Agricultural Water Management 192 (2017) 306–319

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Research Paper

Effects of precision conservation agriculture in a maize-wheat-mungbean rotation on crop yield, water-use and radiation conversion under a semiarid agro-ecosystem

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ARTICLE INFO

Article history:
Received 14 June 2016
Received in revised form 11 June 2017
Accepted 21 July 2017

Keywords:
Farmers fertilizer practices
Nutrient management
Permanent beds
Site specific nutrient management
Zero tillage

ABSTRACT

In recent years, water resources have decreased and water saving has become an important issue in the Indo-Gangetic Plains (IGP) of South Asia. Maize-wheat-mungbean (MWMb), is an alternate to traditional rice-wheat cropping system, can mitigate the effects of the frequency, intensity, and duration of rainfall due to climate change on food security in the semi arid-region of north-western IGP. The objective of this research was to determine the productivity, water-use efficiency (WUE) and incident radiation conversation efficiency (IRCE) of MWMb cropping system under 3 tillage practices [zero tillage (ZT), permanent beds (PB) and conventional tillage (CT) and 4 nutrient management strategies [Control (unfertilized), farmers' fertilizer practice (FFP), recommended dose of fertilizers (Ad-hoc) and a site specific nutrient management (SSNM" using the Nutrient Expert® decision support tool). Results of multi-year trial showed that among tillage practices, ZT and PB practices reduced the system irrigation water requirement by 140–200 mm ha^{-1} and 200–300 mm ha^{-1} respectively, compared to CT system, resulting an enhanced grain yield by 5.7–24.6%, biomass yield by 4.6–20.8%, WUE by 18.4–39.0%, and IRCE by 9.9–34.4%, respectively. Significant ($P \leq 0.05$) improvement in system WUE, grain and biomass yield, and IRCE (by 30.6–59.9, 38.3–80.5, 34.3–64.7 and 13.5–48.5%, respectively) was observed in SSNM compared to the unfertilized plots. Significant ($P \leq 0.05$) interactions between tillage practices and nutrient management strategies was measured with respect to water–use, WUE, grain and biomass yield, and IRCE of MWMb system. Combinations of ZT/PB practices + SSNM/Ad-hoc nutrient management strategies registered significantly ($P < 0.05$) higher system WUE and IRCE, grain and biomass yield compared to CT + unfertilized/FFP. Results of present study showed that SSNM/Ad-hoc based nutrient application coupled with CA-based tillage practices in MWMb system has complementarity to attain higher system productivity, WUE and IRCE compared to the use of these crop management practices in isolation.

1. Introduction

Concerns of multiple challenges of sustainability in rice-wheat (RW) rotation vis-à-vis natural resource degradation in north-west IGP are well documented (Saharawat et al., 2010; Chauhan et al., 2012; Singh et al., 2016) especially the rapidly falling water tables (Yadvinder-Singh et al., 2014; Sharma et al., 2012) and the deteriorating soil health (Parihar et al., 2016a). Diversification of rice with maize in the conventional RW system could help in enhancing crop productivity (Gathala et al., 2013), water-use efficiency (Parihar et al., 2016a,2016b), save irrigation water and labour costs (Gathala

Abbreviations: Ad-hoc, recommended dose of fertilizer; CA, conservation agriculture; CT, conventional tillage; FFP, farmers' fertilizer practice; 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; IRCE, incident radiation conversion efficiency; SSNM, site specific nutrient management; WUE, water-use efficiency; ZT, zero tillage.

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http://dx.doi.org/10.1016/j.agwat.2017.07.021
0378-3774/

et al., 2013; Aulakh and Grant, 2008), and may achieve higher radiation-use efficiency (Sinclair and Muchow, 1999). However, conventional crop management practices entail high production costs (Gathala et al., 2013; Jat et al., 2014a) and are inefficient in water and incoming radiation-use (Fahong et al., 2004; Slattery and Ort, 2015; Gitelson and Gamon, 2015; Schneider et al., 2016).

The Indo-Gangetic Plain (IGP) of India, covering about 44 Mha, is dominated by irrigated cereals-based cropping sequences, of which maize–wheat (MW) rotation is the third most important (1.86 Mha) after rice–wheat and cotton–wheat (Jat et al., 2014a,2014b). India is the world's largest user of irrigation water supplied from ground water (Aeschbach-Hertig and Gleeson, 2012). In India and many parts of the world, the irrigation and fresh water resources are increasingly scarce every year due to extensive subsidies and limited regulations (Postel et al., 1996; Vorosmarty et al., 2000; Haddeland et al., 2014). Considering this scenario, we can expect that water resources will be less available for irrigated agriculture and competition for water will increase in the near future in this region. Within this context, a large increase in water-use efficiency is required to optimize agricultural productivity while reducing pressure on natural resources (Tilman, 1999; Gleick, 2003; Rockström et al., 2007; Teixeira et al., 2014). In this sense, alternative best crop management options like conservation agricultural practices which include zero tillage and permanent beds have demonstrated potential benefits on crop yield and profits while saving water, energy and restoring soil degradation across diverse ecologies (Jat et al., 2013, 2014a; Das et al., 2014). Yield is a complex quantitative trait and greatly influenced by modification in external environment, which results in scale or rank shift in its performance (Dia et al., 2016a, 2016b, 2016c, 2016d, 2017).

Recent studies have shown that permanent bed (PB) planting was suitable for enhancing crop productivity and reducing the production cost as well as to conserve the natural resources (Lichter et al., 2008). It also allowed the maintenance of uniform permanent soil cover for higher moisture/water capture and conservation (Govaerts et al., 2005, 2007a). Direct planting of crops in zero tillage (ZT) and PB plots, with balanced fertilization lead to favourable alterations in soil water aggregates (Parihar et al., 2016a,2016b), total porosity (Jemai et al., 2013), maintaining soil and moisture content (Govaerts et al., 2007a,2007b; Sharma et al., 2011) and, as a consequence, it improved plant water availability (Bergamaschi et al., 2010; Jemai et al., 2013). Conservation agriculture (CA) based (zero tillage and permanent bed) crop establishment practices (generally depends upon three basic principles *viz*; minimal soil disturbance, rational soil cover and crop rotation) also improve soil infiltration (Bhattacharyya et al., 2006; Nielsen et al., 2009), water retention (Datiri and Lowery, 1991) and hydraulic conductivity (Benjamin, 1993; Dia et al., 2009; Parihar et al., 2016a). CA-based ZT system could provide additional nutrients (Blanco-Canqui and Lal, 2009; Kaschuk et al., 2010), improve soil physical health (Jat et al., 2013; Singh et al., 2016), better water-use efficiency (Govaerts et al., 2009) and improve nutrient use efficiency (Unger and Jones, 1998). A healthy soil is capable of producing higher crop yield under favourable as well as extreme climatic conditions (Congreves et al., 2015). Reduction in soil disturbance (tillage) and provision of optimum crop nutrition can enhance dry matter accumulation and improve plants metabolic activities, resulting in better yield, leaf area index (LAI) and crop architecture due to plant x environment interactions (Norman and Campbell, 1989). The absorption of solar radiation depends on leaf area index (LAI) and crop architecture (Plénet et al., 2000).

The use of fertilizer nutrients in sub-optimal, optimal and super-optimal doses potentially affects the crop yield and resource use efficiency. Enhanced crop yield, water, and resource use efficiency under balanced application of fertilizer nutrients have been observed in maize and wheat based systems (Jat et al., 2014a,2014b; Sapkota et al., 2014; Pooniya et al., 2015). The nutrient content of plants, particularly nitrogen, and the LAI also affects the radiation interception efficiency (Dewar, 1996; Scott Green et al., 2003) which in turn affects the conversion efficiency of total incoming solar radiation into dry matter (Fahong et al., 2004). Under field conditions, water stress can modify the plant leaf development and limits its photosynthetic activity and stomatal conductance, hence affecting the whole plant performance, including reduction of crop yield and grain quality (Guimarães, 1996; Fancelli and Dourado Neto, 1991). The incident radiation conversion efficiency (IRCE) also varies with the crop species (Sinclair and Muchow, 1999) under a set of management practices. The water-use efficiency (WUE) is interrelated with IRCE (Sadras and Connor, 1991). These understandings, therefore, lead to support the setting of new benchmarks to evaluate existing agricultural systems and to improve future agricultural systems in order to balance the future need through enhanced yields and the resource use efficiency (Kant et al., 2011; Teixeira et al., 2014).

So, the optimization of both WUE and IRCE of MWMb system is required in north-west part of India for better utilization of the available solar radiation and limited water. Therefore, we conceptualized a research study to investigate and provide new scientific information on the effects of CA-based practices and precision nutrient management in MWMb rotation on crop productivity, water-use and incident radiation conversion efficiency in a sandy loam soil of north-west India. The objective of this research was to assess the productivity, water-use efficiency and incident radiation conversation efficiency of MWMb cropping system under 3 tillage practices and 4 nutrient management strategies.

2. Materials and methods

2.1. Experimental site

The experiment under MWMb rotation was conducted for three consecutive years during 2012–2015 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). Maize was sown during the *rainy* season (July-October), wheat in winter (November-April) and mungbean in summer (April–June) season. The site has a semi-arid climate, typically characterized by hot and dry summer and cold winter with a mean annual precipitation of about 652 mm. The soil of the experimental site is a sandy loam in texture (Typic Haplustept) of Gangetic alluvial origin, and well drained 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}. The moisture content at saturation was 0.38 m^3 m^{-3} and at 0.033 MPa (Field capacity) varied from 22 to 27% and at 1.5 MPa (Permanent wilting point) varied from 8 to 12% in different soil layers of 0–30 cm depth.

2.2. Experiment treatments and design

The experiment was laid out in a split-plot design with tillage/crop establishment practices [Zero tillage with residue retention (ZT), Permanent bed with residue retention (PB), and Conventional tillage with residue 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 (Pampolino et al., 2012) (SSNM)] as sub-plot treatments. The 12 treatment combinations with a harvested subplot size of 30.15 m^2 (7.5 m length x 4.02 m width) were replicated thrice every year (for all the three years) of study. The details of treatment are summarized in Table 1.

Table 1
Description of treatments imposed in maize-wheat-mungbean 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 ($N:P_2O_5:K_2O$ kg ha^{-1}			
	Unfertilized	Farmers Fertilizer Practices (FFP)	Recommended doses (Ad-hoc)	Site specific nutrient management (SSNM)
Maize	00:00:00	110.0:30.0:0.0	150.0:60.0:40.0	170.0:37.0:44.0
Wheat	00:00:00	172.0:57.5:0.0	120.0:60.0:40.0	155.0:63.0:65.0
Mungbean	18.0:46.0:0.0	18.0: 46.0:0.0	18.0: 46.0:0.0	18.0: 46.0:0.0

Note: In the first Rainy season of 2012, mungbean residues (1.5 Mg ha^{-1}, dry weight basis) were applied in maize and in the subsequent seasons and years the preceding crop residues were retained/incorporated in the respective plots.

2.3. Crop establishment

Before initiation of the experiment in 2012, the field was deep (30 cm) tilled using chisel plough to break the hard pan below the plough layer and was laser levelled. The CT planting involved one ploughing each with the disc harrow, followed by a spring-tyne cultivator and rotavator. In ZT, seeds of different crops were directly drilled in the soil using ZT planter with inverted 'T' tynes. In the first year (July 2012), fresh raised beds were developed using bed/ridge former (A.S.S. Foundry &Agri. Works, Jandiala guru, Punjab, India make ridge former), which were maintained as permanent beds (PB) for subsequent years. 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 the crop was planted by using raised bed multi-crop planter. Maize (DHM-117) was sown with seed rate of 20 kg ha^{-1} 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 during 1^{st} fortnight of July in *rainy* season and harvested in last week of October (in 3-years of the study). Wheat (cv. HD 2967) was sown with a seed rate of 100 kg ha^{-1} in the 2^{nd} to 3^{rd} week of November at 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, crop was harvested in 2^{nd} and 3^{rd} week of April during all the study years. Mungbean (*cv*. Pusa Vishal) was sown using a seed rate of 25 kg ha^{-1} in the 2^{nd} fortnight of April 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, harvesting/pod picking was done in 3^{rd} and 4^{th} week of June during all the years.

Fertilizers in the FFP treatment were applied based on survey of 50 farmers' of the area (Delhi NCR region (including the parts of Haryana, Western Uttar Pradesh, Parts of Rajasthan), and Punjab and plains of Uttarakhand, Supplementary Table 4) and was 110:30:0 and 172:57.5:0 kg ha^{-1} of N: P_2O_5: K_2O for maize and wheat, respectively. The Ad-hoc recommendations were based on the economic optima of nutrients for Delhi state by Indian Council of Agricultural Research (ICAR). The Ad-hoc recommendations were 150:60:40 kg ha^{-1} and 120:60:40 kg ha^{-1} of N: P_2O_5: K_2O for maize and wheat, respectively. The site-specific nutrient management (SSNM) doses for maize and wheat were worked out by Nutrient Expert®, an interactive computer-based decision support tool that can provide 4R compliant fertilizer recommendations in Indo-Gangetic plains (Pooniya et al., 2015; Singh et al., 2015; Parihar et al., 2017). It is a user-friendly tool developed by International Plant Nutrition Institute (IPNI) based on the SSNM principles. The nutrient doses calculation by Nutrient Expert® were based on plant nutrient demand for a targeted crop yield, applied nutrient to previous crop, residue recycling, soil fertility status, and the economics of fertilizer input and prices of crop produce in the market. The SSNM recommendations based on the Nutrient Expert® decision support tool were 170:37:44 and 155:63:65 kg ha^{-1} of N: P_2O_5: K_2O (average of all tillage practices in 3-years) for maize and wheat, respectively. Calculated $1/3^{rd}$ dose of N and full dose of P_2O_5 and K_2O were applied during final land preparation. Remaining $2/3^{rd}$ dose of N was applied in two equal splits at the eight leaves (V_8) and tasseling (VT) stages in maize, and at the 1^{st} and 3^{rd} irrigation in wheat. A uniform dose of 18:46 kg ha^{-1} of N: P_2O_5 was applied to mungbean as basal application. In the first *rainy* season of 2012, mungbean residues (1.5 Mg ha^{-1}, dry weight basis) were applied in maize, which was grown on the adjoining non-experimental field. In the subsequent seasons and years, about 30% of the residues of maize (2.35–3.22 Mg ha^{-1}, dry weight basis), wheat (1.61–2.19 Mg ha^{-1}, dry weight basis) and 100% of mungbean (2.50–3.88 Mg ha^{-1}, dry weight basis) were retained in ZT/PB and incorporated in CT plots and the remaining amounts of residues were removed for use as fodder for cattle and fuel.

Weed management in the ZT and PB plots was done by using the herbicide glyphosate was sprayed at 1.0 kg ha^{-1} (about two days before sowing of each crop). However, in the case of CT plots Atrazine at 1.0 kg ha^{-1} as pre-emergence (PE) in maize, Pendimethalin at 1.0 kg ha^{-1} as PE in mungbean and wheat and Cladinofop at 60 g ha^{-1} at 28–32 days after seeding of wheat was applied. In addition to chemical weed management, one hand weeding was also done in all the CT plots only at 30–40 days after sowing. In ZT and PB plots weed infestation was less than CT, except hardy perennial weeds after the first year, which were uprooted manually.

2.4. Evapo-transpiration and Water-use efficiency (WUE) computations

Soil moisture content in the profile (0–120 cm) was determined gravimetrically at 30 cm interval of different soil layers at the initial (at sowing) and final stage (at harvesting) of each crop grown in *rainy*, winter and summer seasons to study profile soil moisture contribution in plant growth and development. For moisture content analysis in permanent bed plots, soil samples were collected from the side of the ridge at the 30 cm interval using a tube auger of 7 cm diameter from three places in each experimental treatment.

Evapo-transpiration (ET) was computed using the field water balance equation (Lenka et al., 2009; Pradhan et al., 2014) as given below:

$$ET = (P + I + C) - (R + D + \Delta S) \quad (1)$$

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 the 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 (Lenka et al., 2009; Pradhan et al., 2014).

Thus Eq. (1) simplifies to,

$$ET = (P + I) - \Delta S \quad (2)$$

Precipitation data were collected from the meteorological observatory of ICAR-IARI, New Delhi. The effective rainfall was calculated by using Cropwat 8.0 by USDA SCS method. Cropwat is a computer program based decision support tool developed by the Food and Agriculture Organization (FAO) of the United Nations to estimate effective rainfall based on climate and soil data. Irrigation was applied during dry spell/moisture stress through surface irrigation at critical growth stages of crops (Supplementary Table 2). 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 the equation 3.

$$Q = Kx1000x(Ha/100)^{\wedge}1.55 \quad (3)$$

Where,Q = Flow rate in liter per second K = a fraction, which is a function of the throat width (0.1771 in our 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 the actual discharge (Savva and Frenken, 2002).

Water applied in each plot was calculated by Eq (4).

$$\text{Water applied in each } (m^2 ha^{-1} = \{(Q - Qc)x\,T\}^{*}10/A) \quad (4)$$

Where, Qc is correction factor for reduction in modular discharge due to submergence; T is time taken for irrigation of a plot (in s) and A is the size of a plot (m^2).

Water-Use Efficiency (WUE) was computed as given in Eq. (5).

$$\text{WUE} = \frac{\text{Yield}\left(\text{kg ha}^{-1}\right)}{\text{ET}\left(\text{m}^3\ \text{ha}^{-1}\right)} \quad (5)$$

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 three years of study. The grain/seed and straw yields of maize, wheat, and mungbean were estimated from an area of 30.15 m^2 using plot thresher. In the case of mungbean after two manual picking of pods, 2, 4-D (Easter) was sprayed @ 0.5 kg ha^{-1} to knock down the plants. The grain/seed yield of maize, wheat, and mungbean were adjusted at 14%, 12% and 12% moisture content respectively and both (grain and biomass yield) were expressed in Mg ha^{-1}.

2.5. Leaf area measurement

The leaf area was estimated at 30 days after sowing (DAS), 60 DAS and 90 DAS in maize and wheat and at 15 DAS, 30 DAS and 45 DAS in mungbean. It was estimated by separating leaves of five randomly selected plants in maize and mungbean and plants from 0.25 m^2 areas in wheat from three places in each plot by using leaf area meter. The leaf area index (LAI) was calculated as the ratio of leaf area to corresponding ground area.

2.6. Incident radiation conversion efficiency computation

Daily incoming solar radiation was calculated as per the procedure described by Allen et al. (1998) using observations of daily bright sunshine hours. Daily incident solar radiation was multiplied by a factor 0.48 (Monteith, 1972) to get incoming incident photosynthetically active radiation (PAR). The daily incident PAR above the crop canopy (maize, wheat, and mungbean) was accumulated for the whole cropping season to get total incident PAR. Incident radiation conversion efficiency was computed by dividing above ground biomass by total incident PAR (Fahong et al., 2004). Although this estimate of solar radiation-use is very approximate (because of unavailability of actual intercepted solar radiation values between top and bottom of crop canopy), they still provide a way of assessing the use efficiency of incident solar radiation.

2.7. Statistical analysis

All data recorded were analyzed with the help of analysis of variance (ANOVA) technique (Gomez and Gomez, 1984) for split-plot design using SAS 9.3 software (SAS Institute, Cary, NC). The least significant difference test was used to decipher the effects of treatments at 5% level of significance ($P \leq 0.05$). Correlation analysis was also performed using SAS 9.3 software.

3. Results and discussion

3.1. Weather

Rainfall during the *rainy* season (July to October) was highest (1199 mm) in 2013 followed by 482 mm in 2012, whereas 2014 season received the lowest amount of rainfall (451 mm). The rainfall received in three months (July to September) amounted more than 75% of total yearly rainfall in 2013, while during 2012 and 2014 seasons it was 59 and 50%, respectively (Fig. 1, Supplementary Table 1 and Supplementary Table 3). The rainfall received in the *winter* season (October to April) was 176.0 mm, 169.1 mm and 311.8 mm during 2012–13, 2013–14 and 2014–15, respectively. During the summer season (May to June), the total amount of rainfall varied from 125.2 mm in 2015–146.8 mm in 2013 (Table 3). However, the mean monthly maximum and minimum temperatures were almost similar in all the three years of study. The monthly mean daily pan evaporation was 4.9, 3.8 and 10.1 mm for *rainy*, *winter* and summer season, respectively (Supplementary Table 1). The total incident solar radiation (MJ m^{-2}) during *rainy* season varied from 2140.0 in 2012, 2118.4 in 2013 and 2242.0 in 2014, and for *winter* from 2696.4 in 2012–13, 2616.4 in 2013–14 and 2638.6 in 2014–15, while in summer from 1384.0 in 2013, 1429.8 in 2014 and 1384.8 in 2015.

3.2. Seasonal evapo-transpiration (ET)

Seasonal evapo-transpiration (ET) of maize, wheat, mungbean and maize-wheat-mungbean (MWMb) system varied significantly ($P \leq 0.05$) with different tillage practices (Table 2) in different seasons of all the 3-years of study. The ET among all the seasons and

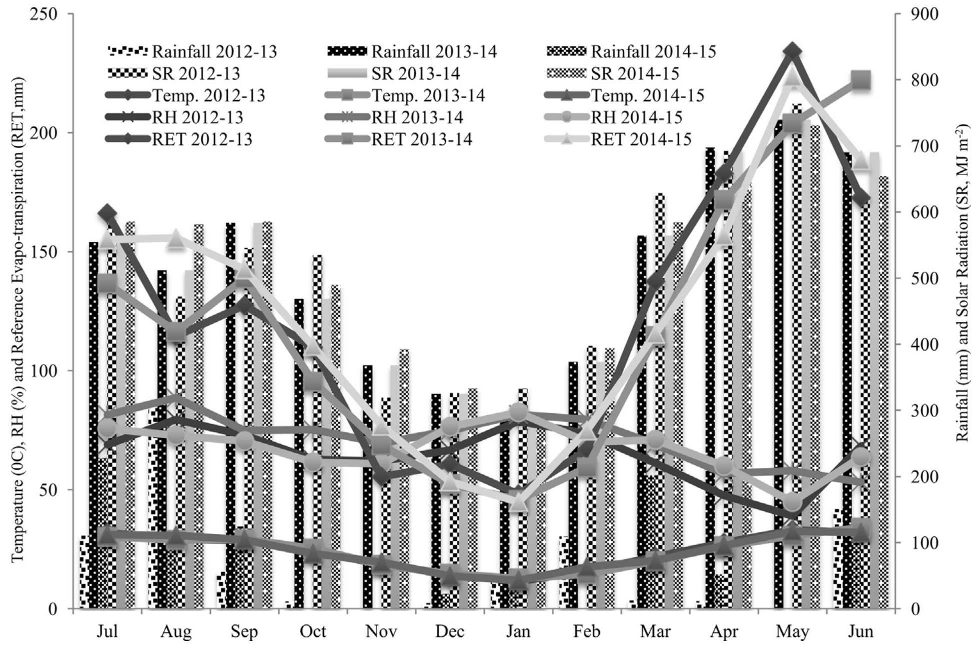

Fig. 1. Weather conditions during the study period.

Table 2
Seasonal evapo-transpiration (ET) in different crops of maize-wheat-mungbean system under different tillage and nutrient management practices.

Treatments	ET (mm)												Irrigation water (mm)		
	Maize			Wheat			Mungbean			MWMb System			MWMb System		
	2012	2013	2014	2012-13	2013-14	2014-15	2013	2014	2015	2012-13	2013-14	2014-15	2012-13	2013-14	2014-15
Tillage practices															
CT	867^{a}	848^{a}	890^{a}	693^{a}	687^{a}	763^{a}	475^{a}	308^{a}	578^{a}	2035^{a}	1843^{a}	2232^{a}	1300^{a}	910^{a}	1300^{a}
PB	742^{c}	779^{c}	761^{c}	563^{c}	560^{c}	637^{c}	403^{c}	266^{c}	507^{c}	1708^{c}	1605^{c}	1905^{c}	1000^{c}	700^{c}	1000^{c}
ZT	785^{b}	802^{b}	805^{b}	605^{b}	604^{b}	678^{b}	429^{b}	281^{b}	529^{b}	1820^{b}	1687^{b}	2013^{b}	1100^{b}	770^{b}	1100^{b}
*Nutrient management practices**															
Unfertilized	792^{d}	804^{d}	813^{d}	613^{d}	611^{d}	687^{d}	430^{d}	279^{d}	532^{d}	1835^{d}	1694^{d}	2032^{d}	1133	793	1133
FFP	795^{c}	807^{c}	816^{c}	617^{c}	614^{c}	690^{c}	433^{c}	282^{c}	535^{c}	1845^{c}	1703^{c}	2041^{c}	1133	793	1133
Ad-hoc	801^{b}	812^{b}	821^{b}	622^{b}	619^{b}	695^{b}	438^{b}	288^{b}	541^{b}	1861^{b}	1719^{b}	2057^{b}	1133	793	1133
SSNM	805^{a}	816^{a}	825^{a}	629^{a}	624^{a}	700^{a}	442^{a}	292^{a}	545^{a}	1876^{a}	1731^{a}	2069^{a}	1133	793	1133
Tillage x Nutrient management															
CT-Unfertilized	859^{c}	840^{b}	882^{c}	683^{c}	679^{c}	762^{b}	473^{b}	301^{c}	576^{b}	2015^{d}	1820^{c}	2219^{c}	1300	910	1300
CT-FFP	863^{b}	845^{b}	887^{b}	689^{b}	685^{b}	760^{b}	472^{b}	307^{b}	575^{b}	2024^{c}	1836^{b}	2222^{c}	1300	910	1300
CT-Ad-hoc	873^{a}	854^{a}	896^{a}	693^{b}	689^{ab}	762b	474^{b}	311^{a}	577^{b}	2040^{b}	1855^{a}	2235^{b}	1300	910	1300
CT-SSNM	873^{a}	855^{a}	897^{a}	707^{a}	693^{a}	770^{a}	482^{a}	314^{a}	585^{a}	2062^{a}	1862^{a}	2252^{a}	1300	910	1300
PB- Unfertilized	740^{h}	776^{g}	759^{h}	560^{g}	558^{g}	629^{i}	396^{h}	264^{g}	500^{h}	1696^{j}	1598^{h}	1888^{j}	1000	700	1000
PB-FFP	739^{h}	776^{g}	758^{h}	560^{f}	557^{g}	635^{g}	401^{g}	263^{g}	505^{g}	1700^{ij}	1596^{h}	1899^{i}	1000	700	1000
PB- Ad-hoc	741^{h}	777^{g}	760^{h}	561^{g}	559^{g}	639^{h}	406^{f}	265^{g}	510^{f}	1708^{i}	1601^{h}	1909^{h}	1000	700	1000
PB-SSNM	749^{g}	785^{f}	768^{g}	570^{e}	567^{f}	644^{f}	409^{f}	273^{f}	513^{f}	1728^{h}	1626^{g}	1925^{g}	1000	700	1000
ZT- Unfertilized	778^{f}	795^{e}	798^{f}	597^{d}	595^{e}	669^{e}	420^{e}	273^{f}	521^{e}	1795^{g}	1663^{f}	1988^{f}	1100	770	1100
ZT-FFP	784^{e}	801^{d}	803^{e}	601^{e}	600^{e}	674^{d}	425^{d}	277^{e}	526^{d}	1810^{f}	1678^{e}	2003^{e}	1100	770	1100
ZT- Ad-hoc	788^{d}	805^{cd}	808^{i}	611^{d}	610^{d}	685^{c}	435^{c}	287^{d}	535^{c}	1834^{e}	1702^{d}	2028^{d}	1100	770	1100
ZT-SSNM	791^{d}	808^{c}	811^{d}	612^{d}	610^{d}	685^{c}	435^{c}	287^{d}	536^{c}	1838^{e}	1706^{d}	2031^{d}	1100	770	1100

CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, Ad-hoc: recommended dose of fertilizers, FFP=Farmer fertilizer practices; SSNM: Site specific nutrient management. *See Table 1 for nutrient doses in respective crop and treatment. Means followed by a similar superscript letter within a column are not significantly different (at $P \leq 0.05$) between treatments of the same year according to least significant difference test.

years was maximum in the CT plots; the PB plots registered lowest ET in maize (742–779 mm), wheat (560–637 mm), mungbean (266–507 mm), and in MWMb system (1605–1905 mm). In all the study years, irrigation was different between treatments and ET decreased significantly with PB/ZT treatments ($P \leq 0.05$). The PB plots had 8.2–14.5%, 16.5–18.8%, 12.3–15.2% and 12.9–16.1% lower ET, in maize, wheat, mungbean crops and MWMb system compared to CT, respectively during all the three years of study. In conservation agriculture, retention of plant residues on the soil surface results in declined evaporation which mainly attributed with the lower soil temperature (Rasmussen, 1999; Gupta and Jat, 2010) compared to CT. Water moves back to the atmosphere in vapour phase through straw mulch/residue retention on the soil surface in ZT/PB whereas no such barrier present in CT. As the sensible heat balance (Heitman et al., 2008) of soil and atmosphere decides the rate of evaporation and the decreased temperature reduces this balance and thus lowers the rate of evaporation from the soil. So, the straw/residue retention tends to act as a one-way water valve on soil surface to check the evaporation. Thus, the CA technologies

Table 3
Total input water (irrigation + effective rainfall) in different crops of maize-wheat-mungbean system under different tillage and nutrient management practices.

Treatments	Total input water (irrigation + effective rainfall) mm								
	Maize			Wheat			Mungbean		
	2012	2013	2014	2012–13	2013–14	2014–15	2013	2014	2015
Tillage practices									
CT	844	788	848	676	675	760	372	253	500
PB	724	728	728	556	555	640	312	223	440
ZT	764	748	768	596	595	680	332	233	460
Nutrient management practices*									
Unfertilized	777	755	781	609	608	693	339	236	467
FFP	777	755	781	609	608	693	339	236	467
Ad-hoc	777	755	781	609	608	693	339	236	467
SSNM	777	755	781	609	608	693	339	236	467
Total rainfall (mm)	481.8	1198.8	451.0	176.0	169.1	311.8	146.8	139.2	125.2
Effective rainfall (mm)	324.0	528.0	328.0	156.0	155.0	240.0	112.3	123.0	240.0

CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, Ad-hoc: recommended dose of fertilizers, FFP=Farmer fertilizer practices; SSNM: Site specific nutrient management. *See Table 1 for nutrient doses in respective crop and treatment.

found to be very effective in reducing disturbance of soil and crop residue with moderation in soil evaporation (Lal et al., 2007).

Similar to tillage effects, in all the study years the main effect of nutrient management was also significantly ($P \leq 0.05$) influenced the ET. Irrespective of study years and crops, higher ET in SSNM treatment resulted due to higher biomass production than all other treatments including control. During all the study years ET in SSNM plots of different crops higher by 1.5–1.6% in maize, by 1.9-2.6% in wheat, by 2.4–4.7% in mungbean and by 1.8–2.2% in MWMb system, than control plots. Interaction effects of tillage and nutrient management were significant ($P \leq 0.05$) on individual crops and system ET (Table 2) in all the study seasons. In all the study years the maximum ET in maize (855–897 mm), in wheat (693–770 mm), in mungbean (314–585 mm) and in MWMb system (1862–2062 mm) was in the CT-SSNM, which was similar to CT-Ad-hoc treatment, while the lowest ET in maize (739–776 mm) and wheat (557–635 mm) was with PB-FFP treatment, and in mungbean (264–500 mm) and in MWMb system (1598–1888 mm) were registered in all PB treatments. Nutrient availability affects aboveground biomass especially the canopy cover which influences soil evaporation (Maskina et al., 1993; Norton and Wachsmann, 2006). Thus, improved nutrient management by SSNM and Ad-hoc increased the LAI of the crop which helped in reducing the evaporation compared to FFP.

3.3. Grain yield and aboveground biomass yield

3.3.1. Maize

ANOVA showed significant ($P \leq 0.05$) effects of tillage on *rainy* season maize crop yield during the 2nd and 3rd years of study (Table 4). The three-year data showed that in 2013 and 2014, grain and biomass yields of *rainy* season maize was significantly ($P \leq 0.05$) higher by 21.5–30.9% and 9.2–23.2% in PB/ZT (maize grain yield in 2013 was similar in ZT and CT treatments) compared to CT planting, respectively. The present findings of higher maize yield in ZT planting could be due to the compound effects of additional nutrients (Blanco-Canqui and Lal, 2009; Kaschuk et al., 2010), lesser weed population (Ozpinar, 2006; Chauhan et al., 2007), improved soil physical health (Jat et al., 2013; Singh et al., 2016), better water regimes (Govaerts et al., 2009) and improved nutrient use efficiency compared to CT (Unger and Jones, 1998). The yields of *rainy* season maize crop also differed significantly ($P \leq 0.05$) under different nutrient management practices. Significant ($P \leq 0.05$) increase in grain yield (57–67%) and biomass yield (40–57%) as compared to the unfertilized was recorded under SSNM and Ad-hoc treatments. Maximum maize grain yield (4.61-4.80 Mg ha^{-1}) and biomass yield (14.51–17.17 Mg ha^{-1}) was recorded under SSNM followed by Ad-hoc (4.17–4.78 Mg ha^{-1}) and (14.41–16.25 Mg ha^{-1}), respectively (Tables 4 and 5), even though there was no significant difference in maize grain yield of FFP, Ad-hoc and SSNM treatments in 2013. The higher yield under SSNM was probably due to optimum supply of nutrients as per crop demand and indigenous soil nutrient supplying capacity (Singh et al., 2016). Singh et al. (2015) found 38.1% greater maize yield in SSNM treatment compared to FFP. Tillage and nutrient management interaction effects were significant ($P \leq 0.05$) on maize grain yield in 2nd and 3rd year of study and biomass yield in all the 3-years of study (Tables 4 and 5). The marginally higher maize grain yield in 2nd year (5.24 Mg ha^{-1}) and biomass yield (16.71 Mg ha^{-1}) was in the PB-Ad-hoc treatment, and during 3rd year the ZT- Ad-hoc treatment registered marginally higher grain yield (5.63 Mg ha^{-1}) and biomass yield (16.17 Mg ha^{-1}). However, the maize grain and biomass yield was observed similar in all the tillage and nutrient management interaction treatments for all the three years (except the biomass yield in 2014 was maximum in ZT-Ad-hoc treatment).

3.3.2. Wheat

Tillage methods had significant effect on wheat grain and biomass yield (in 3-years) and was the highest in PB plots (3.81–4.87 Mg ha^{-1} and 9.22–11.49 Mg ha^{-1}, respectively) compared to CT (3.40–4.21 Mg ha^{-1} and 8.27–10.04 Mg ha^{-1}, respectively) (Tables 4 and 5), however the ZT was intermediate (3.61–4.51 Mg ha^{-1} and 8.83–10.83 Mg ha^{-1}, respectively). In all the three years of study the grain and biomass yields with PB were increased significantly ($P \leq 0.05$) by 12.1–15.7 and 11.5–14.7% compared to CT, respectively. The significantly higher wheat yield in the PB plots compared with CT plots, could be attributed to higher moisture availability because of lower evaporation losses from the furrows in PB plots (Astatke et al., 2002). The present findings are well supported by Dhillon et al. (2000) and Hobbs and Gupta (2003) who reported higher yields in bed-planted wheat than flat-planted wheat. The statistical analysis showed that the main effect of nutrient management on wheat grain and biomass yields were significant ($P \leq 0.05$) in all the three years of fixed site experimentation. SSNM registered increase in grain yield (22.3–124.9%) and biomass yield (16.2–96.6%) compared to unfertilized plots, respectively. Similar to our findings Singh et al. (2015) also reported 30.9% higher wheat yield in SSNM over FFP, which could be attributed to the higher spike density, number of grains per spike and 1000-grain weight (data not presented). However, the tillage and nutrient management interaction effect on wheat grain and biomass yields was not observed.

Table 4
Grain/seed yield of different crops in maize-wheat-mungbean system under different tillage and nutrient management practices.

Treatments	Grain/seed yield (Mg ha^{-1})								
	Maize			Wheat			Mungbean		
	2012	2013	2014	2012–13	2013–14	2014–15	2013	2014	2015
Tillage practices									
CT	3.84	3.43^{b}	3.49^{b}	3.40^{b}	4.21^{b}	4.12^{b}	0.566^{b}	0.612^{b}	0.767^{b}
PB	3.77	4.49^{a}	4.24^{a}	3.81^{a}	4.87^{a}	4.72^{a}	0.609^{b}	0.820^{a}	0.940^{a}
ZT	3.90	3.74^{b}	4.47^{a}	3.61^{ab}	4.51^{ab}	4.42^{ab}	0.716^{a}	0.824^{a}	1.007^{a}
Nutrient management practices*									
Unfertilized	2.77^{c}	2.91^{c}	2.87^{c}	3.23^{c}	2.57^{d}	3.15^{c}	0.534^{b}	0.562^{c}	0.831^{c}
FFP	3.64^{b}	3.89^{b}	3.81^{b}	3.51^{bc}	4.33^{c}	3.88^{b}	0.636^{a}	0.761^{b}	0.873^{bc}
Ad-hoc	4.32^{a}	4.17^{ab}	4.78^{a}	3.75^{ab}	5.44^{b}	5.19^{a}	0.667^{a}	0.833^{ab}	0.936^{ab}
SSNM	4.61^{a}	4.58^{a}	4.80^{a}	3.95^{a}	5.78^{a}	5.47^{a}	0.685^{a}	0.853^{a}	0.979^{a}
Tillage x Nutrient management									
CT-Unfertilized	2.70	2.23^{d}	2.72^{f}	3.14	2.08	2.91	0.412^{c}	0.409	0.546^{d}
CT-FFP	3.69	3.76^{abc}	3.40^{def}	3.24	4.18	3.52	0.495^{bc}	0.661	0.763^{c}
CT-Ad-hoc	4.55	3.32^{bcd}	3.69^{de}	3.55	5.09	4.70	0.720^{a}	0.679	0.883^{bc}
CT-SSNM	4.43	4.42^{ab}	4.15^{cd}	3.67	5.49	5.35	0.636^{a}	0.699	0.874^{bc}
PB- Unfertilized	2.82	3.92^{abc}	2.74^{f}	3.28	3.01	3.75	0.534^{bc}	0.701	0.916^{abc}
PB-FFP	3.45	4.08^{abc}	3.81^{de}	3.75	4.48	4.25	0.636^{ab}	0.754	0.949^{ab}
PB- Ad-hoc	4.20	5.24^{a}	5.01^{ab}	3.90	5.76	5.45	0.630^{ab}	0.900	0.902^{abc}
PB-SSNM	4.59	4.71^{ab}	5.40^{a}	4.32	6.21	5.44	0.634^{ab}	0.925	0.993^{ab}
ZT- Unfertilized	2.79	2.58^{cd}	3.15^{ef}	3.26	2.61	2.78	0.656^{ab}	0.575	1.031^{ab}
ZT-FFP	3.78	3.82^{abc}	4.22^{bcd}	3.54	4.33	3.87	0.776^{a}	0.868	0.906^{abc}
ZT- Ad-hoc	4.22	3.96^{abc}	5.63^{a}	3.78	5.46	5.42	0.649^{ab}	0.921	1.022^{ab}
ZT-SSNM	4.81	4.60^{ab}	4.86^{abc}	3.87	5.65	5.62	0.783^{a}	0.933	1.070^{a}

CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, Ad-hoc: recommended dose of fertilizers, FFP=Farmer fertilizer practices; SSNM: Site specific nutrient management. *See Table 1 for nutrient doses in respective crop and treatment. Means followed by a similar superscript letter within a column are not significantly different (at $P \le 0.05$) between treatments of the same year according to least significant difference test.

Table 5
Above ground biomass yield of different crops in maize-wheat-mungbean system under different tillage and nutrient management practices.

Treatments	Biomass yield (Mg ha^{-1})								
	Maize			Wheat			Mungbean		
	2012	2013	2014	2012–13	2013–14	2014–15	2013	2014	2015
Tillage practices									
CT	14.69	12.46^{c}	11.78^{c}	8.27^{b}	10.04^{b}	9.62^{b}	3.07^{b}	3.19^{b}	3.69^{c}
PB	14.38	15.35^{a}	13.33^{b}	9.22^{a}	11.49^{a}	11.03^{a}	3.37^{a}	4.21^{a}	4.42^{b}
ZT	14.77	13.61^{b}	13.88^{a}	8.83^{ab}	10.83^{ab}	10.58^{ab}	3.59^{a}	4.28^{a}	4.89^{a}
Nutrient management practices*									
Unfertilized	10.94^{c}	10.90^{c}	10.34^{c}	8.13^{c}	6.72^{d}	7.70^{c}	2.82^{b}	2.97^{b}	4.04^{b}
FFP	14.09^{b}	13.20^{b}	12.72^{b}	8.55^{bc}	10.77^{c}	9.32^{b}	3.56^{a}	4.02^{a}	4.33^{a}
Ad-hoc	16.25^{a}	15.03^{a}	14.41^{a}	8.95^{ab}	12.45^{b}	12.02^{a}	3.48^{a}	4.18^{a}	4.39^{a}
SSNM	17.17^{a}	16.09^{a}	14.51^{a}	9.45^{a}	13.21^{a}	12.59^{a}	3.51^{a}	4.41^{a}	4.58^{a}
Tillage x Nutrient management									
CT-Unfertilized	9.57^{c}	8.56^{d}	9.43^{e}	8.07	5.72	6.92^{d}	2.34^{e}	2.35	3.62^{de}
CT-FFP	13.75^{abc}	11.56^{bcd}	11.38^{d}	7.83	10.30	8.70^{c}	2.82^{de}	3.54	3.26^{e}
CT-Ad-hoc	16.42^{ab}	13.47^{abc}	12.27^{d}	8.36	11.71	10.79^{b}	3.90^{ab}	3.15	3.92^{d}
CT-SSNM	19.03^{a}	16.24^{a}	14.06^{bc}	8.79	12.43	12.06^{a}	3.21^{cd}	3.72	3.95^{d}
PB- Unfertilized	12.34^{bc}	13.98^{abc}	9.96^{e}	8.23	7.76	9.21^{c}	2.77^{de}	3.45	3.94^{d}
PB-FFP	12.07^{bc}	13.88^{abc}	13.45^{c}	9.12	11.14	9.91^{bc}	3.79^{abc}	3.97	4.46^{c}
PB- Ad-hoc	16.40^{ab}	16.71^{a}	14.79^{b}	9.28	12.97	12.48^{a}	3.61^{abc}	4.70	4.82^{bc}
PB-SSNM	16.71^{ab}	16.82^{a}	15.13^{b}	10.24	14.09	12.54^{a}	3.31^{bcd}	4.73	4.47^{c}
ZT- Unfertilized	10.91^{bc}	10.16^{cd}	11.64^{d}	8.08	6.68	6.98^{d}	3.36^{bcd}	3.09	4.54^{c}
ZT-FFP	16.45^{ab}	14.15^{abc}	13.34^{c}	8.70	10.87	9.37^{c}	4.08^{a}	4.56	5.26^{ab}
ZT- Ad-hoc	15.92^{ab}	14.91^{ab}	16.17^{a}	9.21	12.66	12.79^{a}	2.91^{de}	4.69	4.44^{c}
ZT-SSNM	15.79^{ab}	15.21^{ab}	14.35^{bc}	9.33	13.11	13.18^{a}	4.01^{a}	4.78	5.33^{a}

CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, Ad-hoc: recommended dose of fertilizers, FFP=Farmer fertilizer practices; SSNM: Site specific nutrient management. *See Table 1 for nutrient doses in respective crop and treatment. Means followed by a similar superscript letter within a column are not significantly different (at $P \le 0.05$) between treatments of the same year according to least significant difference test.

3.3.3. *Mungbean*

Across three years, both tillage and nutrient management practices had significant ($P \le 0.05$) effect on summer mungbean seed and biomass yields. The seed and biomass yields were 26.5–34.6 and 16.9–34.2% higher in ZT compared to CT sowing (Tables 4 and 5), respectively, however the PB and ZT treatments were similar in 2014 and 2015.Our results of higher summer mungbean yield under ZT are in consistent with earlier studies (Parihar et al., 2016a,2016b), might be due to compound effects of improved soil health (Blanco-Canqui and Lal, 2009; Kaschuk et al., 2010; Parihar et al., 2016a; Singh et al., 2016) and better water availability (Govaerts et al., 2009). Similar to tillage effects, the residual effects of nutrient management in previous crops (maize and wheat) also significantly ($P \le 0.05$) affected the seed and biomass yields of summer mungbean. The seed and biomass yields in residual effects of SSNM treatment was 7.7–28.3% and 5.7–48.5% higher compared to FFP and unfertilized, respectively during all the three years of study, however, FFP was at par with SSNM in 2013. The tillage and residual nutrient management interaction effects were found significant in 1st (2013) and 3rd (2015) years of study on seed and biomass yields of summer mungbean (Tables 4 and 5). In both the years (2013 and 2015), ZT-SSNM treatment registered the significantly higher seed (0.78 and 1.07 Mg ha^{-1}) and biomass (4.01 and 5.33 Mg ha^{-1}) yields of summer mungbean compared to CT-FFP and CT-unfertilized treatments, while CT-unfertilized treatment resulted the lowest seed and biomass yields in both the years.

3.3.4. Cropping system yields

Tillage practices had significant ($P \leq 0.05$) effect on MWMb system grain and biological (pooled yields of all the three crops) yields, except in 1st year (2012–13) (Fig. 2). In 2nd year (2013–14), the MWMb system grain and biological yields were significantly higher in PB compared to ZT and CT planting. Thereafter, MWMb system grain and biological yields were significantly higher (18.9–20.1% and 12.9–14.1%, respectively) in PB and ZT compared to CT (Fig. 2). The results of our three-year study clearly showed the positive effects of ZT and PB, and residue retention on grain and biomass yields of MWMb system. In the MWMb system, yield of all the crops (maize, wheat and mungbean) increased over time through adoption of improved tillage practices. Use of crop residues as surface mulch control weeds, moderate soil temperature, reduce evaporation, and improve biological activity (Jat et al., 2009; Gathala et al., 2011; Parihar et al., 2016a). De Vita et al. (2007) reported 20% greater soil water content under no-till than conventional tillage due to reduced water evaporation during the preceding period. The enhanced water content in soil profile with improved soil health (Parihar et al., 2016a) might resulted in higher crop productivity in ZT and PB over CT. Our results are consistent with earlier studies from South Asia which showed higher crop yields under ZT compared to CT in rice-wheat and maize-wheat systems (Jat et al., 2013; Gathala et al., 2013; Singh et al., 2015). Similar to tillage effects, the effect of nutrient management on MWMb system grain and biomass yields were significant ($P \leq 0.05$) for all the three years (Fig. 3). The system grain and biomass yields in SSNM treatments (11.7–14.3 Mg ha^{-1} and 35.8–42.2 Mg ha^{-1}, respectively) were significantly higher compared to other nutrient management treatments, however system grain yield in 2014–15 and biomass yield in 2012–13 were similar in SSNM and Ad-hoc treatments. The system grain and biomass yields were lowest under unfertilized plots (7.6–9.3 Mg ha^{-1} and 25.4–30.2 Mg ha^{-1}, respectively). Singh et al. (2015) also reported 29% higher system 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. The tillage and nutrient management treatments had non-significant ($P \leq 0.05$) interaction effect on system grain and biomass yields of MWMb rotation during all the three study years (data not presented).

3.4. Water-use efficiency (WUE)

In all the three years of study, the amount of water-use and ET for all the three crops of MWMb cropping system was significantly ($P \leq 0.05$) affected by different tillage practices (Tables 2 and 3). ET of maize, wheat, mungbean and MWMb system was higher by 5.4–14.5%, 11.1–18.8%, 8.5–15.2% and 8.5–16.1% in CT compared to PB and ZT, respectively. However, in all the three years of experimentation the amount of applied input water (irrigation + effective rainfall) was significantly lower for maize (5.1–9.5% in ZT and 7.6–14.2%) in PB), for wheat (10.5–11.9% in ZT and 15.8–17.7% in PB), and for mungbean (7.9–10.7% in ZT and 11.9–16.1% in PB) compared to CT (Table 3). Among different nutrient management treatments in MWMb system, amount of applied irrigation water was same in particular season and year of study and varied between years (793–1133 mm ha^{-1}). Application of water for crop production was lowest in PB plots due to lower supply requirement of irrigation water in furrows and higher infiltration opportunity time in flood irrigation system (Aquino, 1998; Aggarwal and Goswami, 2003; Jat et al., 2013; Das et al., 2014). WUE was significantly higher with PB plots of maize (1.75–1.97 kg ha^{-1} m^{-3}) in 2013 and 2014, wheat (1.64–2.05 kg ha^{-1} m^{-3}), mungbean (0.84–1.58 kg ha^{-1} m^{-3}) and MWMb system (1.89–2.39 kg ha^{-1} m^{-3}) in all the three years of study (Table 6 and Fig. 4) compared to ZT and CT, however WUE of maize in 2014, mungbean in all the years and MWMb system in 2012–13 was similar in PB and ZT plots. The retention of residue at the soil surface in ZT system helped in reducing evaporation losses and hence conserving soil moisture. Conserved soil moisture in the seed–zone not only provided better crop establishment and crop growth but also increased water-use efficiency. Further, this increased moisture in seed-zone was led to crop yield enhancement with lesser water consumption under conservation agriculture based ZT and PB practices compared to CT. The higher water-use efficiency under CA-based management practices compared to CT in the same ecology has been reported by other researchers (Jat et al., 2013; Das et al., 2014). The higher yield advantage in CA-based crop management practices supports the concept of better soil moisture environment (Govaerts et al., 2007a; Thierfelder and Wall, 2010). Similar to tillage effects, the nutrient management also significantly ($P \leq 0.05$) affected the WUE of maize, wheat, mungbean and MWMb system in all the 3-years of study (Table 6 and Fig. 5). Significant ($P \leq 0.05$) increase in WUE was recorded under SSNM and Ad-hoc nutrient management for maize (12.7–53.2%), wheat (8.6–91.1%), mungbean (7.9–43.0%), and MWMb system (7.6–59.9%), compared to FFP and unfertilized treatments in all the three study years, however, WUE of wheat in 2012-13 was same with FFP and Ad-hoc and in mungbean similar WUE was observed in SSNM, Ad-hoc and FFP nutrient management during all the years.

Among the different nutrient management practices, unfertilized treatment registered the lowest WUE during the entire study period. However, SSNM and Ad-hoc nutrient management treatments were statistically at par with respect to WUE. Results of the present study showed significant ($P \leq 0.05$) improvement in WUE in SSNM and Ad-hoc nutrient management treatments, that were ascribed to higher yields compared to other treatments. The balanced nutrition under SSNM and Ad-hoc nutrient prescription compared to unfertilized and imbalanced FFP and greater return of leftover surface plant residues attributed to better crop growth with concomitant higher root biomass production and higher WUE (Christensen, 1988). Adequate and balanced nutrient supply has shown to improve WUE in several crops (Corak et al., 1991; Campbell et al., 1992; Varvel, 1994; Correndo Boxler and Garcia, 2012; Parihar et al., 2016a,2016b). There was a significant interaction between tillage and nutrient management treatments with respect to WUE of individual crops (maize, wheat, and mungbean) in all the three years of study, except in wheat during 1st and 2nd years and in mungbean in 2nd year (Table 6).

3.5. Incident radiation conversion efficiency (IRCE)

A total of incident solar radiation conversion efficiency of maize (0.644-0.811 g MJ^{-1}), wheat (0.407–0.558 g MJ^{-1}) and mungbean (0.256–0.359 g MJ^{-1}) was recorded for total biomass production in PB/ZT practices during all the three years of study (Table 7). ZT and PB plots showed 9.3–23.3%, 6.8–14.7%, and 9.9–34.4% higher IRCE compared to CT in maize, wheat and mungbean crops, respectively. Tillage had significant ($P \leq 0.05$) effect on biomass yield of maize,

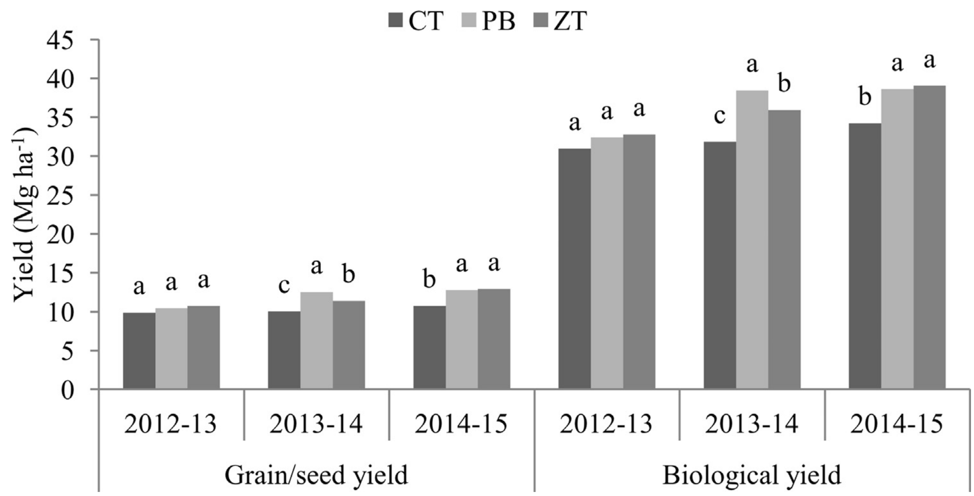

Fig. 2. Yearly grain and biological yields of maize-wheat-mungbean system under different tillage practices. Bars followed by a similar letter within a column are not-significantly different (at P ≤0.05) according to least significant difference test. CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage.

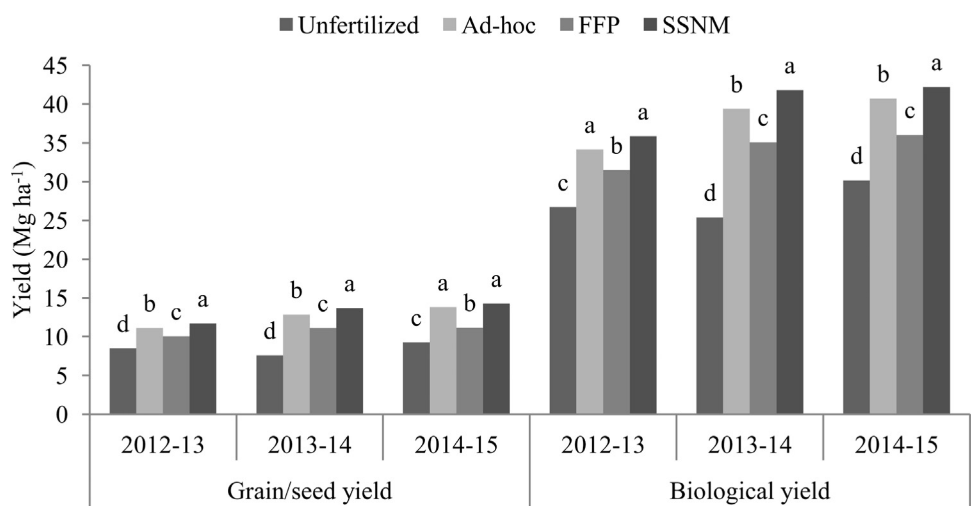

Fig. 3. Yearly grain and biological yields of maize-wheat-mungbean system under different nutrient management practices. Bars followed by a similar letter within a column are not-significantly different (at P ≤0.05) according to least significant difference test. Ad-hoc: recommended dose of fertilizers, FFP: Farmer fertilizer practices; SSNM: Site specific nutrient management.

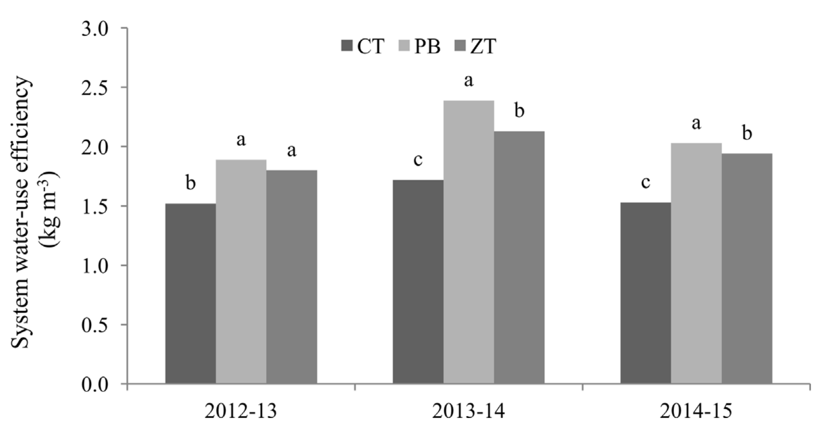

Fig. 4. Water-use efficiency of maize-wheat-mungbean system under different tillage practices. Bars followed by a similar letter within a column are not-significantly different (at P ≤0.05) according to least significant difference test. CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage.

wheat and mungbean crops (Table 5), which might have resulted in significant differences of IRCE. Among all the tillage practices the water availability is the most important factor influencing the IRCE (Sinclair and Muchow, 1999). This statement is further supported by to results of higher IRCE under untilled soil due to higher water availability (Bergamaschi et al., 2010) compared to CT. Further, under ZT/PB the higher values of leaf area index also resulted in increased RUE (Bergamaschi et al., 2010) compared to CT. The

Table 6
Water-use efficiency of different crops in maize-wheat-mungbean system under different tillage and nutrient management practices.

Treatments	Water-use efficiency (kg ha^{-1} m^{-3})								
	Maize			Wheat			Mungbean		
	2012	2013	2014	2012–13	2013–14	2014–15	2012	2013	2014
Tillage *practices*									
CT	1.69	1.47^{c}	1.32^{b}	1.19^{c}	1.46^{c}	1.26^{c}	0.65^{b}	1.03^{b}	0.64^{b}
PB	1.94	1.97^{a}	1.75^{a}	1.64^{a}	2.05^{a}	1.73^{a}	0.84^{a}	1.58^{a}	0.87^{a}
ZT	1.88	1.69^{b}	1.72^{a}	1.46^{b}	1.79^{b}	1.56^{b}	0.84^{a}	1.52^{a}	0.92^{a}
Nutrient management practices*									
Unfertilized	1.39^{c}	1.37^{c}	1.28^{c}	1.34^{c}	1.12^{c}	1.14^{c}	0.66^{b}	1.07^{b}	0.76^{b}
FFP	1.77^{b}	1.64^{b}	1.57^{b}	1.40^{bc}	1.77^{b}	1.36^{b}	0.83^{a}	1.44^{a}	0.82^{a}
Ad-hoc	2.04^{a}	1.86^{a}	1.77^{a}	1.46^{ab}	2.03^{a}	1.75^{a}	0.79^{a}	1.47^{a}	0.82^{a}
SSNM	2.13^{a}	1.97^{a}	1.77^{a}	1.52^{a}	2.14^{a}	1.81^{a}	0.80^{a}	1.53^{a}	0.85^{a}
Tillage x Nutrient management									
CT-Unfertilized	1.11^{e}	1.02^{f}	1.07^{c}	1.18	0.84	0.91^{d}	0.50^{g}	0.78	0.63^{de}
CT-FFP	1.59^{cd}	1.37^{de}	1.28^{f}	1.14	1.50	1.14^{c}	0.60^{fg}	1.16	0.57^{e}
CT-Ad-hoc	1.88^{abc}	1.58^{cd}	1.37^{ef}	1.21	1.70	1.42^{b}	0.82^{abc}	1.01	0.68^{d}
CT-SSNM	2.18^{a}	1.90^{ab}	1.57^{cd}	1.24	1.79	1.57^{b}	0.66^{ef}	1.18	0.67^{d}
PB- Unfertilized	1.67^{bcd}	1.80^{bc}	1.31^{f}	1.47	1.39	1.46^{b}	0.70^{cdef}	1.31	0.79^{c}
PB-FFP	1.63^{bcd}	1.79^{bc}	1.77^{b}	1.63	2.00	1.56^{b}	0.94^{ab}	1.51	0.88^{bc}
PB- Ad-hoc	2.21^{a}	2.15^{a}	1.95^{a}	1.65	2.32	1.95^{a}	0.89^{ab}	1.78	0.95^{ab}
PB-SSNM	2.23^{a}	2.14^{a}	1.97^{a}	1.80	2.48	1.95^{a}	0.81^{bcd}	1.73	0.87^{bc}
ZT- Unfertilized	1.40^{de}	1.28^{e}	1.46^{de}	1.35	1.12	1.04^{cd}	0.80^{bcde}	1.14	0.87^{bc}
ZT-FFP	2.10^{a}	1.77^{bc}	1.66^{bc}	1.45	1.81	1.39^{b}	0.96^{a}	1.64	1.00^{a}
ZT- Ad-hoc	2.02^{ab}	1.85^{bc}	2.00^{a}	1.51	2.08	1.87^{a}	0.67^{def}	1.63	0.83^{c}
ZT-SSNM	1.99^{abc}	1.88^{ab}	1.77^{b}	1.53	2.15	1.92^{a}	0.92^{ab}	1.66	1.00^{a}

CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, Ad-hoc: recommended dose of fertilizers, FFP=Farmer fertilizer practices; SSNM: Site specific nutrient management. *See Table 1 for nutrient doses in respective crop and treatment. Means followed by a similar superscript letter within a column are not significantly different (at $P \leq 0.05$) between treatments of the same year according to least significant difference test.

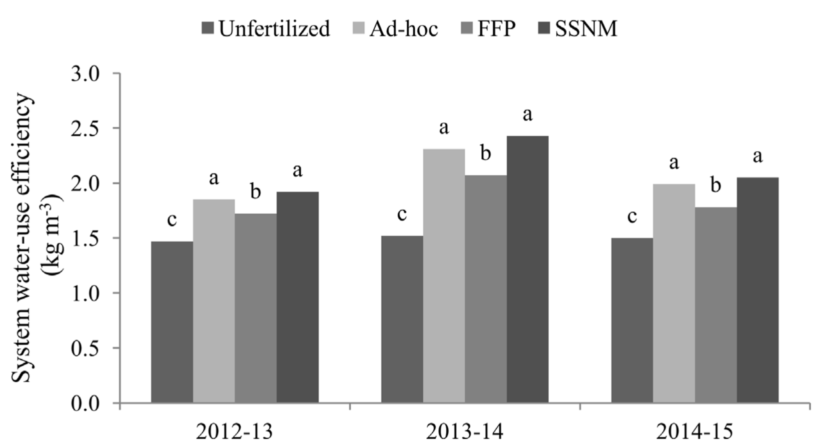

Fig. 5. Water-use efficiency of maize-wheat-mungbean system under different nutrient management practices. Bars followed by a similar letter within a column are not-significantly different (at $P \leq 0.05$) according to least significant difference test. Ad-hoc: recommended dose of fertilizers, FFP: Farmer fertilizer practices; SSNM: Site specific nutrient management.

higher incident radiation conversion efficiency in CA-based management practices (ZT and PB) were also reported elsewhere by other researchers (Fahong et al., 2004; Dalmago et al., 2009).

The effect of nutrient management practices on IRCE in maize, wheat and mungbean were significant ($P \leq 0.05$) and the SSNM and Ad-hoc based nutrient application proved superior over other practices, however in mungbean SSNM, Ad-hoc and FFP were at par to each other (Table 7). Significant ($P \leq 0.05$) increase in IRCE was recorded under SSNM and Ad-hoc nutrient management treatments for maize (13.4–57.1%), wheat (10.1–96.6%) and in SSNM, Ad-hoc and FFP for mungbean (7.4–48.5%) during all the three study years. The leaf N concentration is the most important factor for affecting IRCE along with leaf area index (Sinclair and Muchow, 1999). The improved nutrient management particularly the nitrogen management in SSNM and Ad-hoc treatments compared to FFP and unfertilized might result in higher leaf N concentration and LAI and thus gave higher IRCE. The IRCE was significantly and positively correlated with the LAI of the maize (at 30 DAS $r = 0.79^{**}$, $r = 0.82^{**}$, $r = 0.93^{***}$; at 60 DAS $r = 0.78^{**}$, $r = 0.80^{**}$, $r = 0.93^{***}$ and at 90 DAS $r = 0.84^{***}$, $r = 0.85^{***}$, $r = 0.90^{***}$ for the year 2012, 2013 and 2014, respectively, supplementary Fig. 1), wheat (at 30 DAS $r = 0.92^{***}$, $r = 0.93^{***}$, $r = 0.79^{**}$; at 60 DAS $r = 0.88^{***}$, $r = 0.91^{***}$, $r = 0.96^{***}$ and at 90 DAS $r = 0.83^{***}$, $r = 0.74^{**}$, $r = 0.94^{***}$ for the year 2012–13, 2013–14 and 2014–15, respectively, supplementary Fig. 2) and mungbean (at 15 DAS $r = 0.62^{*}$, $r = 0.78^{**}$, $r = 0.71^{**}$; at 30 DAS $r = 0.43$, $r = 0.84^{***}$, $r = 0.76^{***}$ and at 45 DAS $r = 0.47$, $r = 0.90^{***}$, $r = 0.60^{*}$ for the year 2013, 2014 and 2015, respectively, supplementary Fig. 3). This relation between LAI and IRCE in maize, wheat and mungbean showed that 43–96% variations in IRCE can be explained by leaf area index of respective crop. Further, the *rainy* season maize grain yield was significantly and positively correlated with IRCE ($r = 0.72^{***}$, $r = 0.90^{***}$ and $r = 0.89^{***}$ for the year 2012, 2013 and

Table 7
Incident radiation conversion efficiency of different crops in maize-wheat-mungbean system under different tillage and nutrient management practices.

Treatments	Incident radiation conversion efficiency (g MJ^{-1})								
	Maize			Wheat			Mungbean		
	2012	2013	2014	2012–13	2013–14	2014–15	2013	2014	2015
Tillage practices									
CT	0.791	0.658^{c}	0.569^{c}	0.381^{b}	0.488^{b}	0.442^{b}	0.233^{b}	0.221^{b}	0.271^{c}
PB	0.774	0.811^{a}	0.644^{b}	0.425^{a}	0.558^{a}	0.507^{a}	0.256^{a}	0.292^{a}	0.325^{b}
ZT	0.795	0.719^{b}	0.670^{a}	0.407^{ab}	0.526^{ab}	0.486^{ab}	0.273^{a}	0.297^{a}	0.359^{a}
Nutrient management practices*									
Unfertilized	0.589^{c}	0.576^{c}	0.499^{c}	0.375^{c}	0.326^{d}	0.354^{c}	0.215^{b}	0.206^{b}	0.296^{b}
FFP	0.759^{b}	0.697^{b}	0.614^{b}	0.395^{bc}	0.523^{c}	0.428^{b}	0.271^{a}	0.279^{a}	0.318^{a}
Ad-hoc	0.875^{a}	0.794^{a}	0.696^{a}	0.413^{ab}	0.604^{b}	0.552^{a}	0.264^{a}	0.290^{a}	0.323^{a}
SSNM	0.925^{a}	0.850^{a}	0.701^{a}	0.436^{a}	0.641^{a}	0.578^{a}	0.267^{a}	0.306^{a}	0.336^{a}
Tillage x Nutrient management									
CT-Unfertilized	0.515^{d}	0.452^{f}	0.455^{e}	0.372	0.278	0.318^{e}	0.178^{e}	0.163	0.266^{de}
CT-FFP	0.741^{bc}	0.611^{de}	0.550^{d}	0.361	0.500	0.399^{d}	0.214^{de}	0.246	0.239^{e}
CT-Ad-hoc	0.884^{ab}	0.711^{cd}	0.592^{d}	0.386	0.569	0.495^{b}	0.297^{ab}	0.219	0.288^{d}
CT-SSNM	1.025^{a}	0.858^{ab}	0.679^{bc}	0.406	0.604	0.554^{a}	0.244^{cd}	0.258	0.290^{d}
PB- Unfertilized	0.665^{cd}	0.739^{bc}	0.481^{e}	0.380	0.377	0.423^{cd}	0.210^{de}	0.239	0.290^{d}
PB-FFP	0.650^{cd}	0.733^{c}	0.650^{c}	0.421	0.541	0.455^{bc}	0.288^{abc}	0.275	0.327^{c}
PB- Ad-hoc	0.883^{ab}	0.883^{a}	0.714^{b}	0.428	0.630	0.573^{a}	0.275^{abc}	0.326	0.354b^{c}
PB-SSNM	0.900^{ab}	0.889^{a}	0.730^{b}	0.472	0.684	0.576^{a}	0.252^{bcd}	0.328	0.328^{c}
ZT- Unfertilized	0.587^{cd}	0.537^{ef}	0.562^{d}	0.373	0.325	0.321^{e}	0.255^{bcd}	0.215	0.334^{c}
ZT-FFP	0.886^{ab}	0.748^{bc}	0.644^{c}	0.402	0.528	0.430^{cd}	0.311^{a}	0.316	0.386^{ab}
ZT- Ad-hoc	0.857^{ab}	0.788^{abc}	0.781^{a}	0.425	0.615	0.587^{a}	0.221^{de}	0.325	0.326^{c}
ZT-SSNM	0.850^{ab}	0.803^{abc}	0.693^{bc}	0.431	0.636	0.605^{a}	0.305^{a}	0.331	0.391^{a}

CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, Ad-hoc: recommended dose of fertilizers, FFP=Farmer fertilizer practices; SSNM: Site specific nutrient management. *See Table 1 for nutrient doses in respective crop and treatment. Means followed by a similar superscript letter within a column are not significantly different (at $P \leq 0.05$) between treatments of the same year according to least significant difference test.

Table 8
Correlation matrix (n=36) of different crops grain/seed yield and incident radiation conversion efficiency.

Parameters	IRCE-2012	IRCE-2013	IRCE-2014	IRCE-2015
MGY-2012	0.720***	0.630***	0.705***	–
MGY-2013	0.586***	0.902***	0.621***	–
MGY-2014	0.560***	0.686***	0.890***	–
WGY-2012-13	–	0.968***	0.664***	0.654***
WGY-2013-14	–	0.601***	0.991***	0.883***
WGY-2014-15	–	0.624***	0.868***	0.989***
MuSY-2013	–	0.841***	0.431**	0.646***
MuSY-2014	–	0.470**	0.938***	0.650***
MuSY-2015	–	0.406*	0.599***	0.647***

*, ** and *** indicates significant at $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$ level of significance, respectively. MGY: maize grain yield; WGY: wheat grain yield, MuSY: mungbean seed yield, IRCE: incident radiation conversion efficiency.

2014, respectively, Table 8). Similarly, the wheat and mungbean grain/seed yield was also significantly and positively correlated with IRCE (in wheat $r=0.97^{***}$, $r=0.99^{***}$ and $r=0.99^{***}$ for the year 2012–13, 2013–14 and 2014–15, Table 8) and (in mungbean $r=0.84^{***}$, $r=0.94^{***}$ and $r=0.65^{***}$ for the year 2013, 2014 and 2015, respectively, Table 8). The relationship of the maize grain, wheat grain and mungbean seed yields with IRCE showed that about 52–81% variations in maize grain yield, 94–98% variations in wheat grain yield and about 42–88% variations in mungbean seed yield can be explained by biomass IRCE as evident from (Eq. (6)–(8) Eq. (9)–(11) and Eq. (12)–(14), respectively):

$$\text{Maize grain yield (Mg ha}^{-1}) = 3.371\text{IRCE} + 1.183;\ R^2 = 0.518(2012) \tag{6}$$

$$\text{Maize grain yield (Mg ha}^{-1}) = 5.879\text{IRCE} - 0.400;\ R^2 = 0.813(2013) \tag{7}$$

$$\text{Maize grain yield (Mg ha}^{-1}) = 9.105\text{IRCE} - 1.648;\ R^2 = 0.792(2014) \tag{8}$$

$$\text{Wheat grain yield (Mg ha}^{-1}) = 10.08\text{IRCE} - 0.472;\ R^2 = 0.936(2012\text{–}13) \tag{9}$$

$$\text{Wheat grain yield (Mg ha}^{-1}) = 10.09\text{IRCE} - 0.756;\ R^2 = 0.981(2013\text{–}14) \tag{10}$$

$$\text{Wheat grain yield (Mg ha}^{-1}) = 10.11\text{IRCE} - 0.413;\ R^2 = 0.977(2014\text{–}15) \tag{11}$$

$$\text{Mungbean seed yield (Mg ha}^{-1}) = 2.267\text{IRCE} + 0.054;\ R^2 = 0.707(2013) \tag{12}$$

$$\text{Mungbean seed yield (Mg ha}^{-1}) = 2.624\text{IRCE} + 0.043;\ R^2 = 0.880(2014) \tag{13}$$

$$\text{Mungbean seed yield (Mg ha}^{-1}) = 2.131\text{IRCE} + 0.226;\ R^2 = 0.418(2015) \tag{14}$$

These findings are in agreement with Pradhan et al. (2014); Jha et al. (2012); Kar and Chakravarthy (2001) for mustard, Saha et al. (2012) for pigeonpea and Singer et al. (2011) for soybean and maize. This indicates more total incoming solar radiation is the main force behind the higher crop biomass (Monteith, 1981; Latiri-Souki et al., 1998; Fahong et al., 2004).

The tillage and nutrient management had significant ($P \leq 0.05$) interaction effect on IRCE of maize (during all the three years), wheat (in 2014–15) and mungbean (during 1st and 3rd years). However, the tillage and nutrient management interaction effect on IRCE was not observed in wheat (during 2012–13 and 2013–14) and mungbean (in 2014). The highest IRCE of maize was found in CT–SSNM (1.03), PB–SSNM (0.889) and ZT–Ad-hoc (0.781) treatments in 2012, 2013 and 2014, respectively. Consequently, CT-SSNM, ZT-SSNM, ZT-Ad-hoc and PB-SSNM, PB-Ad-hoc plots registered maximum IRCE of wheat (Table 7). However, IRCE of mungbean was higher in ZT-SSNM, ZT-FFP treatments. In general, we found IRCE followed the pattern of maize followed by wheat and mungbean. The higher IRCE in C_4 (maize) compared to C_3 (wheat and mungbean) plants have been reported by many workers (Sinclair and Muchow, 1999 and references therein). The high energy constituent of both vegetative tissues and seed in mungbean compared to wheat resulted in lower RUE.

4. Conclusions

Our study demonstrated that CA-based (ZT and PB) management practices and Nutrient Expert® decision support tool guided SSNM/Ad-hoc based nutrient application have complementing interactions and thus led to significant improvement in crop productivity, water-use and incident radiation conversion efficiency of MWMb cropping system. CA-based (ZT and PB) management practices resulted in significant improvement in maize, wheat and mungbean yields (3.5–34.6%), water-use efficiency (11.2–53.4%), incident radiation conversion efficiency (6.8–34.4%,), and MWMb system irrigation water saving (18.2–30%) over CT practices. Among the nutrient management options, Nutrient Expert® based SSNM and Ad-hoc had a much larger effect on crop productivity, water-use and incident radiation conversion efficiency compared to other practices. The layering of CA-based management practices with precision nutrient prescriptions using SSNM based decision support tools and/or Ad-hoc offers a new management paradigm for scaling up of the maize-wheat system in north-west IGP and can potentially help in diversifying RW system to address emerging challenges of water scarcity and system sustainability.

Acknowledgements

We sincerely acknowledge Indian Council of Agricultural Research for financial support and ICAR-IIMR and field staff for providing facilities and assistance in conducting this research. The support provided by International Plant Nutrition Institute (IPNI) and also through International Maize and Wheat Improvement Center (CIMMYT), as part of the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), which is carried out with support from CGIAR Fund Donors and through bilateral funding agreements. The views expressed in this document cannot be taken to reflect the official opinions of these organizations. Finally the special thanks to Mr. Sanjeev Kumar for assistance in data management and analysis work.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agwat.2017.07.021.

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