85	3.18	−0.09 ± 0.06	−6.1	2.92	2.57	−0.02 ± 0.02	−5.4
T_3	8.81	8.75	0.06 ± 0.05	25.7	5.82	5.31 *	0.51 ± 0.2	4.5	2.93	2.67	0.26 ± 0.02	5.7
T_4	5.92	5.22	−0.82 ± 0.09	−21.4	4.05	3.98	−0.07 ± 0.09	−5.5	2.42	2.37	−0.05 ± 0.02	−4.2
T_5	9.18 *	9.87	−0.69 ± 0.2	82.1	7.62	7.64	0.02 ± 0.2	8.8	5.04	5.08	0.04 ± 0.01	7.2
T_6	6.62	6.18	−0.79 ± 0.2	−13.6	5.36	5.27	−0.46 ± 0.07	−4.8	3.56	3.28	−0.18 ± 0.02	−1.8
T_7	7.46	7.15 *	0.31 ± 0.03	28.2	5.39	5.65	0.26 ± 0.09	3.9	4.14	4.12	0.02 ± 0.01	1.8
T_8	5.41	4.89	−1.88 ± 0.04	−67.8	3.35	3.08	−0.07 ± 0.06	−6.9	2.72	2.37	−0.02 ± 0.02	−5.6
T_9	8.98 *	9.77	0.79 ± 0.2	57.4	7.03	7.11	0.08 ± 0.2	1.5	3.72	3.81	0.09 ± 0.11	5.1
T_{10}	5.93	5.28	−0.68 ± 0.2	−19.2	4.05	3.98	−0.07 ± 0.09	−5.5	2.42	2.37	−0.05 ± 0.02	−3.9
T_{11}	9.15	9.29	0.14 ± 0.9	19.6	5.72	5.88	0.16 ± 0.09	7.3	4.57	4.58	0.01 ± 0.01	0.6
T_{12}	6.01	5.75	−0.70 ± 0.09	−16.3	4.85	4.18	−0.31 ± 0.09	−5.1	3.42	3.37	−0.15 ± 0.02	−2.4

Treatments details in Table 2; * At 0.05, there is a significant difference between years.

Table 7. Efficiencies of energy use and its dynamics and SOC stocks (0–90 cm) under alternative cropping systems and precision land leveling practices.

Crop Sequences	Organic Carbon of Soil (± Standard Error)			Land Use Efficiency (%)	Precise Energy ($MJha^{-1}$)	Productivity of Energy (GJ ha^{-1})
	0–1200 kg of Soil m^{-2} (Approx. 0–90 cm)					
	2009	2015	Difference			
	kg m^{-2}					
T_1	16.85	16.35	−0.50 ± 0.22	84.8	17.1	186.5
T_2	13.37	12.85	−1.88 ± 0.04	70.4	18.8	98.6
T_3	21.70	22.44	0.74 ± 0.4	82.3	22.3	140.8
T_4	14.67	13.09	−1.80 ± 0.02	66.7	28.4	95.6
T_5	22.33	24.31	1.98 ± 0.03 *	86.2	23.3	198.6
T_6	18.07	16.55	−1.52 ± 0.4	76.3	29.9	123.5
T_7	14.96	14.13	0.97 ± 0.2	84.6	19.6	180.9
T_8	13.08	12.35	−1.97 ± 0.06	68.3	25.9	98.6
T_9	20.79	21.55	0.76 ± 0.4	85.1	20.6	192.2
T_{10}	14.65	13.48	−1.76 ± 0.06	71.2	27.7	105.7
T_{11}	20.89	21.86	0.83 ± 0.2 *	81.5	17.6	132.1
T_{12}	15.56	13.77	−1.62 ± 0.06	64.9	24.7	90.7

Treatments details in Table 2; * indicates significant at 0.05, there is a significant difference between years.

3.6. SOC and Tillage Practices

Under T_7, SOC in the first 400 kg m^{-2} soil (about the top 30 cm) had higher profile than under T_5. While SOC stocks were higher (+10%) in precision land levelling (T_5) than in T_7, they were marginally lower (−5.6%) and (−1.8 %) in T_8 than in T_6, respectively (Table 5). SOC stocks, on the other hand, were consistently lower under T_{12} than they were under T_5 or T_7. (Table 6). There were no significant variations in SOC stocks between T_7 and T_{12} when the 0–400 kg of soil m^{-2} under R-M-S-R-W and R-P-S-R-W with or without land levelling was investigated, whereas T_{12} had 16% less SOC (Table 6). $T_{12's}$ soil disturbance in the top 400 kg of soil m^{-2} may have accelerated the rate of SOC loss compared to T_{11}.

Traditional field levelling has been shown to destabilize aggregates, lowering physical protection and exposing previously inaccessible SOC to microbial destruction [49]. When compared to archival soil samples, six years of treatment demonstrated a decrease in SOC stocks in the first 400 kg of soil m^{-2} for all TLL treatments (Table 6). This shows that six years were insufficient to produce detectable differences in SOC across the T_7,

T_5, and T_{11} plots. Long-term studies are necessary to determine the differences in the effect of management practices, according to several studies [50,51]. Given the high SOC background in the entire soil profile and small annual changes, long-term studies are essential to determine differences in the effect of management practices. When SOC stocks were examined over time in the soil layer immediately below the plough layer (400–800 kg m^{-2}), it was clear that during the period between soil samplings (2009–2015), SOC levels had fallen significantly under T8 plots while remaining virtually unaltered under T_7 or T_5 plots (Table 6). Under T_7 and T_5, there was no difference in SOC stocks between 2009 and 2015. (Table 5). Under R-M-S-R-WTLL (T_8), the yearly rate of SOC loss in the 400–800 kg of soil m^{-2} interval was -6.9 g C m^{-2} $year^{-1}$, while the rate of SOC change in the T_1 and T_5 plots was +7.1 and +8.8 g C m^{-2} $year^{-1}$, respectively (Table 6). SOC stocks under T_1 and T_5 were assumed unaffected by land levelling at this soil mass interval due to the estimation error. As a result, compared to T_1 or less intrusive PLL as T_5 cropping system, significant soil disturbance with T_8 could have resulted in a quick rise in soil aeration (as well as changes in soil temperature and moisture) at larger depths. SOM decomposition would be accelerated if exposed to higher oxidative conditions at deep [52], and this could be the source of SOC depletion at the 400–800 kg of soil m^{-2} interval in T_8 plots. SOC was unaffected by management techniques in the 800–1200 kg of soil m^{-2} interval (about 60–90 cm) and remained constant under all of the examined treatments, as expected (Table 6).

Finally, there were differences across tillage treatments when evaluating soil C changes in the entire 1200 kg of soil m^{-2} (about 90 cm depth) in 2009, but they grew wider to become significant in 2015. Over the last 06 years of the trial, soil C stocks increased by 4.4, 5.1, 5.7, and 7.2, 0.74, 0.76, 0.97, and 1.98 kg C m^{-2} under T_1, T_9, T_3, and T_5 treatments, respectively (Table 5). T_8 twice the rate of SOC change under T_9 or T_5, 57.4, 63.3, 82.1, and 99.2 g C m^{-2} $year^{-1}$, respectively, assuming a constant rate of change in SOC stocks for the last 06 years (Tables 6 and 7). Despite the observed differences between treatments, the differences were statistically significant when C changes for each treatment were evaluated over time (Tables 6 and 7).

After six years, more SOC stores were discovered in the surface 400 kg of soil m^{-2} under T_9 or T_5 compared to T_8. T_8 lost more SOC than T_9 or T_5 with PLL, despite the fact that the temporal difference was not judged significant. Given the parameters of this experiment, it is likely that more than 06 years will be necessary to identify variations between the examined cropping systems and land levelling procedures in the surface 400 kg of soil m^{-2} (approx. 30 cm). SOC stores in the 400–800 kg soil m^{-2} range were found to diminish after only 06 years under T_8, but remained constant under T_9 and T_5. Leveling choices have no effect on SOC stores in the 800–1200 kg of soil m^{-2} range. Comparison between old and fresh soil samples revealed that higher fraction of carbon was recorded in the T_9 and T_5 plots where PLL followed than T_8 plots where TLL was practiced. Further, plots under TLL with time lost the SOC. The yearly SOC change rate (g of cm^{-2} $year^{-1}$) under both alternative cropping systems and precision land leveling practices indicated that rice-black gram-autumn sugarcane-ratoon sugarcane-wheat, maize-autumn sugarcane-ratoon sugarcane-wheat, rice-potato-spring sugarcane-ratoon sugarcane-wheat, rice-mustard-spring sugarcane-ratoon sugarcane-wheat, rice-pea-spring sugarcane-ratoon sugarcane-wheat, and rice-wheat-late spring sugarcane-ratoon sugarcane-wheat under precision laser leveling showed the positive SOC than traditional laser leveling (Figure 3)

3.7. *Efficiencies of Energy Use and Its Dynamics*

Total energy requirements were highest in T_6 (59.9 GJ ha^{-1}) followed by T_4 (55.8 GJ ha^{-1}), T_{10} (53.1 GJ ha^{-1}, T_8 (51.2 GJ ha^{-1}), and T_{12} (48.6 GJ ha^{-1}). Potato cultivation (e.g., in T_{12}) requires high energy inputs in terms of the relatively higher fertilizer, seed, and human labor required in its cultivation. Use efficiency of land under T_5, T_6, T_1, T_{11}, T_3, and T_{11} was recorded as 86.2, 85.1, 84.8, 84.6, 82.3, and 81.5%, respectively which were at par with

T_9 (76.3%), T_{10} (71.2%), T_2 (70.4%), and T_8 (68.3%) (Table 6). However, energy values in terms total input energy and energy productivity were 59.9 and 198.6 GJ ha^{-1} over existing T_{12} system (32.9 and 90.7 GJ ha^{-1}), respectively (Table 7; Figure 4).

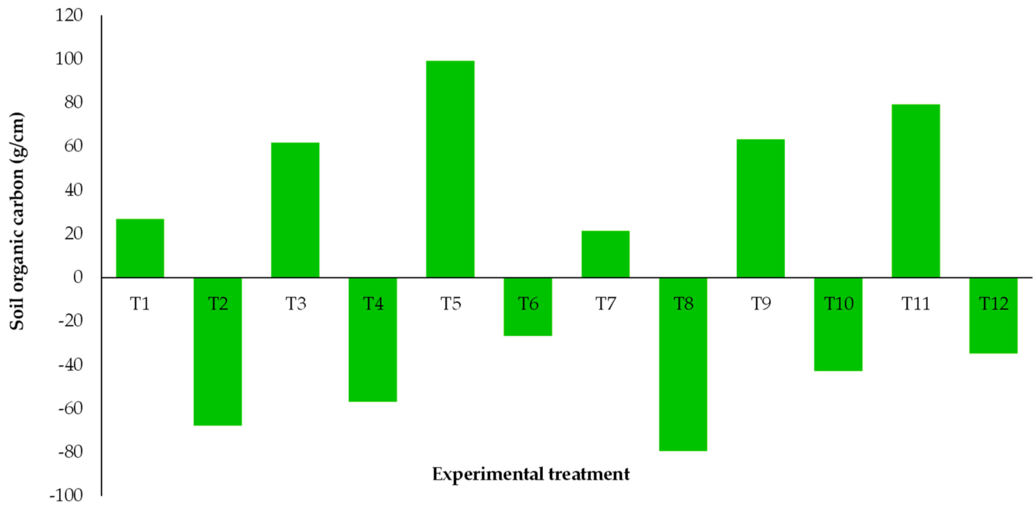

Figure 3. Yearly SOC change rate (g of cm^{-2} year^{-1}) under alternative cropping systems and precision land leveling practices.

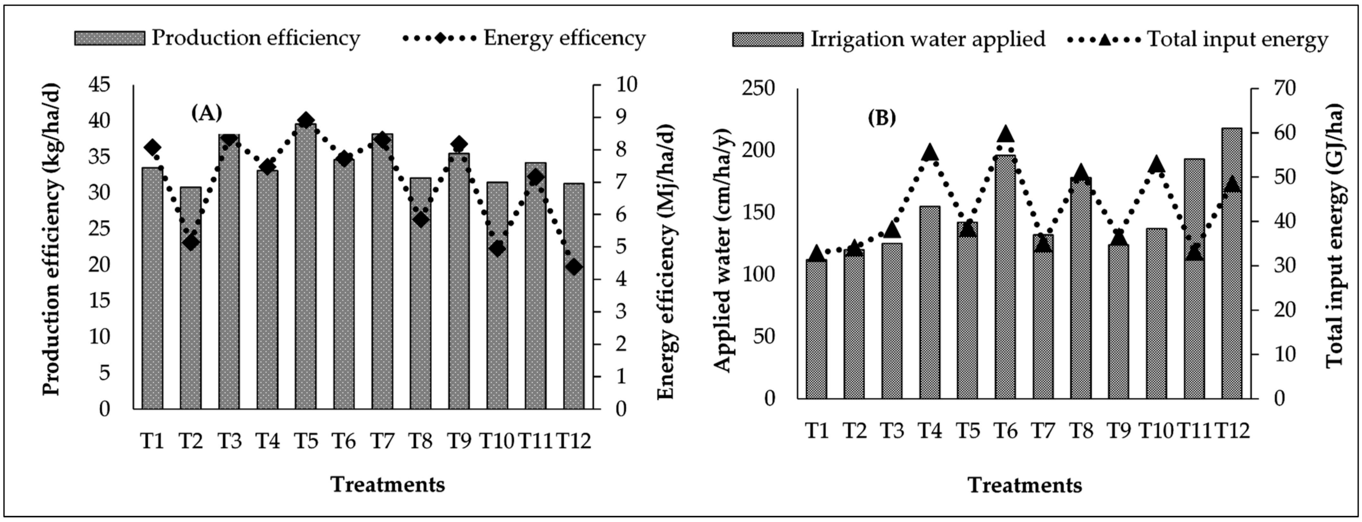

Figure 4. (**A**) Production efficiency and energy-use efficiency and (**B**) total input energy and irrigation water applied under the experimental cropping systems and land leveling practices.

As well, maize and pea legumes have higher energy requirements due to the greater labor required for cob and pod picking. Cropping systems with maize and/or black gram had higher energy requirements as these crops had more frequent pesticide applications; maize also required relatively more fertilizer and irrigation [26]. T_9 and T_3 systems once again showed higher energy efficiency because, despite their higher energy output, their energy use per unit energy output was far lower than other systems. T_7 and T_5 systems also generated high power equivalents, leading to increased net energy returns, which were similar to T_{11} systems, possibly due to higher land productivity.

3.8. Greenhouse Gas Emission and the Carbon Footprint

Over six years, the T_9 cropping system (spring-sown sugarcane with PLL) had the lowest greenhouse gas emissions (0.24 kg CO_2 eq ha^{-1} year^{-1}), while the T_{12} cropping system (late sown spring sugarcane under TLL) had the highest greenhouse gas emissions

(0.97 kg CO_2 eq ha^{-1} year^{-1}) (Table 8). The total CO_2-equivalent emissions were lower in cropping systems which included potato, as relatively more potassium fertilizer than nitrogen fertilizer was applied in these systems: excess or poorly timed nitrogen fertilizer is a key source of agricultural greenhouse gas emissions [53]. Crop residues increased SOC, soil health and thereby reduces the green-house emissions in the top 20-cm soil layer. Further higher SOC stocks offset the input-induced greenhouse gas emissions. Under TLL, farmers till the field at least thrice and plank it once, which results in approximately 4.5 h' per hectare tractor usage to sow two crops each year. Under PLL, the tractor time required to sow each crop is reduced by 2.25 h' per hectare, which saves approximately 19,536 MT CO_2 emissions per annum across western Uttar Pradesh [54].

Table 8. Average emissions and the C-footprint under alternative cropping systems with levelling options from 2009–2015.

Crop Sequences	Average Emissions (kg CO_2 eq ha^{-1} year^{-1})	Footprint of Carbon (kg CO_2 kg^{-1})	Build-Up of C %	Rate of C Build-Up (Mg C ha^{-1} year^{-1})	Sequestrated Carbon (Mg C ha^{-1})
T_1	1565.37	0.51	36.6 ± 0.6	1.46 ± 0.09	8.6 ± 0.8
T_2	3590.63	0.85	33.8 ± 1.8	1.36 ± 0.07	7.9 ± 0.3
T_3	1223.34	0.45	41.0 ± 2.2	1.63 ± 0.09	9.3 ± 0.2
T_4	3119.88	0.75	40.7 ± 2.4	1.82 ± 0.006	8.7 ± 0.8
T_5	944.19	0.24	43.6 ± 0.09	1.88 ± 0.001	9.6 ± 0.7
T_6	2475.63	0.68	40.1 ± 2.31	1.74 ± 0.10	9.1 ± 0.2
T_7	1746.44	0.55	39.3 ± 1.81	1.13 ± 0.021	6.8 ± 0.5
T_8	4275.56	0.86	37.5 ± 3.1	1.02 ± 0.006	6.3 ± 0.8
T_9	1056.73	0.36	39.3 ± 1.8	1.96 ± 0.09	9.4 ± 0.8
T_{10}	3292.35	0.76	37.3 ± 0.06	1.73 ± 0.021	8.5 ± 0.5
T_{11}	1948.04	0.64	34.2 ± 1.8	1.36 ± 0.07	8.2 ± 0.1
T_{12}	5249.33	0.97	31.8 ± 0.6	1.33 ± 0.04	7.6 ± 0.8

Treatments details in Table 2.

3.9. Carbon Buildup, Stabilization and Sequestration

The highest buildup of carbon was observed in T_5 (43.6%), and the lowest (31.8%) in T_{12} (Table 8). The SOC sequestration in other treatments was between 7.6 and 9.8 Mg ha^{-1}. Higher SOC sequestration was observed under PLL in T_5, T_3, and T_6 than rest of other treatments. Further, the rice-wheat-sugarcane system had a net depletion of 7.6 Mg C ha^{-1} in SOC. PLL reduced soil bulk density due to a higher build-up of root biomass and hence SOC stocks [55]. Cropping systems which included a legume crop (e.g., black gram, pea) increased SOC [56]. Land productivity was also enhanced by the pulse crop intercropping or in crop diversification due to higher total C inputs from rhizo-deposition, root biomass and stubble return (Table 7).

3.10. Limitations of PLL

Compared to traditional land levelling practices, PLL improves water productivity and net cultivable area within a field by 3–5%, reduces weeds growth, and improves crop establishment and soil conditions [34]. At the same time, PLL is not without limitations. Implementing PLL is significantly more costly than TLL, and thus the practice is not available to all farmers. PLL also requires the use of a high-powered tractor with a well-trained operator in order to level a field well. While good tractor operators do exist, there is a learning-period in which new operators will be less efficient and effective; during this time farmers will be subsidizing (through fuel and labour costs) the training of new tractor operators. Finally, PLL is most effective on larger fields while the current trend is for smaller disjointed field sizes resulting from land fragmentation as inheritances are split between all eligible heirs [57,58].

3.11. Comparison of PLL and TLL under Field Conditions

Table 9 summarizes key differences between PLL and TLL across a number of performance metrics.

Table 9. Comparison between precision land levelling (PLL) and traditional land levelling (TLL).

SL No.	Precision Land Levelling	Traditional Land Levelling
1.	In PLL the soil surface is smoothed using laser-equipped drag buckets to achieve a soil surface which is level. Soil is moved an average of 2 cm to achieve an even surface across the entire field	Animal- or tractor-drawn planks are used to smooth the surface
2.	A constant slope of 0 to 0.2% is achieved within each field using large horsepower tractors and soil movers that are equipped with global positioning systems (GPS) and/or laser-guided instruments to move the soil either by cutting or filling to create the desired slope/level across the field.	As required simple implements such as a blade and a small bucket are used to shift the soil from higher to lower positions; evenness of slope is estimated by eye.
3.	Crop establishment is improved under PLL and is even across the field.	Germination and crop establishment are uneven across the field, with higher elevations adversely affected by low soil moisture.
4.	Uniformity of crop maturity.	Irregular pattern of crop maturity.
5.	The cultivable land area within each field is increased by 3 to 5%.	Less cultivable land area within each field.
6.	The efficiency with which applied water is used increases by up to 50%.	Water-application efficiency is low.
7.	Cropping intensity increased by up to 40%.	Cropping intensity is lower than under PLL.
8.	Increased average crop yields: e.g., wheat +15%, sugarcane +42%, rice +61% and cotton +66%.	Average crop yields lower than under PLL.
9.	Reduced emergence of salt-affected patches in soils.	No amelioration of the emergence of salt-affected patches in soil.
10.	Reductions in irrigation water of approximately 35–45%.	A considerable proportion (10–25%) of irrigation water is lost during application.
11.	Water-use efficiency is increased, leading to improved water productivity.	Water-use efficiency is reduced through water logging in low lying areas and intermittent drought in higher areas, leading to reduced water-use efficiency and water productivity.
12.	Nutrient use efficiency is significantly higher.	Nutrient leaching in low lying areas reduces nutrient use efficiency and soil health.
13.	Reduced weed presence and improved weed-control efficiency	Higher incidence of weed infestation than under PLL.
14.	Time for crop management operations reduced by 10–15%.	More time required for crop management operations than under PLL.
15.	Less labor required to manage the crop	More labor required for crop management than under PLL
16.	Less fuel/electricity required for irrigation	More fuel/electricity required for irrigation than under PLL.

Sources: [34,57,58].

4. Conclusions

Cropping systems that used PLL had higher total SOC stocks compared to their counterparts with TLL which might be due to inherent low C status of the experimental site. Under R-P-S-R-W_{PLL}, M-S-R-W_{PLL}, R-M-S-R-W_{PLL}, and R-B-S-R-W_{PLL} plots, SOC concentrations and storage were maximum in the upper 0.3 m soil depth. The active C and N pools in the conventional rice-wheat-sugarcane cropping system decreased as system productivity grew with the addition of P to N, and then increased even more with the addition of N, P, and K. In a cropping system, the administration of N fertilizer at the recommended dose to each crop is suggested, as is the careful adjustment of P fertilizer doses, taking into account the type of fertilizer, soil features and yield levels, the extent of P removal, and the growing environment. The active C and N pools in the conventional rice-wheat-sugarcane cropping system decreased as system productivity grew with the addition of P to N, and increased even more with the addition of N, P, and K. In a cropping system, the administration of N fertilizer at the required dose to each crop is suggested, as is the careful adjustment of P fertilizer dose, taking into account the type of fertilizer, soil features and yield levels, the extent of P removal, and the growing environment. Relative to conventional TLL practices, PLL improves carbon sequestration, cropping system energy requirements, water productivity, and system productivity and profitability. Further, we have shown that for sugarcane-based cropping systems, combining PLL with a diversified cropping system rotation will reduce greenhouse gas emissions and conserve irrigation water. Though some factors such as higher cost of laser leveler, required higher power tractor, proper surveying of land to be levelled, trained drivers hinder the adoption of PLL by farmers but all could be resolved with proper and timely interventions by the government providers viz., extension specialist, state level agricultural officers, and subsidy options for the poor to marginal farmers.

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