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Bio-energy, water-use efficiency and economics of maize-wheat-mungbean system under precision-conservation agriculture in semi-arid agro-ecosystem

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ABSTRACT

The maize-wheat-mungbean (MWMb) cropping system is being advocated as an alternative to the traditional rice-based cropping systems of north-western Indo-Gangetic Plains (IGP) to address the issues of energy and nutritional scarcity, residue burning, decline in biomass productivity and water tables. In semi-arid regions, the climate-change-induced variability in rainfall and temperature may have an impact on phenological responses of cereals and pulses which in turn would affect biomass production, economic yield and energy and water-use efficiency (WUE) of the crops. Henceforth, quantification of bioequivalent yields, energy requirement, economics and WUE of MWMb system is essentially required owing to have better understanding of this cropping system. Following a 4-year study was conducted under different tillage and nutrient management. ZT and PB plots had significantly higher pooled average (17.2–20.3%) biomass productivity, (34.4–39.8%) net returns and (49.8–66.2%) biomass water-use efficiency with lesser (8.5–16.1%) water-use than the CT plots. Significantly higher pooled bioenergetic yields (21.7–35.2%), net returns (31.4–37.8%) and biomass water-use efficiency (30.1–35.2%) was observed in SSNM/Ad-hoc plots compared with FFP plots. The total pooled energy input in ZT/PB and SSNM/Ad-hoc plots was significant ($P < 0.05$) higher than CT and FFP plots, respectively, with greater net energy output, energy productivity and energy efficiency. The interactions between tillage and nutrient management practices on pooled input energy and energy productivity of MWMb system was significant ($P < 0.05$). Thus, adoption of conservation tillage (ZT/PB) practices with improved nutrient management (SSNM/Ad-hoc) could be a viable option for achieving higher biomass productivity, water and energy-use efficiency and profitability in MWMb system.

1. Introduction

In any cropping system biomass production is a key indicator for its sustainability and soil health [1]. Under limited water environments rapidly falling water tables [2], deteriorating soil health [3], leading to lower system biomass productivity and energy efficiencies [4], the challenge is far most to sustain the biomass productivity levels through optimized tillage and nutrient management practices. The rice [*Oryza sativa* L.] - wheat [*Triticum aestivum* L.] (RW) system of north-west India is characterized by high fertilizer use [5], high levels of irrigation [6] and intensive

Abbreviations: Ad-hoc, recommended dose of fertilizer; CA, conservation agriculture; CT, conventional tillage; FFP, farmers' fertilizer practice; GEY, glucose equivalent yield; ICAR, Indian Council of Agricultural Research; MWMb, maize (*Zea mays* L.) - *wheat (Triticum aestivum)*- *mungbean* (*Vigna radiata* L.) Wilczek); NE, Nutrient Expert®; PB, permanent beds; PEY, protein equivalent yield; PEYA, protein equivalent yield for adults; SSNM, site specific nutrient management; ZT, zero tillage.

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tillage and energy use [7]. However, the declining biomass factor productivity and reduced resource and energy-use efficiency [8] in RW system has questioned the sustainability of the RW system as a viable option for future food and energy security. Consequently, the possibilities of an alternative crop rotation, which may help improve biomass productivity, water and energy use efficiency and farm profitability [9] under future extreme climatic conditions [10] in this region is being explored.

Maize (*Zea mays* L.), an important crop for food and nutritional security in India, is grown in diverse ecologies and seasons on an area of 8.67 million hectare [11]. Globally, it provides approximately 30% of the food calories to more than 4.5 billion peoples in 94 developing countries, and the demand of maize is expected to double worldwide by 2050 [12]. To meet the rising demand, a quantum jump in maize biomass production is required. In the previous decade (2003–2004 to 2012–2013), the maize area in India expanded by 1.8% and production increased by 4.9% with a productivity growth at 2.6% for each year [13]. Earlier evaluations of maize as an alternate crop to rice with in the RW system failed due to lower biomass yield and market price of maize. However, recent introduction of single cross high biomass yielding, water and energy-use efficient hybrids of maize are provided genotypic options for crop diversification in the RW systems. The Indo-Gangetic Plain (IGP) of India, covering about 44 Mha, is dominated by cereals based cropping sequences. The maize–wheat (MW) system is the third most important (1.86 Mha) cropping system after rice–wheat and cotton–wheat systems [14] in the IGP. The integration of a short-duration mungbean [*Vigna radiata* (L.) Wilczek] crop in the MW system provides an option to improve bio-energy and biomass production, soil health, increase farmer's profits with several other co-benefits [15–18].

Recent published information from different studies conducted in south Asia and elsewhere have shown that the adoption of zero tillage (ZT) and PB, where drilling or planting is done directly through the residue of the previous crop, and balanced fertilization leads to alterations in soil physical properties [19] and it could maintain and improve plant water availability [20]. These reports also indicate that adoption of conservation agriculture based practices requires the least energy in farm operation and enhances biomass productivity with lower production cost and natural resources use compared to other systems [21]. CA based PB/ZT permits uniform permanent maintenance of soil cover for higher moisture/water capture and conservation [22–24]. The reduction in soil disturbance (tillage) and optimum crop nutrition can stimulate the crop growth and development due to improved plant metabolic activities, which may result in higher biomass water-use efficiency [25]. Inappropriate use of inorganic fertilizer [26] affects the biomass yield and water and energy-use efficiency. The enhanced biomass yield and water-use efficiency under balanced fertilizer application have been observed in maize and wheat [27,28]. Energy use, soil conditions and nutrient dynamics change under reduced tillage and hence the nutrient management practices need to be different as compared to conventional tillage systems. More energy has been consumed in fertilizer treatments for MWMb sequence compared to control and increasing the levels of nutrients decreased the energy use efficiency and productivity [29].

Energy plays a vital role for development of a nation as it is required in industries, infrastructure development, agriculture including processing and packaging, transportation, power generation and irrigation projects, education and health services, domestic and other services use. Because of that the developed nations realized energy crisis due to adoption of conventional mechanized agricultural practices earlier than the developing countries [30]. For example in Romania during energy shortage scenario, the tee vegetable oils also have potential for electricity production and heating systems, instead of the current situation of using as biodiesel for improving renewable energetic resources [31–33]. A scientific evaluation is needed to use a holistic approach of principles and procedures known to reduce input energy in land preparation, use of fertilizers and agro-chemicals and irrigation application to enhance energy use efficiency of these operations with precision conservation agriculture. In earlier published literature from various studies the crop residue biomass which either incorporated in soil under conventional tillage or retained on the soil surface by conservation agriculture based practices (ZT/PB), was deliberately not taken into consideration for energy analysis. Despite the fact that during production quantum proportion of energy is retained in the residue contributed from various energy resources as well as residue recycling improves the soil and environment quality. In developing nations like India crop biomass/residues are being used for feeding cattle, thatching house and as domestic fuel. We hypothesized that crop residues of high productive cereal/maize based cropping sequences should be considered as input energy where, preceding crop residue is left intentionally and utilised as input to succeeding crop. This is our contribution to energy journal in existing literature on the energy relation analysis under changing scenario farming practices and climate which also includes crop residues as input energy.

Moreover, no precise information is available on biomass productivity, bio-energy yield, WUE, energy consumption and profitability of intensified maize-wheat-mungbean cropping system in this region as affected by CA based crop establishment and improved nutrient management. Therefore, the present study was set out with following objectives (i) to evaluate the biomass and bio-energy production, and its profitability and water-use efficiency under precision conservation practices, (ii) to find out the most energy use efficient CA based tillage practices (ZT and PB) and Nutrient Expert®-based, site specific nutrient management (SSNM), in intensified maize (rainy)-wheat (winter)-mungbean (summer) crop rotation.

2. Materials and methods

2.1. Experimental site and soil

An experiment under maize-wheat-mungbean (MWMb) system was conducted during four consecutive years (2012–2016) at a fixed site at the research farm of ICAR-Indian Institute of Maize Research, New Delhi, India (28°38′N, 77°11′E and 228.6 m above mean sea level). The soil (0–30 cm) of the experimental site was sampled on 15 June 2012 after the uniformity trial. The soil was sandy loam (TypicHaplustept) in texture with 64.1% sand, 16.9% silt and 19.0% clay, pH 7.9, bulk density 1.63 Mg m^{-3}, hydraulic conductivity (saturated) 0.835 cm h^{-1}, organic carbon 4.89 g kg^{-1} soil, EC 0.32 dS m^{-1}, Alkaline $KMnO_4$-N (152.0 kg ha^{-1}) [34], 0.5 M $NaHCO_3$ extractable P (13.8 kg ha^{-1}) [35], and NH_4OAc-K (152.3 kg ha^{-1}) [36]. The moisture content at saturation was 0.38 m^3 m^{-3}, which varied from 22 to 27% at 0.033 MPa (Field capacity) and 8–12% at 1.5 MPa (Permanent Wilting Point) in different soil layers of 0–30 cm depth.

2.2. Experimental details and crop sowing and agro-techniques

The experiment was laid out in a split-plot design with crop establishment/tillage practices [zero tillage with residue biomass retention (ZT); permanent bed with residue biomass retention (PB); and conventional tillage with residue biomass incorporation (CT)] as main plot and nutrient management [Control (unfertilized); Farmers' Fertilizer Practice (FFP); Recommended dose of fertilizers (Ad-hoc); and Nutrient Expert® decision support tool-based fertilizer application [37] (SSNM)] as sub plot treatments. The 12 treatment combinations with a subplot size of 30.15 m^2 (7.5 m length X 4.02 m width) were replicated thrice for all the four years of study. The details of treatment are given in Table 1. Before initiation of an experiment in 2012, the field was deep (30 cm) tilled using a chisel plough to break the hard pan below the plough layer and was laser levelled. A uniformity trial on summer mungbean was undertaken in 2012 prior to the initiation of the experiment to ensure uniform soil fertility across the entire experimental field. The CT planting involved one ploughing each with a disc harrow, followed by spring-tyne cultivator and rotavator. In ZT, different crops were direct drilled using ZT planter with inverted 'T' tynes. In the first year (July 2012), fresh raised beds were developed using bed/ridge maker, which were maintained as permanent beds (PB) for subsequent years. A 45-HP farmtrac-45 tractor was used for all the field operations. All the operational parameters like operating speed, working depth, working width, effective field capacity, and fuel consumption were measured for every operation performed in the study (Supplementary Table 1). The width of the beds (mid-furrow to mid-furrow) was 67.5 cm, with 37 cm wide flat tops, and 15 cm furrow depth. In every year of experimentation reshaping of permanent beds was done in one-go simultaneously, while planting crop using A.S.S. Foundry Agricultural Engineering Works, Jandiala guru, Punjab, India make zero-till drill-cum-bed planter with adjustable/removable wings and a frame of 180 cm length for making adjustment of furrow opener with diamond type fastening clamps.

Maize was sown during rainy (July–October), wheat in winter (November–April) and mungbean in summer (May–June) season. Maize (DHM-117) was dibbled at spacing of 67.5 cm × 20 cm in ZT and CT plots, while, one row of maize was established on top of the raised bed in PB by keeping plant spacing of 20 cm at 20 kg seed ha^{-1}. Wheat (cv. HD 2967) was sown at 100 kg seed ha^{-1} with a row spacing of 22.5 cm in ZT and CT, while two rows of wheat were planted on the top of the PB keeping a row spacing of 18.5 cm. Mungbean (*cv.* Pusa Vishal) was sown at 25 kg seed ha^{-1} with a row spacing of 30 cm in ZT and CT, while two rows of mungbean were planted on the top of the PB keeping a row spacing of 18.5 cm.

Fertilizers in the FFP treatment were applied based on a survey of 50 farmers' of the area and the details of nutrient management treatments are given in Table 1. Calculated 1/3rd dose of N and full dose of P_2O_5 and K_2O were applied during final land preparation in maize and wheat and full dose of N and P_2O_5 to mungbean. Remaining 2/3rd dose of N were applied in two equal splits at eight leaves (V_8) and tasseling (VT) stages in maize, and at first and third irrigation in wheat. For managing weeds, herbicide glyphosate was sprayed @ 1.0 kg ha^{-1} in the ZT and PB plots about two days before sowing of all the crops. However, in case of CT plots Atrazine @ 1.0 kg ha^{-1} as pre-emergence (PE) in maize, Pendimethalin @ 1.0 kg ha^{-1} as PE in wheat and mungbean, while Cladinofop @ 60 g ha^{-1} was applied as post emergence at 28–32 days after seeding in wheat. In addition to chemical weed management, one hand weeding was also done in all the CT plots only at 30–40 days after sowing.

2.3. Measurements and calculations

At maturity, the crops were harvested manually at a height of about 20 cm above ground for wheat, and 40 cm for maize during all the four years of experimentation. In case of mungbean after manual picking of pods, 2, 4-D (Easter) was sprayed @ 0.5 kg ha^{-1} to knock down the plants. Mature pods were manually picked twice followed by threshing. The biomass yield of maize, wheat and mungbean were estimated from a harvested area of 20.1 m^2 (7.5 m length X 2.68 m width) using plot seller/thresher. The straw/stover yields of all the crops were adjusted on the oven dry weight basis by oven drying of 1.0 kg representative sub-sample from each plot at 65 °C for 48 h. Biomass grain moisture was determined using a grain moisture meter. The grain biomass yields of maize, wheat and mungbean were adjusted at 14%, 12% and 12% moisture content, respectively [11] and biomass yields were expressed in t ha^{-1}. To compute the system biomass productivity of the MWMb cropping system, the yield of non-maize crops was converted into maize equivalent yield (t ha^{-1}) using equation (1) with wheat as an example suggested by Parihar et al. [11].

$$\text{Maize equivalent yield}\left(\text{t ha}^{-1}\right) = \frac{\text{Wheat yield}\left(\text{t ha}^{-1}\right) \times \text{minimum support price of wheat}\left(\text{US\$ t}^{-1}\right)}{\text{Minimum support price of maize}\left(\text{US\$ t}^{-1}\right)} \quad (1)$$

The biomass yield of different crops was adjusted for differences in energy costs of the synthesis of the cereals (maize and wheat) and legume (mungbean) as bioenergetic/glucose equivalent yield (GEY). The biological maize equivalent yield was calculated based on bio-energetics (amount of substrate required for growth of seeds). The amount of glucose required for synthesis and maintenance of the studied crops varied from 1.18 to 1.93 kg to produce one kg of

Table 1
Description of treatments imposed in maize-wheat-mungbean cropping system during experimentation.

Crop	Main-plot: Tillage and crop establishment		
	Zero tillage (ZT)	Permanent beds (PB) (37 cm bed and 30 cm furrow)	Conventional tillage (CT)
Maize	100% mungbean residues retained	100% of mungbean residues retained	100% mungbean residues incorporated
Wheat	30% maize residues retained	30% maize residues retained	30% maize residues incorporated
Mungbean	30% wheat residues retained	30% wheat residues retained	30% wheat residues incorporated

Crop	Sub-plot: Nutrient management practices (N:P:K kg ha^{-1})			
	Unfertilized	Farmers Fertilizer Practices (FFP)	Recommended doses (Ad-hoc)	Site specific nutrient management (SSNM)
Maize	0:0:0	110.0:13.2:0.0	150.0:26.2:33.3	170.0:16.3:36.5
Wheat	0:0:0	172.0:25.3:0.0	120.0:26.2:33.3	155.0:27.7:54.0
Mungbean	18.0:20.1:0.0	18.0: 20.1:0.0	18.0: 20.1:0.0	18.0: 20.1:0.0

substrate. The GEY was calculated based on energy requirement to produce one kg of cereal and pulse as described by Penning de Varies et al. [38]. The glucose equivalent yield (t ha^{-1}) of the MWMb cropping system was calculated by adding equivalent yield of the component crops grown in the cropping sequence. Protein equivalent yield of individual crop was calculated based on the protein content in biomass grain and grain yield. Nitrogen content in the grain was determined by modified Kjeldahl's method [39]. Grain nitrogen content varied from 1.50 to 1.87% in maize, 1.91–2.32% in wheat, and 3.87–3.90% in mungbean. Protein content was calculated by multiplying the estimated nitrogen content described by Lindner [40] with standard factor given by AOAC [41] for each crop i.e. for maize-6.25; wheat-5.80 and mungbean-5.70. The system protein yield includes the protein yield of all the crops (maize, wheat and mungbean). An annual adult protein demand equivalent is calculated based on the 60 g person^{-1}day^{-1} as per the recommendations of Indian council of medical research [42].

In the first rainy season of 2012, mungbean biomass residues (1.5 t ha^{-1}, dry weight basis) were applied. In the subsequent all the years about 30% of the residues biomass of maize and wheat were retained/incorporated in the plots and the remaining amounts of residues were removed for use as cattle fodder and fuel. The amount of residue biomass inputs retained/incorporated from maize and wheat in the plots were estimated on the basis of stubble by straw/stover ratios of these crops obtained in measured biomass (in the CT plots). While during all the years the total amount of mungbean biomass residue was added after manual picking of pods. Thus, the yearly estimated amounts of maize + wheat + mungbean biomass residues retained/incorporated in various treatments are given in Table 2.

The energy inputs referred to renewable and non-renewable energy. Non-renewable energy comprised manual, fuel, machinery, chemical fertilizers (N, P and K) and agro-chemicals etc., whereas, renewable energy consisted of seed, manual, crop residue, etc. The primary data on various inputs and agronomic practices were used for estimation of energy consumption. The energy output from the biomass grain/seed and straw/stover yield was also computed. The loss of output was very negligible due to natural calamities and pests. Thus, the loss or waste was not included in the calculation. For estimation of energy inputs and outputs (expressed in MJ ha^{-1}) for each item of inputs and management practices, energy equivalents were given in Table 3 as suggested by Mittal and Dhawan [43], Parihar et al. [44] and Singh et al. [45]. Energy use indices were calculated using the following formula as suggested

Table 2
Estimated total amount of residue biomass inputs (t ha^{-1}) of preceding crop for succeeding crop grown in maize-wheat-mungbean sequence during different years of experimentation.

Treatments[a]	2012–13			2013–14			2014–15			2015–16			MWMb system				Total
	Maize	Wheat	Mung bean	Maize	Wheat	Mung bean	Maize	Wheat	Mung bean	Maize	Wheat	Mung bean	2012–13	2013–14	2014–15	2015–16	
Tillage practices																	
CT	1.5	3.22	1.61	2.50	2.51	1.92	2.58	2.35	1.81	2.92	2.49	1.65	6.32	6.93	6.74	7.06	27.05
PB	1.5	3.14	1.78	2.76	3.11	2.19	3.39	2.53	2.08	3.48	2.87	2.17	6.43	8.06	8.00	8.52	31.01
ZT	1.5	3.22	1.72	2.87	2.74	2.08	3.46	2.57	2.03	3.88	2.73	1.99	6.44	7.69	8.06	8.61	30.80
S.E.M. (D.F. = 4)		0.171	0.030	0.056	0.062	0.047	0.166	0.044	0.051	0.260	0.193	0.261	0.165	0.049	0.202	0.869	0.077
Nutrient management																	
Un-fertilized	1.5	2.35	1.62	2.29	2.21	1.37	2.40	2.02	1.50	3.21	2.28	1.46	5.47	5.87	5.93	6.94	24.21
FFP	1.5	3.55	1.72	2.81	3.06	2.31	3.35	2.65	2.25	3.45	2.45	1.89	6.76	8.18	8.25	7.80	30.99
Ad-hoc	1.5	3.05	1.66	2.93	2.61	2.12	3.26	2.54	1.80	3.46	3.01	2.15	6.22	7.66	7.60	8.62	30.10
SSNM	1.5	3.83	1.82	2.82	3.26	2.45	3.55	2.71	2.35	3.60	3.04	2.24	7.14	8.54	8.62	8.89	33.19
S.E.M. D.F. = 18)		0.347	0.047	0.092	0.094	0.052	0.136	0.072	0.044	0.281	0.389	0.351	0.220	0.170	0.129	0.879	0.072

[a] See Table 1 for treatment details.

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

Particulars	Unit	Energy equivalent (MJ unit^{-1})	Reference
A. Inputs			
a. Human labor (R)			
1. Adult man	Man-hour	1.96	[43]
2. Women	Women-hour	1.57	[43]
b. Diesel	Litre	56.31	[43,44]
c. Farm machinery	Kg	62.70	[43,44]
d. Chemical fertilizers			
1. N	Kg	60.60	[43–45]
2. P_2O_5	Kg	11.10	[43–45]
3. K_2O	Kg	6.7	[43–45]
e. Chemicals			
1. Herbicides	Kg	254.45	[43–45]
2. Insecticides	Kg	184.63	[43–45]
f. Seed	Kg		
1. Maize	Kg	14.70	[43,45]
2. Wheat	Kg	14.70	[43,45]
3 Mungbean	Kg	14.70	[43,45]
B. Outputs			
1. Maize grain	Kg	14.70	[43,45]
2. Maize stover	Kg	12.50	[43,45]
3. Wheat grain	Kg	14.70	[43,45]
4. Wheat straw	Kg	12.50	[43,45]
5. Mungbean grain	Kg	14.70	[43,45]
6. Mungbean stover	Kg	12.50	[43,45]

by Mittal and Dhawan [43] and Singh et al. [45].

Net energy (MJ ha^{-1}) = Energy output (MJ ha^{-1}) − Energy input (MJ ha^{-1}) (2)

Energy efficiency = Energy output (MJ ha^{-1})/Energy input (MJ ha^{-1}) (3)

Energy productivity (kg MJ^{-1}) = Biomass yield (kg ha^{-1})/Energy input (MJ ha^{-1}) (4)

Soil moisture content in the profile (0–120 cm) was determined gravimetrically at initial and final stages of crops growth in rainy, winter and summer seasons to study profile contribution of soil moisture in plant growth and development. Evapo-transpiration (ET) was computed using the field water balance equation [46,47] as given below:

$$ET = (P + I + C) - (R + D + \Delta S) \quad (5)$$

Where; ET is the evapo-transpiration (mm), P is the effective precipitation (mm), I is the irrigation (mm), C is the capillary rise (mm), R is the runoff (mm), D is the deep percolation (mm) and ΔS is change in soil profile moisture (mm).

As the groundwater level was very low (8–10 m depth), C was assumed to be negligible. There was no runoff (R) from the experimental plots as they were bunded upto a sufficient height (40 cm height) and also no case of bund overflow was observed during the study period. As soil moisture studies were made up to a soil depth of 120 cm and the profile was sandy loam with loamy and clay loam layers having a high bulk density of 1.71–1.72 Mg m^{-3} below 60 cm, deep percolation below the 120 cm profile (D) was assumed to be negligible [46,47].

Thus Eq. (5) simplifies to,

$$ET = (P + I) - \Delta S \quad (6)$$

Precipitation data were collected from the meteorological observatory of ICAR-IARI, New Delhi. The effective rainfall was calculated by using USDA SCS method (Cropwat 8.0). Irrigation was applied through surface irrigation at critical growth stages of different crops. A measured amount of water was supplied. The applied irrigation water was measured using a 'parshall flume (3″)' installed in the open channel under free flow conditions. The flow rate was calculated by using Equation (5).

$$Q = K \times 1000 \times (Ha/100)\hat{}1.55 \quad (7)$$

Where,

Q = Flow rate in liter per second
K = a fraction, which is a function of the throat width (0.1771 in this study)
Ha = water depth in converging section (cm)

The discharge was corrected by measuring height in the middle of the throat (Hb) of parshall flume due to submergence. The percentage variation between Ha and Hb was used to measure the submergence and correction factor was subtracted from Q to get actual discharge [48].

The water applied in each plot was calculated by equation.

$$\text{Water applied } (m^3\ ha^{-1}) = \{(Q - Qc) \times T\}^{*}10/A \quad (8)$$

Where, Qc is correction factor for reduction in modular discharge due to submergence; T is time taken for irrigation of a plot (in seconds) and A is size of plot (m^2). Changes in soil moisture content (ΔS) were calculated by soil moisture estimation by gravimetric method.

Water Use Efficiency (WUE) was computed as

$$WUE = \frac{Net\ returns\ (US\$\ ha^{-1})}{ET\ (mm)}$$

The economic analysis was done by considering the variable production costs only. The variable costs included human labour, use of machinery (tractor, plough, planter, sprayer, fertilizer machine, bed forming machine, etc), the input cost (seed, fertilizer, and pesticide), irrigation, harvesting and threshing. The production cost, however did not include the value of the land. The market price for different key inputs was taken for calculation of gross returns (GR). Net returns (NR) were calculated by deducting the total cost (TC) of cultivation from gross returns (GR) (NR = GR-TC). The cropping system net returns were computed by adding the net returns of all the crops grown in a sequence within each calendar year. System BC ratio was calculated by dividing net returns with total cost (TC) of cultivation (BC ratio = Net returns/cost of cultivation). For better comparisons, all the economics data (cost of cultivation and net returns) were converted from Indian rupees (INR) to US$ using an exchange rate (INRUS$$^{-1}$) of 55 (2012–2013 and 2013–2014) and 64 (2014–2015) and 67 (2015–2016).

2.4. Statistical analyses

The data on biomass and bioenergetic yields, WUE, energy use and economics for all four years (2012–2013, 2013–2014, 2014–2015 and 2015–2016) were analysed to decipher the main and interaction effects of tillage and nutrient management practices. Analysis of variance was performed using the SAS statistical package version 9.3 with general linear model in split-plot design (SAS Institute Cary, NC, USA). The least significant difference test at 5% probability was used to decipher the main and interaction effects of treatments.

3. Results

3.1. Weather

The average annual rainfall of last 30 years was 709 mm, of which 70–80% is received during July–September with the mean annual evaporation of 850 mm. Mean metrological parameters during cropping seasons were recorded at ICAR-IARI metrological observatory adjacent to the experimental field. The rainfall during *rainy* season (July–October) was highest (1199 mm) in 2013 followed by 711 mm in 2015 and 482 mm in 2012 whereas 2014 season received the lowest amount of rainfall (451 mm) (Fig. 1). The rainfall received in winter season (October to April) was 176.0 mm, 169.1 mm, 311.8 mm and 22.2 mm during 2012–2013, 2013–2014, 2014–2015 and 2015–2016, respectively. During summer season (May–June), the total amount of rainfall varied from 48.2 mm (2016) to 146.8 mm (2013). However, the mean monthly maximum and minimum temperature was almost similar in all the four years of study. The monthly mean pan evaporation varied between 3.8 and 10.1 mm in different cropping seasons. The site has a subtropical and semi-arid climate, typically characterized by hot and dry summer and cold winter.

3.2. Estimated biomass residue retained/incorporated

The organic biomass/residues inputs to soil from maize, wheat

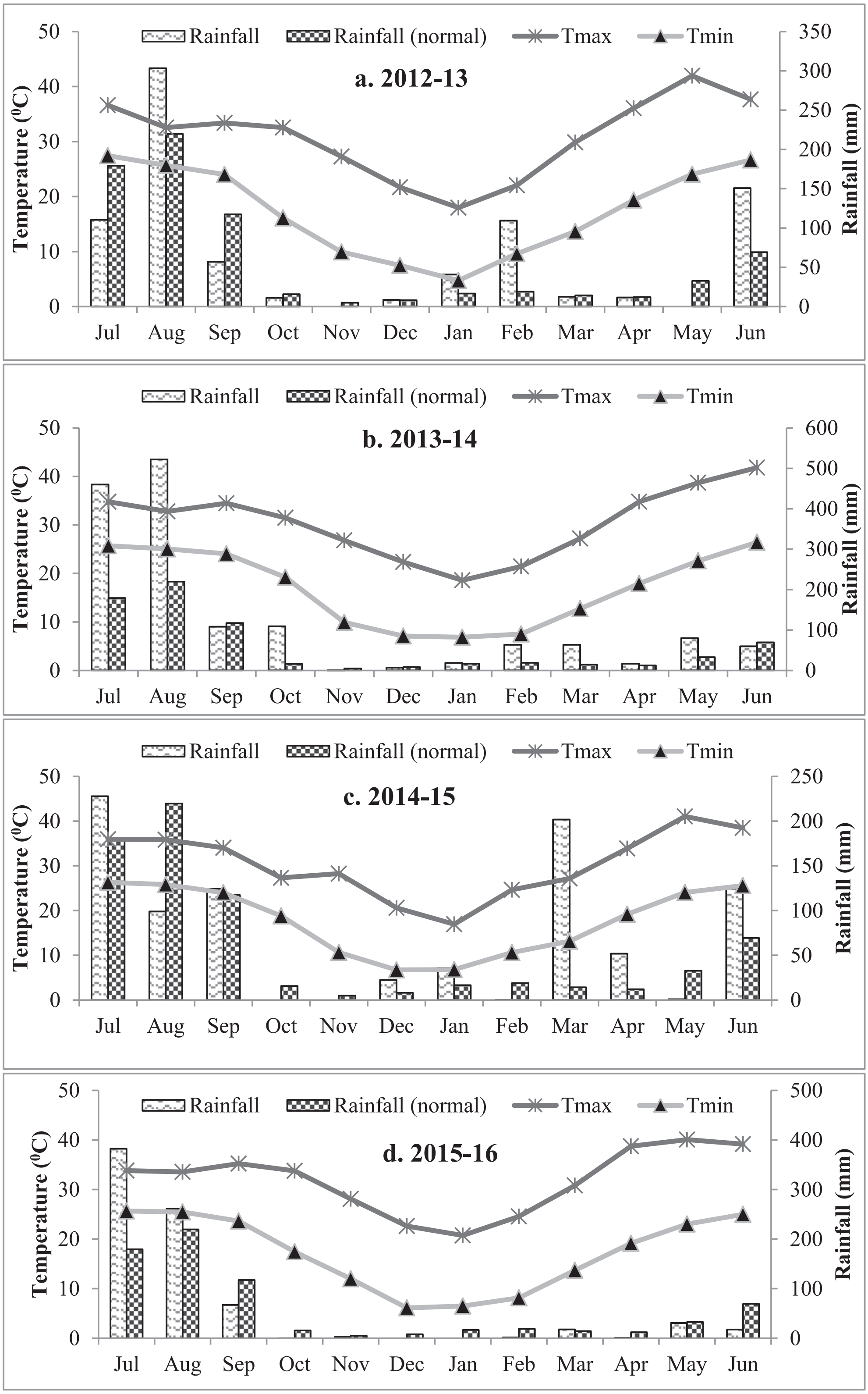

Fig. 1. Long-term (normal) rainfall, monthly rainfall, and temperature during the experimentation period.

and mungbean (Table 2) varied with responses of these crops to different tillage and nutrient management treatments for above-ground biomass production. In MWMb system, the roots and rhizo-deposition from all crops contributed significant amounts of biomass input to the soil. During 4-years, the cumulative residue biomass input in MWMb system under PB was 31.0 t ha^{-1} compared with only 27.1 t ha^{-1} for CT plots (Table 2). Plots with SSNM, Ad-hoc and FFP nutrient management had 32, 29 and 30% higher cumulative residue inputs in MWMb system than unfertilized plots, respectively (Table 2).

3.3. Bioenergetic equivalent yields

The PB/ZT plots had 14-19% and 22–27% higher pooled average glucose equivalent and protein equivalent yield than CT plots (Table 4), respectively. The SSNM/Ad-hoc plots registered increase in pooled average GEY (22–29%) and PEY (27–35%) compared to FFP plots, respectively. Tillage and nutrient management interaction effects were non-significant ($P < 0.05$) on pooled average GEY and PEY were non-significant (data not presented). Mungbean integration in traditional maize-wheat (MW) system increased the protein yield (1.95 t ha^{-1}) significantly compared to MW system alone (0.99 t ha^{-1}). Thus, intensification of MW system with mungbean could meet out the adult protein demand of 54 person yr^{-1} compared to 45 person yr^{-1} (pooled average basis) in MW system alone, irrespective of tillage and nutrient management practices (Fig. 2 and Table 4). On pooled average basis, CA based MW system intensification meet out the additional adult protein demand by 22–27% than CT-MW system. On protein demand equivalent basis, CA based tillage practices with SSNM/Ad-hoc nutrient management in MWMb system can accommodate 10–18 more persons to fulfilled their protein demand in a year than conventional (CT) MW system under farmer fertilizer practices.

3.4. Biomass yield, water-use efficiency and economic

Tillage and nutrient management practices had significant ($P < 0.05$) effect on MWMb system pooled average grain biomass productivity, water use efficiency and economics in 4-years of study (Table 5). The year-wise cost of cultivation for different crops in MWMb system was almost similar in PB and ZT but was lower than CT plots. PB and ZT plots registered maximum MWMb system pooled average grain biomass productivity (12.1–12.4 t ha^{-1}), WUE (1.019–1.131 US$ net returns ha-mm^{-1}), net returns (US$ 1819–1891 ha^{-1}) and benefit cost ratio (1.68–1.73), respectively. Similar to tillage effects, the nutrient management also significantly ($P < 0.05$) affected the MWMb system pooled average grain biomass productivity, WUE and economics (Table 5). Significant ($P < 0.05$) increase in MWMb grain biomass productivity, WUE and economics was recorded in SSNM and Ad-hoc treatments for pooled average system grain biomass productivity (18–24%), WUE (30–35%), net returns (31–38%), and BC ratio (31–32%), compared to FFP treatments, respectively. However, SSNM and Ad-hoc nutrient management treatments remained statistically at par with respect to system biomass productivity, WUE, net returns and BC ratio. Tillage and nutrient management interaction effects were

Table 4
Glucose equivalent yield (GEY), protein equivalent yield (PEY) and protein equivalent yield for adults (PEYA) of maize-wheat-mungbean system under different tillage and nutrient management practices.

Treatments*	GEY (t ha^{-1})					PEY (t ha^{-1})					PEYA (adults ha^{-1} $year^{-1}$)				
	2012–13	2013–14	2014–15	2015–16	Pooled	2012–13	2013–14	2014–15	2015–16	Pooled	2012–13	2013–14	2014–15	2015–16	Pooled
Tillage practices															
CT	5.29	5.62^{c}	5.73^{b}	6.11^{c}	5.7^{c}	0.95	1.02^{c}	1.05^{b}	1.08^{c}	1.03^{c}	43.6	46.4^{c}	48.1^{b}	49.4^{c}	46.9^{c}
PB	5.56	6.93^{a}	6.77^{a}	7.83^{a}	6.8^{a}	1.03	1.35^{a}	1.35^{a}	1.50^{a}	1.31^{a}	47.1	61.5^{a}	61.4^{a}	68.4^{a}	59.6^{a}
ZT	5.60	6.21^{b}	6.77^{a}	7.39^{b}	6.5^{b}	1.04	1.21^{b}	1.35^{a}	1.42^{b}	1.25^{b}	47.6	55.1^{b}	61.5^{a}	64.7^{b}	57.2^{b}
Nutrient management															
Un-fertilized	4.45^{d}	4.11^{d}	4.71^{c}	5.11^{c}	4.6^{d}	0.76^{d}	0.72^{d}	0.86^{c}	0.91^{d}	0.81^{d}	34.7^{d}	32.9^{d}	39.3^{c}	41.5^{d}	37.1^{d}
FFP	5.29^{c}	6.12^{c}	5.86^{b}	6.33^{b}	5.9^{c}	0.95^{c}	1.12^{c}	1.12^{b}	1.20^{c}	1.10^{c}	43.3^{c}	51.2^{c}	51.0^{b}	54.6^{c}	50.0^{c}
Ad-hoc	5.92^{b}	7.13^{b}	7.43^{a}	8.26^{a}	7.2^{b}	1.12^{b}	1.40^{b}	1.47^{a}	1.57^{b}	1.39^{b}	51.3^{b}	64.0^{b}	67.2^{a}	71.4^{b}	63.5^{b}
SSNM	6.26^{a}	7.64^{a}	7.68^{a}	8.73^{a}	7.6^{a}	1.21^{a}	1.52^{a}	1.54^{a}	1.66^{a}	1.48^{a}	55.0^{a}	69.2^{a}	70.5^{a}	75.9^{a}	67.7^{a}

*See Table 1 for treatment details. Same letter within each column indicate no significant difference among the treatments (at $P < 0.05$) according to least significant difference test.

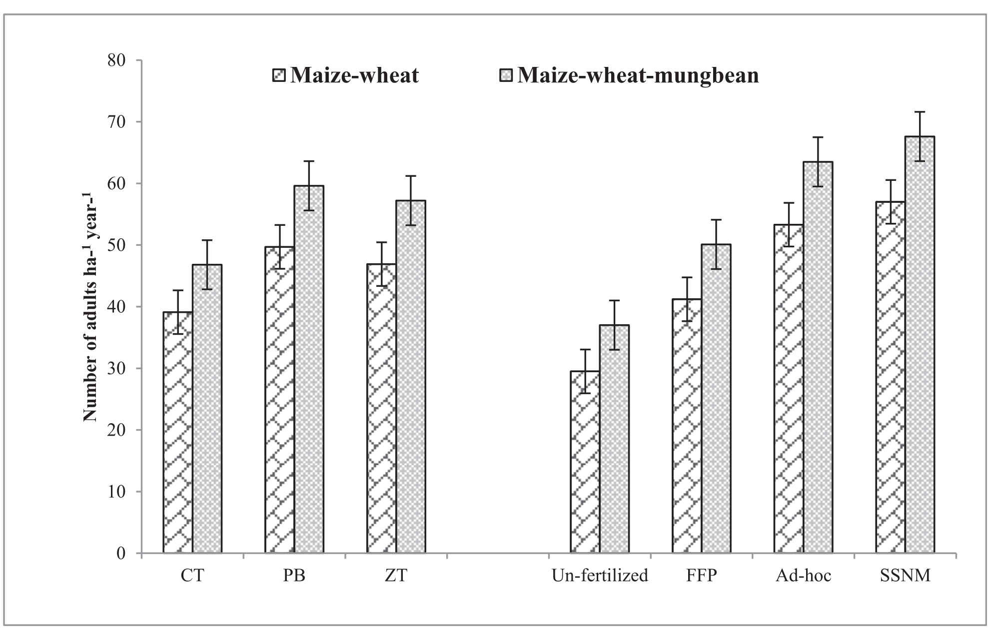

Fig. 2. Protein equivalent yield for adults (based on 60 g d^{-1} $adult^{-1}$) due intensification of maize-wheat system with mungbean under different tillage and nutrient management practices. See Table 1 for treatment details.

Table 5
System grain biomass productivity (maize equivalent yield), water-use efficiency (WUE) and economics of maize-wheat-mungbean cropping system under different tillage and nutrient management practices.

Treatments*	Grain biomass productivity (t ha^{-1})					WUE (US\$ net returns ha-mm^{-1})					Net returns (US\$ ha^{-1})					BC ratio				
	2012–13	2013–14	2014–15	2015–16	Pooled	2012–13	2013–14	2014–15	2015–16	Pooled	2012–13	2013–14	2014–15	2015–16	Pooled	2012–13	2013–14	2014–15	2015–16	Pooled
Tillage practices																				
CT	9.9	10.0^{c}	10.7^{b}	10.6^{c}	10.3^{c}	0.610^{b}	0.798^{c}	0.616^{b}	0.698^{c}	0.680^{c}	1243	1475^{c}	1378^{b}	1318^{c}	1353^{c}	1.06^{b}	1.17^{c}	1.24^{b}	1.22^{c}	1.17^{c}
PB	10.4	12.5^{a}	12.8^{a}	14.0^{a}	12.4^{a}	0.824^{a}	1.348^{a}	0.976^{a}	1.375^{a}	1.131^{a}	1409	2165^{a}	1861^{a}	2127^{a}	1891^{a}	1.23^{a}	1.81^{a}	1.73^{a}	2.16^{a}	1.73^{a}
ZT	10.7	11.4^{b}	12.9^{a}	13.4^{b}	12.1^{b}	0.814^{a}	1.113^{b}	0.948^{a}	1.203^{b}	1.019^{b}	1482	1883^{b}	1911^{a}	1998^{b}	1819^{b}	1.31^{a}	1.56^{b}	1.80^{a}	2.04^{b}	1.68^{b}
Nutrient management																				
Un-fertilized	8.5^{d}	7.6^{d}	9.3^{c}	9.5^{c}	8.7^{d}	0.614^{b}	0.634^{c}	0.618^{c}	0.775^{c}	0.660^{c}	1115^{b}	1050^{c}	1236^{c}	1268^{c}	1167^{d}	1.16^{b}	1.04^{c}	1.36^{b}	1.46^{c}	1.26^{b}
FFP	10.1^{c}	11.1^{c}	11.2^{b}	11.8^{b}	11.0^{c}	0.674^{b}	1.012^{b}	0.740^{b}	0.985^{b}	0.853^{b}	1228^{b}	1709^{b}	1490^{b}	1623^{b}	1513^{c}	1.00^{c}	1.33^{b}	1.37^{b}	1.64^{b}	1.34^{b}
Ad-hoc	11.1^{b}	12.8^{b}	13.8^{a}	14.3^{a}	13.0^{b}	0.845^{a}	1.322^{a}	0.999^{a}	1.270^{a}	1.109^{a}	1563^{a}	2242^{a}	2031^{a}	2112^{a}	1987^{b}	1.36^{a}	1.87^{a}	1.81^{a}	1.99^{a}	1.76^{a}
SSNM	11.7^{a}	13.7^{a}	14.3^{a}	15.0^{a}	13.7^{a}	0.864^{a}	1.377^{a}	1.030^{a}	1.339^{a}	1.153^{a}	1605^{a}	2364^{a}	2110^{a}	2255^{a}	2084^{a}	1.28^{a}	1.81^{a}	1.82^{a}	2.12^{a}	1.76^{a}

*See Table 1 for treatment details. Same letter within each column indicate no significant difference among the treatments (at $P < 0.05$) according to least significant difference test.

non-significant ($P < 0.05$) on MWMb system pooled average grain biomass productivity, WUE and economics in 4-year study (data not presented).

3.5. Energy input and output of the cropping system

3.5.1. Energy input

The total energy for different inputs *viz.*, residue biomass (71–89%) followed by fertilizers (2–18%) consumed the bulk of the input energy in all the treatments (Fig. 3). Diesel consumption for agronomic crop management practices was the third most energy intensive component in all the tillage and nutrient management treatments. Energy consumption for other crop management practices was low or negligible. Energy inputs consumed for maize-wheat-mungbean cropping system in different tillage practices varied between 11.3×10^4 MJ ha^{-1} (CT) and 12.1×10^4 MJ ha^{-1} (PB/ZT) (Table 6). Among nutrient treatments, the lowest input energy were consumed by unfertilized (8.7×10^4 MJ ha^{-1}) followed by FFP (12.1×10^4 MJ ha^{-1}), Ad-hoc (12.9×10^4 MJ ha^{-1}) and SSNM (13.7×10^4 MJ ha^{-1}). Tillage and nutrient management interaction effects were significant ($P < 0.05$) on total energy consumption in MWMb system (Table 6). The maximum energy input in MWMb system (13.8×10^4 MJ ha^{-1}) was in the PB-SSNM treatment, while the CT- Unfertilized treatment registered lowest input energy (8.1×10^4 MJ ha^{-1}). Actually this difference in energy consumption is due to the addition of differential amount of residue biomass and nutrients, because energy input for other management practices varied non-significantly from treatment to treatment. The interesting point is that out of the total energy input the amount of renewable energy (mainly contributed by residue biomass) was greater than the non-renewable for every treatment.

3.5.2. Energy outputs and energy efficiency

Bio-energy net outputs of maize-wheat-mungbean system (grain, by products and total biomass) in different tillage and nutrient management treatments followed the same trend of system biomass productivity (Tables 5 and 6). In MWMb rotation, significantly higher net bio-energy outputs, energy productivity and energy efficiency were produced under CA based PB/ZT plots, which were 16–21%, 7–9% and 7–9% higher over CT plots. Among all the nutrient management treatments applied in maize–wheat-mungbean rotation, Ad-hoc and SSNM treatments resulted significantly higher net bio-energy outputs (by 20 and 25%), energy productivity (by 7 and 6%) and energy efficiency (by 7 and 6%), respectively than FFP. Though the net bio-energy outputs and energy efficiency did not vary due to the interaction effects of tillage and nutrient management treatments (data not presented), whereas energy productivity was significantly influenced by interaction effect of tillage and nutrient management treatments and it was maximum (0.796 kg MJ^{-1}) in PB-Unfertilized followed by ZT-Unfertilized and lowest with CT-FFP treatment (Table 6).

4. Discussion

The results of our 4-year study showed the positive effects of ZT and PB with residue biomass retention on glucose equivalent yields (GEY) and protein equivalent yields (PEY) of MWMb system. In the present study, these CA based practices resulted in higher GEY and PEY of MWMb system than CT. Earlier studies from South Asia also showed higher crop yields under ZT compared to CT in rice-wheat and maize-wheat cropping systems [7,49] and 8% higher yield of wheat in bed planting at Turkey and Mexico [24,50]. Naresh et al. [51] also observed that wheat grain yield increased by 13·5% with raised bed planting compared with flat-bed planting in western IGP under maize–wheat system. In contrast to our findings, Lahmar

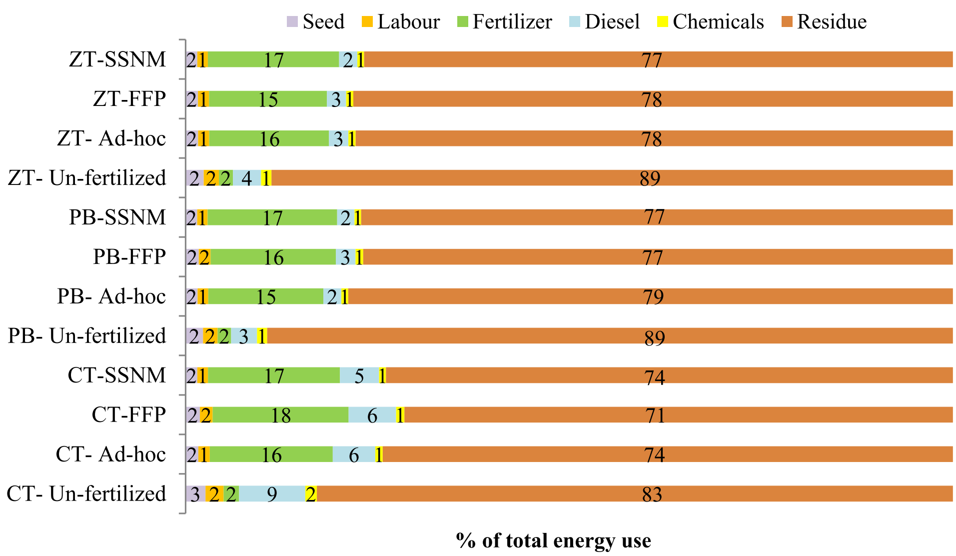

Fig. 3. Energy use pattern (pooled average of 4-years) in maize-wheat-mungbean cropping system under different tillage and nutrient management practices. See Table 1 for treatment details.

[52], concluded from data of several studies on fertile soils of Europe that the crop biomass yields were lower with CA compared with CT practices. The higher biomass yields of maize, wheat, and MWMb system in ZT could be due to the compound effects of additional nutrients [53–55], due to lesser weed population [56,57], improved soil physical health [7,19,58], better water regimes [59], and improved nutrient use efficiency over CT [60]. The MWMb system bioenergetic (GEY and PEY) yields increased over the years in all CA based tillage treatments which shows that the impact of CA treatments with residue biomass retention enhanced with advancing year of adoption. On the line of the present study, additional biomass yield benefits over time from the legume (due to N-accumulation through biological N_2 fixation and leaf litter) were also observed by Sakala et al. [61]. In contrast, Parihar et al. [11], observed that PB and ZT management practices produced significantly higher GEY (mean of 6-years) of maize, wheat and MWMb system than CT.

Similar to tillage, the results of our 4-year study also showed the positive effects of SSNM and Ad-hoc nutrient management practices on bienergetic (GEY and PEY] yields of MWMb system. In the MWMb system, biomass yield increased over time by adoption of improved nutrient management practices compared to FFP and unfertilized treatments. Our results of higher system biomass productivity are consistent with earlier studies from western IGP, which reported 29% higher system biomass yield in SSNM treatment compared to FFP, which might be due to optimum supply of nutrients as per crop demand and indigenous soil nutrient supplying capacity [62].

Result of present study revealed that the amount of water use (ET) in CT plots of MWMb system was 205–308 mm more than the CA (ZT and PB) plots in all the four years (data not presented). An earlier study conducted at the same location observed 100 mm more water consumption in CT plots than the PB plots [6]. It was due to the fact that the furrows acted as pathways for removing the excessive rain water as well as conserving rainwater in dry spells [63] and higher infiltration of supplied water through flood irrigation system in furrows [7,9,50,64]. The significantly higher ($P < 0.05$) WUE of MWMb system under CA practices compared to CT was also due to lesser water use (by 10–15%) in CA plots compared to CT plots. Das et al. [6] and Ozpinar [65] reported 30% higher WUE in the pigeonpea-wheat system in PB plots with 84% decreased water use in a sandy loam soil of Delhi (India). The earlier planting, eased weed management, increased access to nutrients due to retention of residue biomass at the soil surface in ZT/PB system helped in reducing evaporation losses and hence conserving soil moisture [66]. Higher soil moisture in the seed-zone not only provides better crop establishment and crop growth but also increases biomass water use efficiency. The increase in seed-zone moisture was accompanied by increase in crop biomass yield with lesser water consumption under ZT and PB plots compared to CT plots. The higher biomass water-use efficiency of MWMb system under CA based management practices compared to CT in the same ecology has also been reported by Parihar et al. [11]. The higher biomass yield advantage in CA based management practices supports the concept of better soil moisture environment [23,67].

Among the different nutrient management treatments, unfertilized treatment registered the lowest WUE during entire study period. The SSNM and Ad-hoc treatments were statistically at par with respect to WUE. Results of the present study showed significant ($P < 0.05$) improvement in WUE in SSNM and Ad-hoc treatments ascribed to higher biomass yields compared to other treatments. The beneficial effect of balanced nutrition under SSNM and Ad-hoc treatments compared to unfertilized and imbalanced FFP on the WUE was attributed to better crop growth with concomitant higher root biomass production and greater return of leftover surface plant residues biomass [68].

This study analysed the positive effects of CA practices (ZT and PB) on energy consumption, net energy, energy productivity and energy use efficiency of diversified crops of MWMb system and on economics of MWMb system. The adoption of the CA practices resulted in enhancement of MWMb system pooled average net energy outputs (by 16–21%), energy productivity and efficiency (by 7–9%) and net returns (by 34–40%) compared to CT, which shows the higher energy accumulation capacity in CA due to better environment for crop growth in terms of higher nutrient availability, better root growth and modulation of micro climatic conditions with better water retention. Similar to current study, Parihar et al. [69] and Ozpinar and Ozpinar [70] also reported higher energy outputs under CA plots compared with CT plots at

Table 6
Energy input, net energy, energy productivity and energy efficiency for maize-wheat-mungbean cropping system under different tillage and nutrient management practices.

Treatments*	Input energy (10^4 MJ ha^{-1})					Energy productivity (Kg MJ^{-1})					Net energy (10^4 MJ ha^{-1})					Energy efficiency				
	2012–13	2013–14	2014–15	2015–16	Pooled	2012–13	2013–14	2014–15	2015–16	Pooled	2012–13	2013–14	2014–15	2015–16	Pooled	2012–13	2013–14	2014–15	2015–16	Pooled
Tillage practices																				
CT	10.8^{a}	11.5^{c}	11.3^{c}	11.6^{c}	11.3^{c}	0.77	0.64^{c}	0.65^{b}	0.61^{c}	0.68^{b}	22.1	20.7^{c}	20.5^{b}	20.0^{c}	20.8^{c}	9.7	8.0^{c}	8.2^{b}	7.7^{c}	8.4^{b}
PB	10.5^{c}	12.5^{a}	12.5^{b}	13.1^{b}	12.1^{a}	0.82	0.72^{a}	0.67^{ab}	0.69^{a}	0.73^{a}	23.6	26.8^{a}	23.9^{a}	26.8^{a}	25.3^{a}	10.2	9.1^{a}	8.6^{a}	8.6^{a}	9.1^{a}
ZT	10.6^{b}	12.1^{b}	12.5^{a}	13.2^{a}	12.1^{b}	0.83	0.68^{b}	0.69^{a}	0.65^{b}	0.71^{a}	23.9	23.9^{b}	24.4^{a}	24.6^{b}	24.2^{b}	10.4	8.6^{b}	8.7^{a}	8.2^{b}	9.0^{a}
Nutrient management																				
Un-fertilized	8.0^{d}	8.4^{d}	8.6^{d}	9.8^{d}	8.7^{d}	0.85	0.70^{a}	0.76^{a}	0.67^{a}	0.74^{a}	19.5^{c}	17.0^{c}	18.9^{c}	18.7^{c}	18.5^{d}	10.6	8.7^{a}	9.5^{a}	8.4^{a}	9.3^{a}
FFP	10.8^{c}	12.5^{c}	12.5^{c}	12.7^{c}	12.1^{c}	0.79	0.64^{b}	0.61^{d}	0.61^{b}	0.66^{c}	22.2^{b}	22.7^{b}	20.9^{b}	21.3^{b}	21.8^{c}	9.8	8.1^{b}	7.8^{c}	7.7^{b}	8.3^{c}
Ad-hoc	11.5^{b}	13.2^{b}	13.2^{b}	13.7^{b}	12.9^{b}	0.80	0.69^{a}	0.67^{b}	0.66^{a}	0.70^{b}	24.8^{a}	26.7^{a}	25.8^{a}	27.3^{a}	26.1^{b}	10.0	8.7^{a}	8.5^{b}	8.4^{a}	8.9^{b}
SSNM	12.3^{a}	13.9^{a}	14.1^{a}	14.4^{a}	13.7^{a}	0.80	0.69^{a}	0.64^{c}	0.66^{a}	0.70^{b}	26.2^{a}	28.6^{a}	26.2^{a}	28.0^{a}	27.3^{a}	10.1	8.7^{a}	8.2^{b}	8.3^{a}	8.9^{b}
Tillage x Nutrient management																				
CT- Un-fertilized	7.7^{d}	7.54^{d}	7.72^{e}	9.36^{c}	8.1^{d}	0.785	0.631^{ab}	0.753	0.603	0.693^{bcd}										
CT-FFP	10.72^{bc}	11.21^{bc}	11.81^{c}	10.84^{bc}	11.1^{c}	0.717	0.650^{ab}	0.560	0.596	0.631^{d}										
CT- Ad-hoc	11.61^{ab}	13.52^{a}	11.86^{c}	12.86^{ab}	12.5^{ab}	0.793	0.585^{b}	0.650	0.615	0.661^{cd}										
CT-SSNM	13.23^{a}	13.62^{a}	13.68^{ab}	13.42^{a}	13.5^{ab}	0.797	0.678^{ab}	0.621	0.631	0.682^{bcd}										
PB- Un-fertilized	8.52^{cd}	9.15^{cd}	9.13^{d}	9.82^{c}	9.2^{d}	0.889	0.813^{a}	0.745	0.737	0.796^{a}										
PB-FFP	10.00^{bcd}	13.13^{ab}	12.62^{bc}	13.16^{a}	12.2^{bc}	0.766	0.629^{ab}	0.636	0.631	0.665^{cd}										
PB- Ad-hoc	11.49^{ab}	13.49^{ab}	13.81^{ab}	14.62^{a}	13.4^{ab}	0.816	0.727^{ab}	0.669	0.677	0.722^{bc}										
PB-SSNM	12.12^{ab}	14.21^{a}	14.24^{a}	14.63^{a}	13.8^{a}	0.796	0.728^{ab}	0.642	0.707	0.718^{bc}										
ZT- Un-fertilized	7.89^{d}	8.64^{d}	8.80^{de}	10.14^{c}	8.9^{d}	0.881	0.656^{ab}	0.771	0.667	0.744^{ab}										
ZT-FFP	11.59^{ab}	13.14^{ab}	12.91^{bc}	13.95^{a}	12.9^{ab}	0.871	0.645^{ab}	0.639	0.586	0.685^{bcd}										
ZT- Ad-hoc	11.32^{ab}	12.45^{ab}	13.87^{ab}	13.62^{a}	12.8^{ab}	0.776	0.757^{ab}	0.686	0.695	0.728^{abc}										
ZT-SSNM	11.49^{ab}	13.97^{a}	14.29^{a}	15.03^{a}	13.7^{a}	0.799	0.676^{ab}	0.669	0.649	0.698^{bcd}										

*See Table 1 for treatment details. Same letter within each column indicate no significant difference among the treatments (at $P < 0.05$) according to least significant difference test.

same study site and elsewhere, respectively. In semi arid agro-ecologies of India the energy consumed in land preparation under conventional tillage in MWMb cropping system was 91 and 107% higher energy than zero tillage raised bed and flat bed planting, respectively. Raised beds planting saved the energy through irrigation by 38% over flat beds in MWMb cropping system [30]. The higher net returns of MWMb system in ZT and PB were attributed mainly to reduce production cost due to less field/tillage operations and higher crop productivity with lesser inputs as well as water applications. In agreement with the current results the higher net returns and reduction in cost of cultivation with ZT and PB was also reported by many workers in cereal based cropping systems [7,50,71,72].

In the current study, the effect of nutrient management on MWMb system pooled average net energy output, energy productivity, energy use efficiency and economics were significant ($P < 0.05$) for all the four years. The system net energy output, energy productivity, energy use efficiency and net returns (pooled average of 4-years) in SSNM and Ad-hoc treatments were higher by 20–25%, 6–7%,6–7% and 31–38% compared to FFP treatment, respectively. Singh et al. [73] also reported economic benefit of INR 1,09 789 ha^{-1} in MW system in SSNM treatment, which might be due to higher biomass yields because of optimum supply of nutrients as per crop demand and indigenous soil nutrient supplying capacity. The higher economic returns in SSNM plots over FFP, state recommendation (SR), improved state recommendation (ISR) and soil testing laboratory recommendation (STLR) plots underlines the significance of balanced nutrition to counter the crop yield stagnation as well as low farm profitability due to increasing cost of fertilizer [74].

5. Conclusions

In the semi-arid environment of north-western India, the CA-based ZT and PB practices and SSNM based balanced use of inorganic fertilizers guided by the Nutrient Expert® fertilizer decision support tool, caused a significant improvement in the bioenergetic yields, WUE, net energy outputs, energy productivity and efficiency, system biomass productivity and economics of the MWMb cropping system. These novel results showed great promise for similar South Asian agro-ecologies for sustainability of cereal based system. Thus, CA-based tillage/crop establishment practices supplemented with plant nutrients through renewable resources like residue biomass layered with SSNM/Ad-hoc nutrient management practice may be deployed and adopted by farmers (depending upon their resources) for improving bioenergetic yields, biomass productivity, water and energy use efficiency and economic profit under MWMb system. However, the long-term impact (regarding crop biomass productivity, water and energy use efficiency and agro-ecology) of CA-based tillage/crop establishment with residue retention layered with SSNM/Ad-hoc nutrient management practices is a key future research issue in North-West IGP and other similar ago-ecologies of South Asia. Moreover, if the policy makers can able to attract Indian farmers' inclination towards intensification of traditional maize-wheat cropping system with mungbean for only 50% of existing area (total 1.86 mha) it would be able to meet out the protein demand of additional 8.1 million malnourished populations every year.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2016.12.068.

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