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# Long-Term Conservation Agriculture and Intensified Cropping Systems: Effects on Growth, Yield, Water, and Energy-use Efficiency of Maize in Northwestern India

Chiter M. PARIHAR[1], Malu R. YADAV[2], Shankar L. JAT[1,*], Aditya K. SINGH[1], Bhupender KUMAR[1], Vijay POONIYA[2], Sanatan PRADHAN[2], Rakesh K. VERMA[2], Mangi L. JAT[3], Raj K. JAT[4], Muli D. PARIHAR[5], Hari S. NAYAK[2] and Yashpal S. SAHARAWAT[6]

[1] *Indian Council of Agricultural Research-Indian Institute of Maize Research, New Delhi 110012 (India)*
[2] *Indian Council of Agricultural Research-Indian Agricultural Research Institute, New Delhi 110012 (India)*
[3] *International Maize and Wheat Improvement Center, New Delhi 110012 (India)*
[4] *Borlaug Institute for South Asia, Samastipur 848125 (India)*
[5] *Chaudhary Charan Singh Haryana Agricultural University, Hisar 125004 (India)*
[6] *International Center for Agricultural Research in the Dry Areas, Kabul 11082010 (Afghanistan)*

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## ABSTRACT

Conservation agriculture (CA)-based best-bet crop management practices may increase crop and water productivity, while conserving and sustaining natural resources. We evaluated the performance of rainy season maize during 2014 under an ongoing long-term trial (established in 2008) with three tillage practices, *i.e.*, permanent bed (PB), zero tillage (ZT), and conventional tillage (CT) as main plots, and four intensified maize-based cropping systems, *i.e.*, maize-wheat-mungbean, maize-chickpea-*Sesbania* (MCS), maize-mustard-mungbean, and maize-maize-*Sesbania*) as subplot treatments. In the seventh rainy season of the experiment, maize growth parameters, yield attributes, yield, and water- and energy-use efficiency were highest at fixed plots under ZT. Maize growth parameters were significantly ($P < 0.05$) superior under ZT and PB compared with CT. Maize yield attributes, including cobs per m$^2$ (7.8), cob length (0.183 m), grain rows per cob (13.8), and grains per row (35.6), were significantly higher under ZT than CT; however, no significant effect of cropping systems was found on maize growth and yield attributes. Zero tillage exhibited the highest maize productivity (4 589 kg ha$^{-1}$). However, among the cropping systems, MCS exhibited the highest maize productivity (4 582 kg ha$^{-1}$). In maize, water use was reduced by 80.2–120.9 mm ha$^{-1}$ under ZT and PB compared with CT, which ultimately enhanced the economic water-use efficiency by 42.0% and 36.6%, respectively. The ZT and PB showed a 3.5%–31.8% increase in soil organic carbon (SOC) at different soil depths (0–0.45 m), and a 32.3%–39.9% increase in energy productivity compared with CT. Overall, our results showed that CA-based ZT and PB practices coupled with diversified maize-based cropping systems effectively enhanced maize yield and SOC, as well as water- and energy-use efficiency, in northwestern India.

*Key Words*: conventional tillage, economic water-use efficiency, permanent bed, rainy season, soil organic carbon, zero tillage

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## INTRODUCTION

The intensive cereal-based systems of northwestern India with intensive conventional tillage (CT) have posed serious challenges for the future food security of the country. Although the rice-wheat (RW) cropping system of the region has significant contribution to the food stock of the country, over exploitation of ground water has declined the depth of water table (Hobbs and Gupta, 2000; Sharma *et al.*, 2012) and led to stagnant yield levels. These adverse factors of crop production are augmented by conventional crop management practices, resulting in higher production costs and inefficient use of inputs. Adoption of alternate tillage practices in RW system may be an option for improving the sustainability of existing cropping systems, while the diversification of rice with maize is an another efficient and environment friendly alternative in existing RW cropping system (Aulakh and Grant, 2008). Such an approach has been advocated by the government agencies. Variability induced by recent climate change has been advantageous to maize due to its lower water requirement compared with rice; therefore, this may be a better alternative to rainy season rice in

*Corresponding author. E-mail: sliari@gmail.com.

this region to enhance crop and system productivity, and to sustain soil health and environmental quality (Meelu *et al.*, 1979).

Previously, maize with conventional management practices has been used as an alternate crop to rice in RW system, but it was not successful due to economic competition with rice. However, in recent years, the introduction of single cross hybrid (SCH) technology and the development of high-yielding maize hybrids with different crop duration (early, medium, and late) have provided genotypic options for crop diversification. However, these hybrids alone could not attract the attention of growers under traditional crop management practices in northwestern India. Maize, an important crop for food and nutritional security in India, is grown in diverse ecologies and seasons in the country on an area of 8.67 Mha (GoI, 2015). Globally, it provides approximately 30% of food calories to more than 4.5 billion people in 94 developing countries, and the demand for maize is expected to double worldwide by 2050; therefore, there is a need for higher maize production (Srinivasan *et al.*, 2004). In the past decade (from 2003–2004 to 2012–2013), the area under maize production has expanded by 1.8%, production has increased by 4.9%, and productivity has raised by 2.6% year$^{-1}$ in India, mainly because of the increased maize demand (GoI, 2015).

In the present scenario, to explore the maximum yield potential of these new maize SCHs under the emergence of natural resources over exploitation, and to offset the production cost and environmental impacts, conservation agriculture (CA)-based crop production technologies are gaining the attention of the growers in this region (Ladha *et al.*, 2009; Jat *et al.*, 2009; Saharawat *et al.*, 2012). The CA-based crop management practices can effectively increase the growth and yield attributes of crops (Jat *et al.*, 2014), crop productivity (Jat *et al.*, 2013; Das *et al.*, 2014), and water-use efficiency (WUE) (Jat *et al.*, 2014: Parihar *et al.*, 2016a). Furthermore, the intensive traditional tillage practices lead to reduction in soil organic matter (SOM) due to the high levels of oxidation and breakdown of organic carbon (C), and ultimately degrading soil properties (Biamah *et al.*, 2000; Gathala *et al.*, 2011). Published experimental results across the globe have shown increased productivity and soil quality, mainly through SOM build-up (Ladha *et al.*, 2009; Bhattacharyya *et al.*, 2013) and higher soil organic C (SOC) content under zero tillage (ZT) compared with conventionally tilled soils (West and Post, 2002; Alvarez, 2005, Parihar *et al.*, 2016b).

Adoption of CA principles with best-bet crop management practices would be helpful for the expansion of maize (*Zea mays* L.) area in northwestern India. Therefore, to generate new information for the sustainable intensification of maize-based systems in northwestern India, a long-term study was initiated at Indian Council of Agricultural Research (ICAR)-Indian Institute of Maize Research (IIMR) farm, New Delhi to evaluate the impacts of tillage and crop establishment practices on the performance of intensified maize-based cropping systems. Here, we studied crop performance, yield, water productivity, and energy-use efficiency of the seventh rainy season maize crop planted in fixed plots under three different long-term tillage practices in combination with diversified maize-based cropping systems.

## MATERIALS AND METHODS

### *Study site*

A long-term field experiment was established in the rainy season of 2008 under a set of tillage and crop establishment practices in four diversified maize-based cropping systems at the research farm (28°40′ N, 77°12′ E; 228.6 m elevation) of the ICAR-IIMR, Pusa Campus, New Delhi, India. The climate of this area is semi-arid, with an average mean annual rainfall of 650 mm (70%–80% during July–September) and a mean annual evaporation of 850 mm. Daily metrological parameters during the cropping season were recorded at ICAR-Indian Agricultural Research Institute (IARI) Metrological Observatory adjacent to the experimental field. The mean minimum temperature, maximum temperature, and total rainfall during rainy season, 2014 (July–October) were 23.7 °C, 33.3 °C, and 451 mm, respectively. The soil of the experimental site (before rainy season, 2008) was sandy loam in texture (Typic Haplustept) with a pH of 7.8, 0.32 dS m$^{-1}$ electrical conductivity, 158.4 kg ha$^{-1}$ $KMnO_4$-oxidizable nitrogen (N) (Subbiah and Asija, 1956), 11.6 kg ha$^{-1}$ 0.5 mol L$^{-1}$ $NaHCO_3$-extractable phosphorus (P) (Olsen *et al.*, 1954), 248.4 kg ha$^{-1}$ 1 N $NH_4OAc$-extractable potassium (K) (Prasad, 1998), 1.6 mg kg$^{-1}$ diethylenetriaminepenta acetic acid-extractable zinc (Zn), 6.7 mg kg$^{-1}$ iron (Fe), and 1.3 mg kg$^{-1}$ copper (Cu). Depth-wise initial (prior to *rainy season*, 2008) SOC content was 4.40, 4.21, and 3.70 g kg$^{-1}$ soil at 0–0.15, 0.15–0.30, and 0.30–0.45 m, respectively.

### *Experimental design*

The experiment was conducted with three main-plot treatments, consisting of tillage and crop establishment practices (ZT, permanent bed (PB), and CT) and four intensified maize-based cropping systems (maize-wheat-mungbean (MWMb), maize-chickpea-*Sesbania* (MCS), maize-mustard-mungbean (MMuMb), and maize-maize-*Sesbania* (MMS)) in subplots. The experiment was designed in a split-plot arrangement with three replications at fixed location for all the study years. Each experimental unit consisted of 16.5 m $\times$ 4.0 m plots.

*Crop establishment*

The field was deep ploughed using a chisel plough to break the hard pan below the plough layer, and then laser-leveled before the start of the experiment (prior to rainy season, 2008). Planting involved ploughing with a disc harrow, followed by a spring-tine cultivator and rotavator. Under ZT, maize seeds were directly drilled in the soil using a ZT planter with inverted 'T' tines. In the first year (July 2008), fresh raised beds were developed using a bed/ridge former, which were re-shaped and maintained as PBs in subsequent years. Residues of every preceding crop were retained or incorporated as such in different plots. In the first year of the study (before the start of the experiment in rainy season, 2008), an equal quantity of mungbean and *Sesbania* residue (1.5 Mg ha$^{-1}$) was retained under ZT and PB and incorporated into CT. Similarly, during subsequent years, the total amount of residues was not retained, because maize, wheat, mustard, and mungbean residues were used by the farmers of this region for cattle feeding, fuel, *etc.* Furthermore, about 20%–40% of the maize stover, wheat straw, mustard stalk, and chickpea straw were retained in all the ZT and PB plots and was incorporated into the CT plots.

The quality protein maize hybrid HQPM-1 was sown during the first fortnight of July with a row spacing of 0.67 m in the ZT, PB, and CT plots and 0.25 m between plants in all the plots with a seed rate of 20 kg ha$^{-1}$. Maize was sown using a zero-till multi-crop bed planter under PB, a zero-till multi-crop planter under ZT, and a multi-crop planter under CT. The crop was harvested at the end of October during rainy season.

*Fertilizer and herbicide management*

The crop received a common dose of nutrients, amounting to 150 kg N, 60 kg $P_2O_5$, 40 kg $K_2O$, and 25 kg $ZnSO_4$ per hectare at the time of the establishment of this study in rainy season, 2008. One-third N and whole $P_2O_5$, $K_2O$, and $ZnSO_4$ were applied as basal fertilizer at sowing, while the remaining two-thirds N was top-dressed by broadcasting urea in two equal splits at five-fully opened leaf and tasseling growth phases. At the time of top dressing, fertilizer was broadcasted carefully to ensure that fertilizers were applied in the rows of the targeted plants only.

For optimal weed management, the herbicide glyphosate was sprayed at 1.0 kg active ingredient (a.i.) ha$^{-1}$ in all the ZT and PB plots approximately 2 d before sowing of the crop. However, in the case of the CT plots, atrazine was applied at 1.0 kg a.i. ha$^{-1}$ as a pre-emergent herbicide for weed control. In addition to chemical weed management, one-hand weeding was also performed in all the CT plots 30–40 d after sowing. Conversely, no weeding was performed in the ZT and PB plots, except for the uprooting of hardy perennial weeds.

*Measurement of crop growth parameters, yield attributes, and yields*

Growth parameters, including days to emergence, plant height (at 30-d interval), days to 50% silking, days to maturity, reproductive period, dry matter accumulation (DMA) (at 30-d interval), and leaf area (at 30-d interval), were recorded by closely following crop growth. The leaf area was estimated at 30-d interval by separating the leaves of five plants randomly selected from each plot using leaf area meter. The crop growth rate (CGR, g plant$^{-1}$ d$^{-1}$) at 30-d interval was calculated using the following formula:

$$\mathrm{CGR} = \frac{W_2 - W_1}{T_2 - T_1} \tag{1}$$

where $W_1$ and $W_2$ are the dry weights at the first and second stages, respectively (g), and $T_1$ and $T_2$ are days at the first and second stages, respectively.

At maturity, maize was harvested manually by cutting at 0.40 m height. The yield attributes were estimated as per the standard procedure by sampling from five random places in each plot. The cobs and stover of the maize crop were harvested manually from 10.72-m$^2$ area and threshed by a maize sheller to estimate the grain yield. The stover yield of maize was adjusted on an oven dry-weight basis and expressed in kg ha$^{-1}$. Grain moisture was determined by using a grain moisture meter, and grain yield was adjusted to that at 14% grain moisture.

*Plant nutrient analysis*

Nitrogen, P, and K contents (g kg$^{-1}$ grain) in grain were determined by the modified Kjeldahl method, vanadomolybdophosphoric acid yellow color method, and flame photometer method (Prasad *et al.*, 2006), respectively. Iron and Zn contents (mg kg$^{-1}$ grain) in grain were determined as described by Prasad *et al.*

(2006).

*Soil moisture storage, evapo transpiration (ET), and economic WUE*

Soil moisture content in the profile (0–1.20 m) was determined gravimetrically at regular intervals during rainy season, 2014 to study the distribution of soil water. Seasonal ET (mm) was computed using the field water balance equation as given below (Pradhan *et al.*, 2014):

$$\mathrm{ET} = (P + I + C) - (R + D + \Delta S) \tag{2}$$

where $P$ is the effective precipitation (mm), $I$ is irrigation (mm), $C$ is capillary rise (mm), $R$ is runoff (mm), $D$ is deep percolation (mm), and $\Delta S$ is the change in profile soil moisture storage (mm). As the groundwater table was very low (8–10 m depth), $C$ was assumed to be negligible. There was no runoff ($R$) from the field plots as they were bunded to a sufficient height (0.40 m), and also no case of bund overflow was observed during the study period. Studies on soil moisture were performed to a soil depth of 1.20 m, as the soil profile was sandy loam (Typic Haplustept) with loamy and clay loam layers having a high bulk density of 1.70–1.72 Mg $m^{-3}$ below 0.60 m. Deep percolation out of the 1.20 m profile ($D$) was assumed to be negligible (Pradhan *et al.*, 2014). Thus, Eq. 2 was simplified to:

$$\mathrm{ET} = (P + I) - \Delta S \tag{3}$$

Precipitation data were collected from the Meteorological Observatory of ICAR-IARI, New Delhi. The effective rainfall was calculated using the USDA method (Cropwat 8.0). Irrigation was applied through surface irrigation at critical growth stages of the maize crop, and a measured amount of water was supplied to each plot. Applied irrigation water was measured using a Parshall flume (3″) installed in the open channel under free flow condition. The $\Delta S$ values were calculated by soil moisture sampling using the gravimetric method. Economic WUE (US\$ $ha^{-1}$ $mm^{-1}$) was computed using net return (NR, Indian rupees (INR) $ha^{-1}$) and ET (mm) with the following formulae:

$$\text{Economic WUE} = \frac{\mathrm{NR}}{\mathrm{ET}} \tag{4}$$

$$\mathrm{NR} = \mathrm{GR} - \mathrm{TC} \tag{5}$$

where GR is the gross return, and TC is the total cost of cultivation.

*Soil organic C*

Soil organic C contents at different soil depths (0–0.15, 0.15–0.30, and 0.30–0.45 m) were determined using finely ground (250-μm sieved) soil with an Elementar® Vario total organic C dry combustion analyzer (Langenselbold, Germany) in triplicate samples.

*Energy calculation*

Primary data of various inputs and management practices for rainy season maize were collected to determine energy consumption and energy-use efficiency. The energy output from the economic and byproduct yield was also estimated. Output loss due to natural disasters and pests was negligible. Thus, the loss or waste was not included in the calculation. Net energy (MJ $ha^{-1}$) and energy productivity (EP, kg $MJ^{-1}$) were calculated using the following formulae as suggested by Mittal and Dhawan (1988) and Parihar *et al.* (2013):

$$\text{Net energy} = \text{energy output} - \text{energy input} \tag{6}$$

$$\mathrm{EP} = \frac{\text{Output (grain + by-product)}}{\text{Energy input}} \tag{7}$$

*Economic and production cost analysis*

Economic analysis was performed by considering the variable production costs only, which included human labor, use of machinery (*e.g.*, tractor, plough, planter, *etc.*), input cost (seed, fertilizer, and pesticide), irrigation, harvesting, and threshing. However, the production cost did not include the value of the land. The market price for different key inputs was 1.72 US\$ $kg^{-1}$ maize seed, and the cost of fertilizers on a nutrient basis was as follows: 0.18 US\$ $kg^{-1}$ for N, 0.16 US\$ $kg^{-1}$ for P, 0.26 US\$ $kg^{-1}$ for K, and 0.78 US\$ $kg^{-1}$ for $ZnSO_4$. The cost incurred for human labor was based on people $d^{-1}$ $ha^{-1}$. A minimum wage of 5.14 US\$ $person^{-1}$ $d^{-1}$ was considered for calculation of labor cost involved in production. The minimum support price fixed by the Indian government for grain (0.20 US\$ $kg^{-1}$) and the prevailing market price of stover (0.013 US\$ $kg^{-1}$) were used to calculate GR. For better comparison, all input and production costs (cost of cultivation and GR) were converted from INR to US\$ based on the prevailing exchange rate of 64 INR US\$$^{-1}$.

*Statistical analysis*

All data recorded were analyzed with the help of analysis of variance (ANOVA) (Gomez and Gomez, 1984) for the split-plot design using SAS 9.3 software (SAS Institute, Cary, USA). The least significant difference test was used to decipher the main and interaction effects of treatments at $P < 0.05$.

## RESULTS

### *Growth parameters*

Growth parameters of maize, including days to emergence, plant height (at 30-d intervals), days to 50% silking, days to maturity, and reproductive period varied, significantly ($P < 0.05$) with different tillage practices; however, no significant difference was found in plant height at 30 days after sowing (DAS) (Table I). The maximum maize plant height at 60 DAS and at harvest was found under ZT (1.70 and 1.90 mm, respectively) with the lowest days to maturity (107.8 d); however, PB exhibited the highest reproductive period (52 d) and the lowest days to emergence (4.3 d) and days to 50% silking (56.1 d). Statistical analyses revealed that the main effect of diversified maize-based cropping systems (Table I) and interaction effects of tillage practices and diversified cropping systems (data not presented) on maize growth parameters, were not significant ($P > 0.05$).

Tillage practices had significant ($P < 0.05$) effects on maize DMA at 60 and 90 DAS and leaf area at all stages. Both ZT and PB exhibited increases in DMA (9.2%–14.1%) at 60 and 90 DAS and leaf area (8.3%–16.5%) at 30, 60, and 90 DAS, compared with CT (Table II). Similar to tillage practice effects, the cropping system treatments also significantly affected maize leaf area at 60 and 90 DAS. The leaf area of maize at 60 and 90 DAS in MCS and MWMb were 13.9%–23.2% and 10.3%–22.7% higher compared with MMS, respectively. However, there was no significant difference in DMA and CGR at all stages and leaf area at 30 DAS across the cropping system treatments.

### *Yield and yield attributes*

Tillage practice and cropping system had non-significant ($P > 0.05$) interaction effects on yield attributes (data not shown). The tillage practices had a significant ($P < 0.05$) effect on maize cob and biological yields and yield attributes (Table III). However, maize planted in PB and/or ZT plots did not differ with respect to cob and biological yields and yield attributes. The PB and ZT showed an increase in cob yield (3.8%–14.9%), biological yield (6.2%–13.7%), cobs per $m^2$ (13.6%–14.8%), cob length (5.0%–8.4%), grain rows per cob (4.8%–7.9%), and grains per row (8.4%–13.0%) compared with CT. The diversified cropping systems had significant ($P < 0.05$) effects on maize cob and biological yields. The maximum yield was recorded in the MCS system, which was 5.8%, 8.9%, and 10.9% higher compared with MWMb, MMuMb, and MMS, respectively. However, the effects of diversified cropping systems on yield attributes of maize were not significant (Table III).

### *Plant nutrient contents*

Contents of N, K, Fe, and Zn in maize grain were

TABLE I

Effects of long-term tillage practices and diversified cropping systems on growth parameters and phenological stages of maize after six cropping cycles

| Treatment | Plant height | | | Days to emergence | Days to 50% silking | Days to maturity | Reproductive period |
|---|---|---|---|---|---|---|---|
| | 30 DAS[a)] | 60 DAS | At harvest | | | | |
| | m | | | d | | | |
| Tillage practice[b)] | | | | | | | |
| PB | 0.59a[c)] | 1.69a | 1.89a | 4.3c | 56.1c | 108.1b | 52.0a |
| ZT | 0.57a | 1.70a | 1.90a | 5.2b | 56.6b | 107.8b | 51.3a |
| CT | 0.55a | 1.56b | 1.74b | 6.1a | 59.2a | 109.3a | 50.1b |
| Cropping system[d)] | | | | | | | |
| MWMb | 0.57a | 1.67a | 1.86a | 5.2a | 57.2a | 108.3a | 51.1a |
| MCS | 0.58a | 1.72a | 1.88a | 5.1a | 57.1a | 108.0a | 50.9a |
| MMuMb | 0.57a | 1.62a | 1.82a | 5.2a | 57.2a | 108.6a | 51.3a |
| MMS | 0.56a | 1.60a | 1.81a | 5.1a | 57.6a | 108.7a | 51.1a |
| | | | | $LSD_{0.05}$[e)] | | | |
| Tillage practice | NS[f)] | 0.12 | 0.137 | 0.61 | 0.38 | 1.00 | 1.00 |
| Cropping system | NS | NS | NS | NS | NS | NS | NS |

a) DAS = days after sowing.
b) PB = permanent bed; ZT = zero tillage; CT = conventional tillage.
c) Values in a column followed by the same letter are significantly different at $P < 0.05$ according to the least significant difference test.
d) MWMb = maize-wheat-mungbean; MCS = maize-chickpea-*Sesbania*; MMuMb = maize-mustard-mungbean; MMS = maize-maize-*Sesbania*.
e) Least significant difference at $P < 0.05$.
f) Not significant.

TABLE II

Effects of long-term tillage practices and diversified cropping systems on dry matter accumulation, leaf area, and crop growth rate of maize after six cropping cycles

| Treatment | Dry matter accumulation | | | | Leaf area | | | Crop growth rate | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 30 DAS[a)] | 60 DAS | 90 DAS | At harvest | 30 DAS | 60 DAS | 90 DAS | 0–30 DAS | 30–60 DAS | 60–90 DAS |
| | g plant$^{-1}$ | | | | m$^2$ plant$^{-1}$ | | | g plant$^{-1}$ d$^{-1}$ | | |
| Tillage practice[b)] | | | | | | | | | | |
| PB | 30.4a[c)] | 71.3a | 129.2a | 141.5a | 0.328a | 0.549a | 0.433b | 1.01a | 1.36a | 1.93a |
| ZT | 30.0a | 71.9a | 131.6a | 144.9a | 0.314ab | 0.543a | 0.466a | 1.00a | 1.39a | 1.99a |
| CT | 29.2a | 63.0b | 118.3b | 129.6b | 0.287a | 0.478b | 0.400c | 0.97a | 1.13a | 1.84a |
| Cropping system[d)] | | | | | | | | | | |
| MWMb | 30.2a | 70.1a | 127.3a | 139.6a | 0.321a | 0.541b | 0.473a | 1.01a | 1.33a | 1.91a |
| MCS | 31.6a | 71.5a | 132.3a | 144.6a | 0.335a | 0.559a | 0.476a | 1.05a | 1.33a | 2.03a |
| MMuMb | 29.8a | 67.0a | 124.1a | 136.4a | 0.294a | 0.503c | 0.399b | 0.99a | 1.24a | 1.90a |
| MMS | 27.8a | 66.3a | 121.6a | 133.9a | 0.288a | 0.491d | 0.386b | 0.93a | 1.28a | 1.84a |
| | $LSD_{0.05}$[e)] | | | | | | | | | |
| Tillage practice | NS[f)] | 5.27 | 10.51 | 10.51 | 0.028 1 | 0.026 5 | 0.026 5 | NS | NS | NS |
| Cropping system | NS | NS | NS | NS | NS | 0.012 5 | 0.024 9 | NS | NS | NS |

a) DAS = days after sowing.
b) PB = permanent bed; ZT = zero tillage; CT = conventional tillage.
c) Values in a column followed by the same letter(s) are not significantly different at $P < 0.05$ according to the least significant difference test.
d) MWMb = maize-wheat-mungbean; MCS = maize-chickpea-*Sesbania*; MMuMb = maize-mustard-mungbean; MMS = maize-maize-*Sesbania.*
e) Least significant difference at $P < 0.05$.
f) Not significant.

TABLE III

Effects of long-term tillage practices and diversified cropping systems on yield attributes and yields of maize after six cropping cycles

| Treatment | Cobs | Cob length | Cob girth | Grain rows | Grain | 100-grain weight | Cob yield | Biological yield | Shelling | Harvest index |
|---|---|---|---|---|---|---|---|---|---|---|
| | m$^{-2}$ | m | | cob$^{-1}$ | row$^{-1}$ | g | kg ha$^{-1}$ | | % | |
| Tillage practice[a)] | | | | | | | | | | |
| PB | 7.7a[b)] | 0.177ab | 0.129a | 13.4ab | 34.2ab | 26.7a | 5 368b | 16 215b | 80.6a | 27.0a |
| ZT | 7.8a | 0.183a | 0.132a | 13.8a | 35.6a | 25.6a | 5 939a | 17 351a | 77.3a | 26.5a |
| CT | 6.8b | 0.169b | 0.125a | 12.7b | 31.5b | 27.1a | 5 169b | 15 264c | 77.8a | 26.5a |
| Cropping system[c)] | | | | | | | | | | |
| MWMb | 7.4a | 0.177a | 0.131a | 13.7a | 34.0a | 25.9a | 5 530ab | 16 660ab | 78.8a | 26.4a |
| MCS | 7.6a | 0.181a | 0.130a | 13.2a | 34.5a | 26.2a | 5 851a | 17 203a | 78.6a | 26.7a |
| MMuMb | 7.3a | 0.174a | 0.128a | 13.1a | 33.8a | 26.8a | 5 374b | 15 924bc | 78.8a | 26.8a |
| MMS | 7.2a | 0.172a | 0.126a | 13.0a | 32.8a | 27.0a | 5 214b | 15 320c | 78.2a | 26.8a |
| | $LSD_{0.05}$[d)] | | | | | | | | | |
| Tillage practice | 0.68 | 0.010 4 | NS[e)] | 0.75 | 3.04 | NS | 461 | 839 | NS | NS |
| Cropping system | NS | NS | NS | NS | NS | NS | 367 | 1 032 | NS | NS |

a) PB = permanent bed; ZT = zero tillage; CT = conventional tillage.
b) Values in a column followed by the same letter(s) are not significantly different at $P < 0.05$ according to the least significant difference test.
c) MWMb = maize-wheat-mungbean; MCS = maize-chickpea-*Sesbania*; MMuMb = maize-mustard-mungbean; MMS = maize-maize-*Sesbania.*
d) Least significant difference at $P < 0.05$.
e) Not significant.

significantly ($P < 0.05$) influenced by tillage practices (Table IV). However, the P content in maize grain was not significantly affected by tillage practices. An increase in maize grain N (6.7%–8.1%), K (4.4%–13.2%), Fe (29.8%–39.0%), and Zn (7.6%–9.9%) was observed under PB and ZT compared with CT. Similarly, cropping systems also significantly influenced the N, Fe, and Zn contents in maize grains. However, there was no significant variation in the P and K contents in maize grains ($P < 0.05$) among the cropping systems. Increased maize grain N (6.4%–11.3%), Fe (20.6%–30.6%), and Zn (9.4%–22.9%) contents were found in MCS compared with MWMb, MMS, and MMuMb, respectively. However, the interaction effects of tillage practices and cropping systems were not significant on N, P, K, Fe, and Zn content in maize grains (data not shown).

TABLE IV

Effects of long-term tillage practices and diversified cropping systems on nutrient contents of grains after six cropping cycles

| Treatment | N | P | K | Fe | Zn |
|---|---|---|---|---|---|
| | g kg$^{-1}$ | | | mg kg$^{-1}$ | |
| Tillage practice[a)] | | | | | |
| PB | 15.1a[b)] | 3.34a | 4.46ab | 36.2a | 16.3a |
| ZT | 15.2a | 3.52a | 4.83a | 33.8a | 16.0a |
| CT | 14.1b | 3.38a | 4.27b | 26.0b | 14.8b |
| Cropping system[c)] | | | | | |
| MWMb | 14.8b | 3.48a | 4.50a | 31.3b | 15.9b |
| MCS | 15.8a | 3.34a | 4.76a | 37.7a | 17.3a |
| MMuMb | 14.2c | 3.28a | 4.28a | 28.9c | 14.1c |
| MMS | 14.4bc | 3.56a | 4.54a | 30.2bc | 15.5b |
| | $LSD_{0.05}$[d)] | | | | |
| Tillage practice | 0.53 | NS[e)] | 0.40 | 2.58 | 1.10 |
| Cropping system | 0.55 | NS | NS | 1.98 | 0.79 |

a)PB = permanent bed; ZT = zero tillage; CT = conventional tillage.
b)Values in a column followed by the same letter(s) are not significantly different at $P < 0.05$ according to the least significant difference test.
c)MWMb = maize-wheat-mungbean; MCS = maize-chickpea-*Sesbania*; MMuMb = maize-mustard-mungbean; MMS = maize-maize-*Sesbania*.
d)Least significant difference at $P < 0.05$.
e)Not significant.

*Water use and economic WUE*

Irrigation, effective rainfall, and changes in soil moisture were significantly higher under CT (9.1%–13.7%) than PB and ZT (Table V). Among different cropping systems, MCS received the least amount of water (814 mm ha$^{-1}$), while MMS received the highest amount of water (823.2 mm ha$^{-1}$). The main effects of tillage practices were significant ($P < 0.05$) on maize economic WUE. In our long-term study, the maximum maize economic WUE was observed under ZT (0.89 US\$ ha$^{-1}$ mm$^{-1}$), which was similar to that observed under PB (0.85 US\$ ha$^{-1}$ mm$^{-1}$) and significantly higher than under CT (0.62 US\$ ha$^{-1}$ mm$^{-1}$). Similar to tillage practices, cropping systems had a significant ($P < 0.05$) effect on maize economic WUE. In our study, the maximum economic WUE (0.87 US\$ ha$^{-1}$ mm$^{-1}$) was observed in MCS, which was 7.1%–21.2% higher than other cropping systems. There was a significant interaction effect of tillage practices and cropping systems on economic maize WUE ($P < 0.05$, Fig. 1). The maximum economic WUE (1.05 US\$ ha$^{-1}$ mm$^{-1}$) was observed under ZT-MCS; while the lowest economic WUE (0.56 US\$ ha$^{-1}$ mm$^{-1}$) was found

TABLE V

Effects of long-term tillage practices and diversified cropping systems on water use and water-use efficiency (WUE) of maize after six cropping cycles

| Treatment | Irrigation | Total seasonal rainfall | Effective rainfall | Change in profile soil moisture storage | Water use | Economic WUE |
|---|---|---|---|---|---|---|
| Tillage practice[a)] | mm | | | | mm ha$^{-1}$ | US\$ ha$^{-1}$ mm$^{-1}$ |
| PB | 400 | 451 | 328 | −37.3a[b)] | 764.9c | 0.85a |
| ZT | 440 | 451 | 328 | −38.0a | 805.6b | 0.89a |
| CT | 520 | 451 | 328 | −38.2a | 885.8a | 0.62b |
| Cropping system[c)] | | | | | | |
| MWMb | 453 | 451 | 328 | −37.7ab | 818.7ab | 0.81ab |
| MCS | 453 | 451 | 328 | −33.1a | 814.0b | 0.87a |
| MMuMb | 453 | 451 | 328 | −38.3ab | 819.2ab | 0.76bc |
| MMS | 453 | 451 | 328 | −42.3b | 823.2a | 0.71c |
| | | | $LSD_{0.05}$[d)] | | | |
| Tillage practice | – | – | – | NS[e)] | 8.05 | 0.094 |
| Cropping system | – | – | – | 6.09 | 6.09 | 0.084 |

a)PB = permanent bed; ZT = zero tillage; CT = conventional tillage.
b)Values in a column followed by the same letter(s) are not significantly different at $P < 0.05$ according to the least significant difference test.
c)MWMb = maize-wheat-mungbean; MCS = maize-chickpea-*Sesbania*; MMuMb = maize-mustard-mungbean; MMS = maize-maize-*Sesbania*.
d)Least significant difference at $P < 0.05$.
e)Not significant.

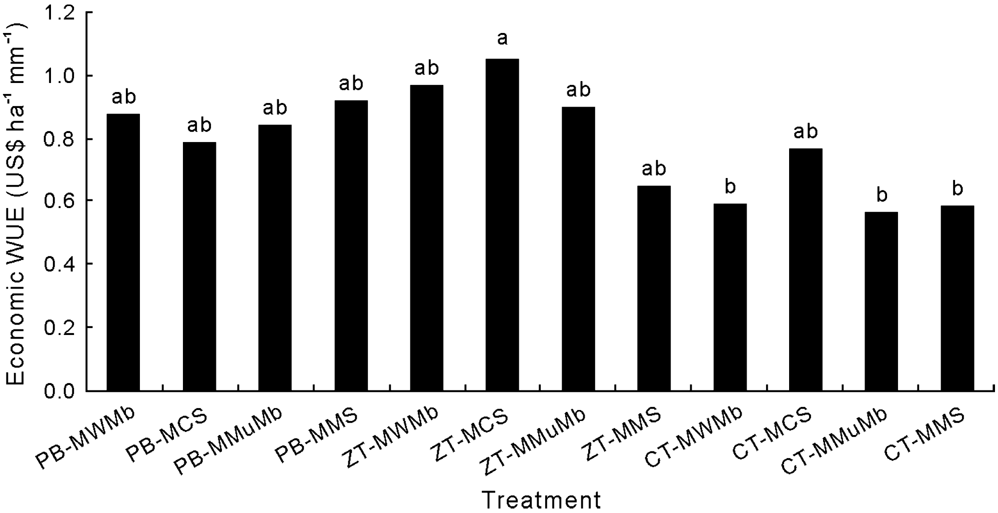


Fig. 1 Interaction effects of long-term tillage practices and diversified cropping systems on economic water-use efficiency (WUE) of maize in the seventh rainy season. Bars with the same letter(s) are not significantly different at $P < 0.05$ according to the least significant difference test. PB = permanent bed; ZT = zero tillage; CT = conventional tillage; MWMb = maize-wheat-mungbean; MCS = maize-chickpea-*Sesbania*; MMuMb = maize-mustard-mungbean; MMS = maize-maize-*Sesbania*.

under the CT-MMuMb treatment.

*Soil organic C*

The long-term CA practices (PB and ZT) had a significant ($P < 0.05$) effect on SOC contents of different soil layers (Fig. 2a). The SOC contents under PB and ZT were significantly ($P < 0.05$) higher (21.4%–31.8%) than CT at 0–0.15 and 0.15–0.30 m soil depths. However, the SOC contents of the ZT, PB, and CT plots were statistically similar at 0.30–0.45 m soil depth. The effect of diversified maize-based cropping systems on SOC content were significant ($P < 0.05$) for the surface soil depths (0–0.15 and 0.15–0.30 m). Maximum SOC contents at both soil depths were observed in the MCS system, which were 3.7%, 19.1%, and 20.6% higher compared with the MWMb, MMS, and MMuMb systems, respectively (Fig. 2b). Tillage practices and cropping systems had significant ($P < 0.05$) interaction effect on SOC content of 0–0.15 and 0.15–0.30 m soil layers and the highest SOC contents were found under PB-MWMb at 0–0.15 m soil depth and under PB-MCS at 0.15–0.30 m soil depth. However, the interaction effect of tillage and cropping systems on SOC was not found at 0.30–0.45 m soil depths (data not shown).

*Energy-use efficiency*

The main effects of tillage practices and cropping systems on the net energy output and energy productivity of maize were significant ($P < 0.05$) during the

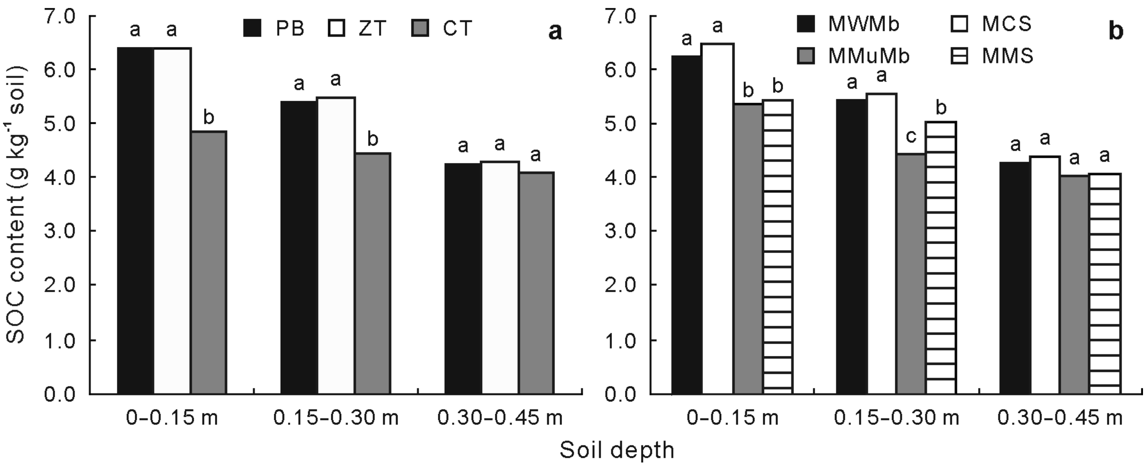


Fig. 2 Effects of long-term tillage practices (a) and diversified cropping systems (b) on soil organic C (SOC) content at different soil depths after six cropping cycles. Bars with the same letter within a depth are not significantly different at $P < 0.05$ according to the least significant difference test. PB = permanent bed; ZT = zero tillage; CT = conventional tillage; MWMb = maize-wheat-mungbean; MCS = maize-chickpea-*Sesbania*; MMuMb = maize-mustard-mungbean; MMS = maize-maize-*Sesbania*.

seventh rainy season crop (Table VI). The net energy output and energy productivity of maize increased by 10.1%–16.4% and 32.3%– 39.9% under PB and ZT compared with CT, respectively. Among the cropping systems, the maximum net energy output ($195.5 \times 10^3$ MJ ha$^{-1}$) and energy productivity (1.26 kg MJ$^{-1}$) were observed in MCS, which were 3.1%–11.8% and 2.5%–10.2% higher than MWMb, MMuMb, and MMS, respectively. The interaction effects of tillage practices and cropping systems on net energy output and energy productivity of maize were not significant (data not shown).

TABLE VI

Effects of long-term tillage practices and diversified cropping systems on energy productivity of maize after six cropping cycles

| Treatment | Input energy | Net energy | Energy productivity |
|---|---|---|---|
| | — $\times 10^3$ MJ ha$^{-1}$ — | | kg MJ$^{-1}$ |
| Tillage practice[a] | | | |
| PB | 12.7c[b] | 186.5b | 1.28b |
| ZT | 12.8b | 197.3a | 1.35a |
| CT | 15.8a | 169.5c | 0.97c |
| Cropping system[c] | | | |
| MWMb | 13.8a | 189.5ab | 1.23ab |
| MCS | 13.8a | 195.5a | 1.26a |
| MMuMb | 13.8a | 180.2bc | 1.17bc |
| MMS | 13.8a | 172.5c | 1.13c |
| | $LSD_{0.05}$[d] | | |
| Tillage practice | 0.000 001 8 | 10.00 | 0.07 |
| Cropping system | NS[e] | 12.54 | 0.08 |

[a] PB = permanent bed; ZT = zero tillage; CT = conventional tillage.
[b] Values in a column followed by the same letter(s) are not significantly different at $P < 0.05$ according to the least significant difference test.
[c] MWMb = maize-wheat-mungbean; MCS = maize-chickpea-*Sesbania*; MMuMb = maize-mustard-mungbean; MMS = maize-maize-*Sesbania*.
[d] Least significant difference at $P < 0.05$.
[e] Not significant.

## DISCUSSION

Maize cob and biological yields were higher under ZT compared with CT. Our findings of higher maize yields and yield attributes under ZT are consistent with the findings of Jat *et al.* (2013), Gathala *et al.* (2013), and Parihar *et al.* (2016a). In contrast to our findings, Lahmar (2010) summarized that crop yields were lower in CA compared with CT practices on fertile soils of Europe. The higher yield of maize under ZT could be due to the compound effects of additional nutrients (Blanco-Canqui and Lal, 2009; Kaschuk *et al.*, 2010), reduced competition for resources due to less weed population (Ozpinar, 2006; Chauhan *et al.*, 2007), improved soil physical health (Jat *et al.*, 2013), enhanced soil C (Baker *et al.*, 2007; Thomas *et al.*, 2007; Kaiser *et al.*, 2014; Parihar *et al.*, 2016b), and better water regimes (Govaerts *et al.*, 2009) with higher resource-use efficiency, aeration, and efficient nutrient use over CT (Unger and Jones, 1998). In addition, soil structure affects crop yield through complex root-based mechanisms, which might affect the biomass production (Passioura, 2002). The better root growth found under CA compared with CT might be attributed to less compaction (Blanco-Canqui *et al.*, 2006).

In our study, water-use for maize production was the lowest in the PB plots, which might be due to the lower water application in raised bed system, since water advancement occurs at a faster rate in these plots (Aquino, 1998; Das *et al.*, 2014). Due to higher moisture storing up in CA plots, the conserved moisture from preceding cropping season might be helpful in sowing and germination of succeeding maize, as residue retention and no-tillage operation allow catching this opportunity, while the maize germination under CT requires additional water. This not only led to better crop establishment under CA but also provide better opportunities for crop growth with higher economic WUE. A higher economic WUE under CA-based tillage practices was observed in our study compared with CT, similar observation of greater WUE in CA practices were also been reported in earlier studies (Jat *et al.*, 2013; Das *et al.*, 2014, Parihar *et al.*, 2016a). This was due to the higher yield and NRs of the maize with less water consumption under ZT and PB than CT. In this regard, Jat *et al.* (2013) also found that the no-till bed requires 11% less water compared with CT, with 16% higher WUE. The higher yield advantage during the low rainfall season (rainy season, 2014) in our study supports the concept of a better moisture environment under CA-based management practices, indicating that these practices are better for famers during a bad monsoon period through soil water conservation/increased water availability (Govaerts *et al.*, 2007; Thierfelder and Wall, 2010).

Apart from increasing the crop yield and economic WUE, CA-based tillage practices and diversified cropping systems were also found to increase the plant nutrient contents. The higher contents of plant nutrients in maize grains under CA might be due to better root development, which enhanced nutrient concentration in maize due to increased forage area for nutrient extraction under ZT and PB. Furthermore, the retention of mungbean/*Sesbania* residue recycled the nutrients in soil layers and ultimately enhanced nutrient availability in the crop root zone and hence, increased nutrient uptake. The SOM at a higher content under ZT and PB chelates the micronutrients. In this study, the adoption of CA practices resulted in enhanced net energy outputs by $17 \times 10^3$–$28 \times 10^3$ MJ ha$^{-1}$ compared with CT, which indicates a higher energy productivity in CA. This may be due to better crop growth environment in terms of higher nutrient availability, better root growth, and modulation of micro climatic conditions with better water retention. Consistent with our results, higher energy output under ZT and PB have been previously reported by Parihar *et al.* (2011).

Among the cropping systems, irrespective of tillage and crop establishment practices, the seventh rainy season maize cob, biological yields, energy-use efficiency, and nutrient contents were higher in the MCS system than other three cropping systems (MWMb, MMuMb, and MMS). This might be due to the inclusion of two legumes (one in winter and another in summer) in MCS compared with only summer legume in other cropping systems (Congreves *et al.*, 2015; Parihar *et al.*, 2016a). The inclusion of summer legumes in the preceding season might have improved soil fertility, particularly organic C and N availability, thereby improved maize growth, yield, and nutrient content. Furthermore, the inclusion of summer mungbean and *Sesbania* enhanced soil fertility (Sharma and Behera, 2009), which might have contributed to productivity enhancement over the years as a legume effect. The component crops of four diversified cropping systems having different rooting depths explore water and nutrients from different soil layers (Hobbs *et al.*, 2008), enhance soil biological diversity (Kaschuk *et al.*, 2010), increase residue breakdown with legumes in the rotation (Fillery, 2001), lower incidence of plant diseases (Kirkegaard *et al.*, 2008) and insect pests (Witmer *et al.*, 2003), and may be responsible for cropping system effect.

Diversified cropping systems significantly influenced the quantity of water-use, which was the lowest in the MCS system due to the lower water requirement and higher moisture availability in pulse plots (Zhang *et al.*, 2000). At all the soil depths, MCS showed higher C content compared with other cropping system plots, which might be due to the differences in the quantity and chemical composition of the applied crop residue biomass and/or root exudates (Congreves *et al.*, 2015). In our study, MCS plots demonstrated the highest SOC content. The rotation of legumes with deep-rooted legumes in the cropping systems helps in recycling of nutrients from sub-surface to surface layers through leaf fall and twig decay. This, in turn, increased nutrient availability in the rhizosphere of maize (at shallow depth), where root density of maize is the maximum. Increased contents and uptake of N, P, and K due to the inclusion of legumes were also reported by Aziz *et al.* (2015) and Parihar (2014).

## CONCLUSIONS

To overcome multiple challenges like yield plateau, water and labor shortages, high energy costs, diminishing farm profits, and climatic change-induced variability in northwestern India, CA-based practices are potential alternatives. The seventh rainy season study under a long-term CA experiment investigating tillage practices and diversified maize-based cropping systems found that sustainable intensification of maize systems (with legume inclusion) using CA-based management (ZT and PB) well enhanced the growth, yield, SOC content, economic WUE, and energy-use efficiency of maize. Therefore, in northwestern India rainy season maize can be grown with CA-based MCS/MWMb system.

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