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Applications of organic manure increased maize (*Zea mays* L.) yield and water productivity in a semi-arid region

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ABSTRACT

Organic manure application has been neglected in recent years, reflecting the rapid replacement with synthetic fertilizer. Exploration of the restorative effect of organic manure on the soil fertility, quality and sustainable productivity is urgently needed. A 4-year field experiment (2011–2014) investigated variation of grain yield, soil water-nutrient content and plant growth in a local cultivar (Zheng Dan 958) of maize (*Zea mays* L.) at three planting densities with extra organic manure application in a semi-arid region of Northwestern China. Soil water content in 0–50 cm and below 150 cm soil profile was maintained stably at 25% and 18% under organic manure application over four consecutive years, and soil water use in the depth of 50–150 cm was improved. Organic manure helped residual soil nutrient mineralization after harvest with 25%, 198% and 41% increases in total nitrogen (N), available phosphorus (P) and soil organic matter (SOM) over three years respectively. Adequate content of N, P and SOM after maize harvest played an important role for stable high yield in the next season. Consequently, the biomass allocation into shoot and grains was optimized and presented as a slight increase in harvest index (HI). Based on the improvement of water-nutrient status in manured soil, maize water productivity (WP) increased by 3–8%, which positively associated with the yield increase by 5–10% at high planting density. Organic manure could be used to improve soil environment, promote yield and WP in maize in dryland agriculture.

1. Introduction

Plastic film mulch, increased plant densities and chemical fertilizer input have been extensively used in intensive agricultural production areas of China (Bu et al., 2013; Liu et al., 2014), such as the Loess Plateau, a typical semi-arid region. These strategies contribute to rainfall capture, decrease in soil surface evaporation and increase in crop yield and water productivity (Cui et al., 2013; Chen, 2014; Zhang, 2014). Although high planting density increases the radiation interception and simultaneously leads to intensified soil water consumption (Jiang et al., 2014), this strategy negatively affects maize biomass allocation (Wang et al., 2010). Furthermore, continual use of chemical fertilizer, film mulching and high planting density have caused soil degradation (Ju et al., 2009), particularly the occurrence of chain reactions, soil compaction, thereby worsening water storage and soil nutrients content, which consequently impairs soil quality (Zhao et al., 2009; Wang et al., 2013) and then restrains crop production (Chen et al., 2012; Li et al., 2013; Meng, 2013). Alternatively, organic manure possesses the potential of stabilizing crop production via improving soil water-nutrient condition in the semi-arid intensive agricultural region of China. Manure has been utilized as a major amendment method to maintain soil fertility (Liang et al., 2012), prior to the 1950s.

Abbreviations: WP, water productivity; HI, harvest index; N, total nitrogen; P, available phosphorus; SOM, soil organic matter; SWC, soil water content; SBD, soil bulk density; ET, evapotranspiration; SWS, soil water storage; SD, soil depth; Pi, precipitation.

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Organic manure application is compatible with tillage practices conversion from conventional to sustainable tillage systems via improving the soil quality and crop growth worldwide (Shah et al., 2012; Carr et al., 2013; Ahmad et al., 2013; Parija and Kumar 2013). In northwest India, the combined application of organic and inorganic fertilizers could increase the activities of soil invertase and the available nutrient contents (Manna et al., 2007). Similarly, greenhouse experiments indicate that cow manure improved soil organic matter (SOM), nitrogen (N), phosphorus (P) and soil permeability in a dryland sandy soil in Japan (Uzoma et al., 2011), particularly, the increase of soil available P contributed to crop P uptake and without any additional P input for nearly 10 years (Eghball et al., 2004; Lithourgidis et al., 2007). Previous studies confirm that the increased levels of N, P and SOM positively associated with crop yield increase beyond the manure application years (Liu et al., 2013), suggesting that the effects of manure can last for several years (Nevens and Reheul, 2003; Eghball et al., 2004; Dordas et al., 2008). Other studies consider that organic manure typically mineralize within only a few cropping seasons, therefore, to obtain a sustainable and stable increase in yield, organic manure should be applied for consecutive years (Su et al., 2006; Khan et al., 2007; Uzoma et al., 2011; Molina et al., 2014). Meanwhile, continual application of manure in a given soil decreases bulk density and increases soil porosity, thereby improves resource use efficiency (Nevens and Reheul, 2003). Nyamangara et al. (2004) reports that organic manure improves plant growth for high yield via an optimized soil environment. Addition of 42 Mg ha^{-1} organic manure results in an economic optimum of silage maize yield on a sandy loam soil, with a substantial retention of mineral fertilizer N and N use efficiency increase (Nevens and Reheul, 2003; Nyamangara et al., 2004). Moreover, with two years of manure applications on a calcareous loam, maize dry matter production in plots increased by an average of 39% (Bocchi and Tano, 1994; Gil et al., 2008). Importantly, organic manure could replace inorganic fertilizer without yield loss, consistent with the increase in the kernel weight per cob and number of kernels per cob of 35% and 32% in northern Greece (Dordas et al., 2008). However, on the Loess Plateau, there are few reports concerning how organic manure improves soil water-nutrients status and maize growth to ensure sustainable and stable yield increase (Liang et al., 2012; Liu et al., 2013; Liu et al., 2014). Thus, exploration of crop yield potential and sustainable soil productivity under organic manure remains a challenge for stable food production in semi-arid farming region of China (Cui et al., 2013). The objective of our study was to determine how the organic manure application improved soil water-nutrient status and sustainable productivity in maize on the China Loess Plateau.

2. Materials and methods

2.1. Field experimental sites

Field experiments were conducted at the Chang Wu Agro-ecological Experimental Station (35°12′30″ N, 107°40′30″ E, altitude 1200 m), Chinese Academy of Sciences, located in the south-central region of the Loess Plateau, a semi-arid region of northwestern China. The soil is classified as Cumuli-Ustic Isohumosols according to Chinese Soil Taxonomy System (Gong, 2007), and contains 37% of clay, 59% of silt and 4% of sand with a bulk density of 1.3 g cm^{-3} and a pH (soil water solution) of 8.3. Organic matter, total nitrogen, available phosphorus and available potassium contents in the top 30 cm were 10.4 g kg^{-1}, 0.6 g kg^{-1}, 3.0 mg kg^{-1} and 129.0 mg kg^{-1}, respectively. The climate at the experimental site is temperate and semi-arid monsoonal with a mean annual temperature of 9.1 °C and a mean annual precipitation of 584.6 mm. Approximately 80% of the rainfall occurs from June to September.

2.2. Experimental design and plot arrangement

The experiments were conducted in a split plot design with three replicates from 2011 to 2014. The seeds of a local cultivar (Zheng Dan 958) of maize were sown in April of the four years (2011–2014) after soil preparation and harvest was in September. The plots were 5 m wide × 6 m long with 80 cm plastic film mulched and 40 cm rowledge. Plastic film mulching ensured the appropriate water and temperature for seeds emergence. The experimental conditions including chemical fertilizer with organic manure application under three densities are showed in Table 1. Basal fertilizers were applied in all treatments prior to the sowing, e.g. 135 kg ha^{-1} N as urea (46%, N), 112.5 kg ha^{-1} P_2O_5 as superphosphate (17%, P_2O_5), 112.5 kg ha^{-1} K_2O as potassium sulphate (54%, K_2O). Organic manure as a rate of 52.5 t ha^{-1} (ox manure contained total C, N, K and P of 362.1 g kg^{-1}, 20.3 g kg^{-1}, 8.5 mg kg^{-1} and 18.2 mg kg^{-1}, respectively, based on the dry matter) was applied in T2, T4 and T6 each year (the first year in 2011 spring), scattered uniformly in each plot then ploughed under to 0–30 cm soil layer. No organic manure was applied in treatments T1, T3 and T5 (controls). Additional 90 kg ha^{-1} of N as urea was applied in all treatments at the jointing stage. Three planting densities were arranged as the second factors: T1 and T2 at 60,000 plants ha^{-1}, T3 and T4 at 75,000 plants ha^{-1}, T5 and T6 at 90,000 plants ha^{-1}. Daily precipitation and temperature were recorded during growth period (Fig. 1).

2.3. Biomass collection

To investigate biomass accumulation, shoot samples were collected at each harvest. Three adjacent plants of similar sizes were harvested from each plot. The aboveground portion was separated into grains, leaves and stems, then exposed for 1 h to 105 °C and dried to a constant weight at 80 °C to determine the shoot biomass allocation.

2.4. Measurement of soil water content and determination of soil nutrients

Soil water content was measured gravimetrically at fore-sown and post-harvest. Soil samples were collected at the center of each plot with an auger at 10 cm intervals over a depth of 0–100 cm and at 20 cm intervals over a depth of 100–200 cm, instantly packed into aluminum specimen boxes, numbered and dried at 105 °C to constant weight for calculating soil water content and soil water

Table 1
The experimental design and fertilizer applications.

Treatment code	Organic manure (t ha^{-1})	Planting Density (Plants ha^{-1})	N (Kg ha^{-1})	P_2O_5 (Kg ha^{-1})	K_2O (Kg ha^{-1})	Additional N at jointing stage (Kg ha^{-1})
T1	0	60,000	135	112.5	112.5	90
T2	52.5	60,000	135	112.5	112.5	90
T3	0	75,000	135	112.5	112.5	90
T4	52.5	75,000	135	112.5	112.5	90
T5	0	90,000	135	112.5	112.5	90
T6	52.5	90,000	135	112.5	112.5	90

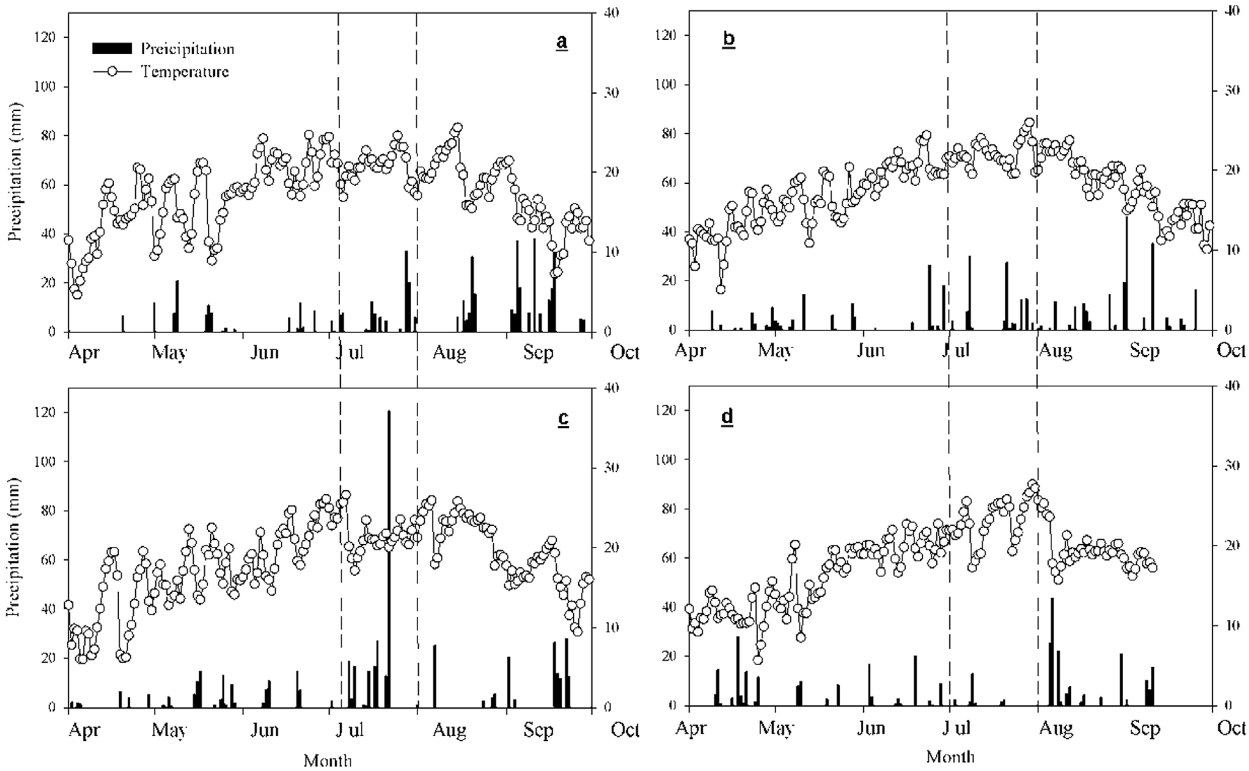

Fig. 1. Daily meteorological data during the four growing seasons, Daily precipitation (bars) and daily average temperature (lines) of 2011 (a), 2012 (b), 2013 (c) and 2014(d) are presented. Precipitation and temperature data in July over four seasons are highlighted with the two vertical dash lines in each figure showing variation among the years.

storage. Bulk density of 0–20 cm soil profile was measured at the sowing stage in 2011 and after harvest in 2014 using a foil sampler, with three replications per plot. The topsoil samples (0–20 cm depth) were collected before seeding and after harvest without factitious interference. They were then subjected to natural withering for measurement of the soil organic matter (SOM) with $FeSO_4$ titration, total N (N) using a Kieldahl apparatus, and available-P (P) with 0.5 M sodium bicarbonate ($NaHCO_3$) – molybdenum antimony colorimetric method.

2.5. Data treatment and statistical analyses

Grain yield was estimated from all the plants within a 2-m length of two middle rows. Subsequently, all cobs were collected, and the grains were manually stripped from every cob, followed by air drying to 10% water content and weighed to determine the final yield. Seasonal evapotranspiration (ET) was determined according to the following equations (Fang et al., 2014):

$$SWS\,(mm) = SWC \times SBD \times SD \tag{1}$$

$$ET\,(mm) = (Pi + I + C) - (R + D) + \Delta SWS \tag{2}$$

Where SWS is soil water storage in 2 m depth, SWC is soil water content mass percentage (Mg Mg^{-1}), SBD is soil bulk density, SD is soil depth, P_i is precipitation, I is irrigation, C is the upward flux into the root zone, R is surface runoff, D is downward drainage out of the root zone, ΔSWS (mm) is the change in soil water storage between seeding and harvesting stage.

Runoff was never observed as the experimental field was flat. The groundwater table is very deep (about 80–90 m), so C was assumed to be negligible. There was no heavy rain or waterlogging events during the experimental period, so deep drainage was assumed to be insignificant (Fang et al., 2014), and all treatments were not irrigated. Consequently, ET can be reduced to:

$$ET\,(mm) = \Delta SWS + Pi \tag{3}$$

Water productivity (WP) and harvest index (HI) were calculated using the following equations (Zhang et al., 2011; Pereira et al., 2012):

$$WP\left(kg.mm^{-1}\right) = \frac{GY}{ET} \tag{4}$$

$$HI\left(g.g^{-1}\right) = \frac{GB}{GB + SB} \tag{5}$$

Where GY is grain yield, GB represents grain biomass and SB represents shoot biomass.

Two-way ANOVAs were used to determine significances among organic manure, densities and cultivated years in SPSS Statistics 17. Means exhibiting significant differences between treatments, between years and between treatments within each year were separated using Duncan's Multiple Comparison analysis ($P < 0.05$).

3. Results

3.1. Vertical changes in soil water content (SWC)

About 70–85% of the precipitation in the experimental field occurred during the maize growing season (Fig. 1), i.e. 429.8, 440.0, 503.1 and 375.6 mm respectively in each year. The quantity and distribution of rainfall from July-September were able to satisfy the high water demand of maize, except in July 2014, when the rainfall was only 21.8 mm and the temperature was high. Compared to the raining pattern, similar changes in the daily average temperature were observed, with 12.8 °C at seeding, peaking at 21.6 °C in July and gradually decreasing to 15.0 °C at harvest.

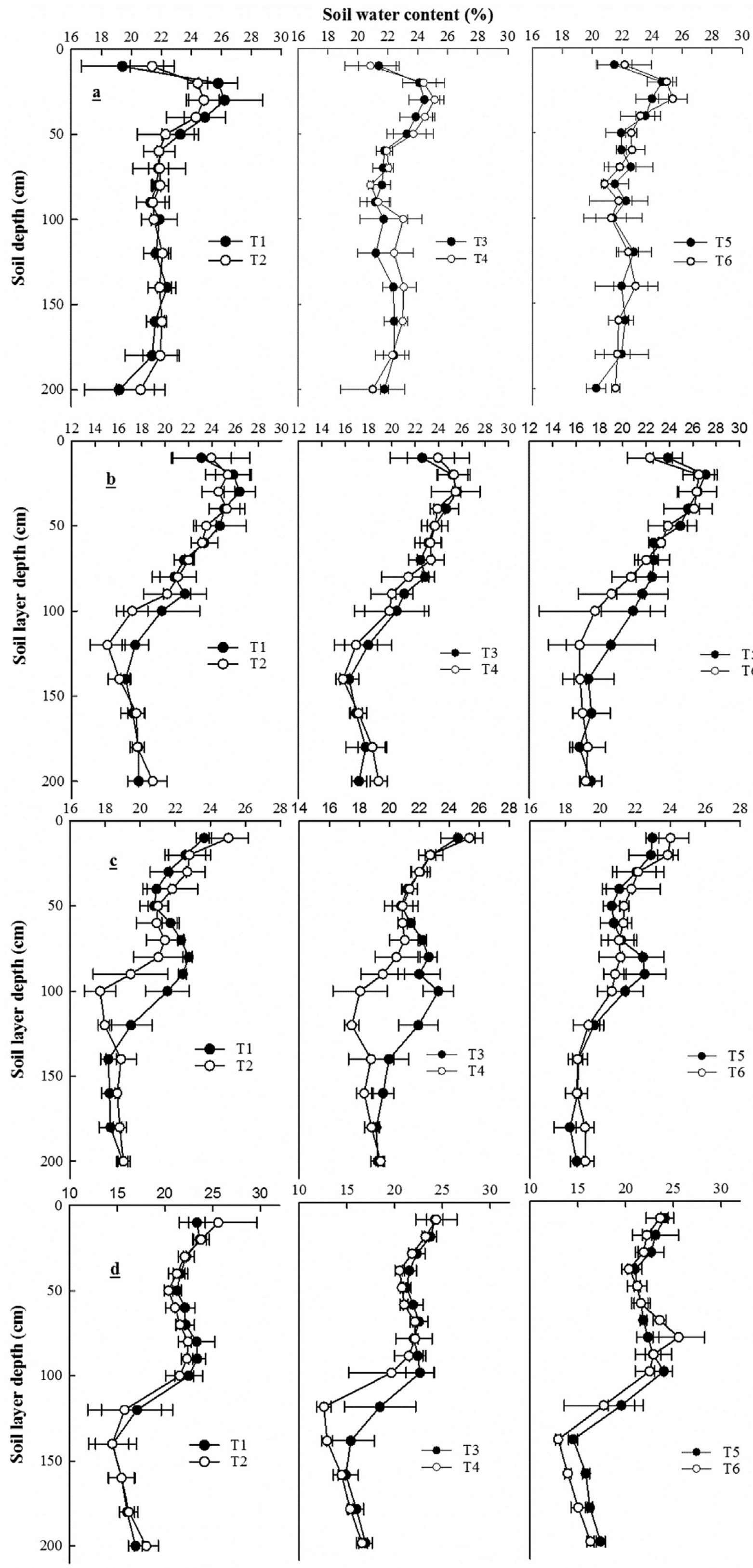

Fig. 2. Variation in vertical distribution of soil moisture at maturity in four growing seasons of 2011 (a), 2012 (b), 2013 (c) and 2014 (d) with (open circles) and without (closed circles) organic manure applications. Planting density: T1 and T2 at 60,000 plants ha^{-1}, T3 and T4 at 75,000 plants ha^{-1}, T5 and T6 at 90,000 plants ha^{-1}.

SWC of 0–50 cm and below 150 cm was relatively stable over four years, while SWC of 50–150 cm soil layer decreased under the consecutive application of organic manure over four years (Fig. 2). In 2011 and 2012 (average rainfall), SWC showed slight decrease in the deeper soil layer (50–150 cm) under organic manure, compared with that in the same soil layer of controls. Importantly, significant

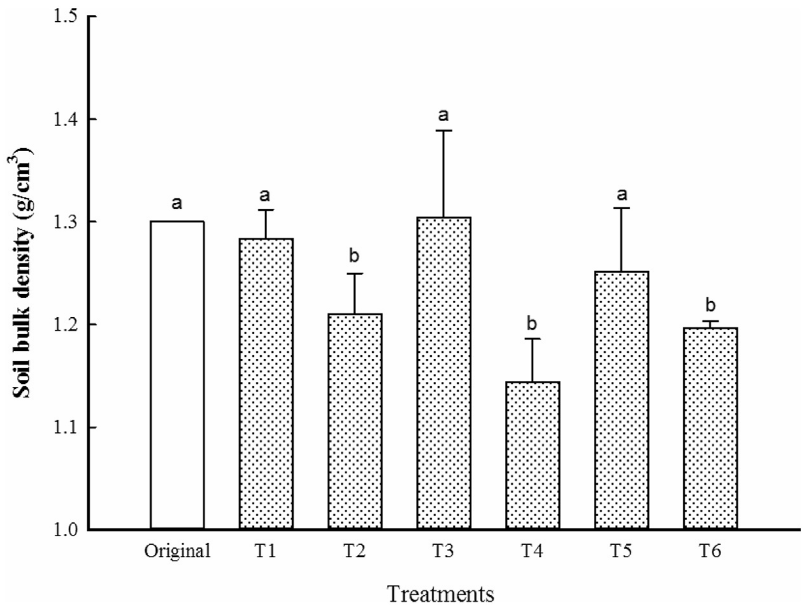

Fig. 3. Mean soil bulk density (SBD) measured at fore-sowing in 2011 (open bar) and after the last harvest in 2014 (filled bars). Bars followed with different letters are significantly difference at *P* < *0.05*. Data are the mean + standard error.

decrease of SWC occurred at 50–150 cm soil layer in the next two growing seasons (wet year, 2013; dry year, 2014) under organic manure, synchronously a stable SWC was maintained at about 25% in 0–50 cm and at about 18% below–150 cm soil layers. Organic manure improved the soil water use at 50–150 cm soil layer (SWC decreased to about 15%) in the drought year (2014). Moreover, SWC significantly decreased at medium planting densities under organic manure application compared with that in low and high planting densities.

3.2. Soil bulk density and main nutrient contents in the topsoil

Soil bulk density (SBD) significantly decreased ($P < 0.05$) under three planting densities with organic manure application (Fig. 3). SBD of T2 (1.21 g cm^{-3}), T4 (1.14 g cm^{-3}) and T6 (1.20 g cm^{-3}) decreased significantly ($P < 0.05$) compared with that of T1 (1.28 g cm^{-3}), T3 (1.30 g cm^{-3}) and T5 (1.25 g cm^{-3}) respectively, while SBD showed no significant differences among three planting densities without organic manure application.

Organic manure significantly increased topsoil nutrient content over three years compared to that without organic manure. Furthermore, relative contents of SOM, N and P significantly increased over three years compared to original content at fore- sowing of 2011 (Figs. 4 and 5). SOM significantly increased by 13.5, 33.8 and 21.5% in three planting densities under organic manure application compared with original value over three years (Fig. 4a). Compared to the original values, total N of topsoil increased by 18.5, 37.6 and 17.9% under organic manure application over three years (Fig. 4b), and in three planting densities, available P increased by 97.3, 169.1 and 145.2% over three years, respectively (Fig. 4c).

Compared with that without organic manure application over three years, SOM increased significantly by 38.2, 50.2 and 34.5% in three planting densities, respectively (Fig. 5a), N content of the topsoil increased by 18.9, 38.3 and 17.9% (Fig. 5b), and interestingly, P content in the topsoil significantly increased by 330.4, 131.9 and 132.5% in three densities from 2011 to 2013. In addition, a high P increase by 312% was observed in 2013 after two-year consecutive organic manure application (Fig. 5c), which implied that soil available P content exceeded the demand of maize growth.

3.3. Variation of harvest index over four continuous growing seasons

After the consecutive application of organic manure, mean harvest index (HI) increased from 0.32 to 0.41 in T2, 0.34–0.53 in T4, and 0.40–0.53 in T6 over four seasons (Table 2), and showed the maximum in T4 (0.53, 2012) and T6 (0.53, 2013). HI increased with the increase in planting density. However, no significant difference was observed between manure and non-manure treatments at the same plant density in each of four testing years. Moreover, with same planting density, mean HI had significant increase in 2012, 2013 and 2014 compared with that in 2011. With organic manure application (T4 and T6), stable and high HI was observed.

3.4. Grain yield and water productivity (WP)

Over four study years, grain yield ranged from 11.5 to 14.5 Mg ha^{-1} under organic manure application, and increased with the plant density increase (5.3%, 6.8% and 10.0% in three densities, respectively) compared to no manure treatments over the four years (Tables 3 and 5). The highest yield was observed generally in T6 (Table 5). And the initial manure application did not significantly impact on the maize final yield. However, with continuous manure application, maize yield showed a stable, significant increase ranging from 4.8 to 16.3% compared to the first season.

ET slightly increased with additional organic manure application and precipitation increase. Table 4 shows the significant differences among the four years, but not the six treatments. Based on the change of yield and ET, mean WP increased from 24.6 to 37.4 kg mm^{-1} for the treatments with organic manure application, and from 23.2 to 35.9 kg mm^{-1} for those without manure input, moreover, mean WP increased by 3.5, 3.0 and 7.9% in three densities with organic manure application over four years (Table 5). The highest WP appeared in T6 from 2011 to 2014, increasing by 9.0%, 9.8%, 7.4% and 5.6%, respectively, compared with that in T5.

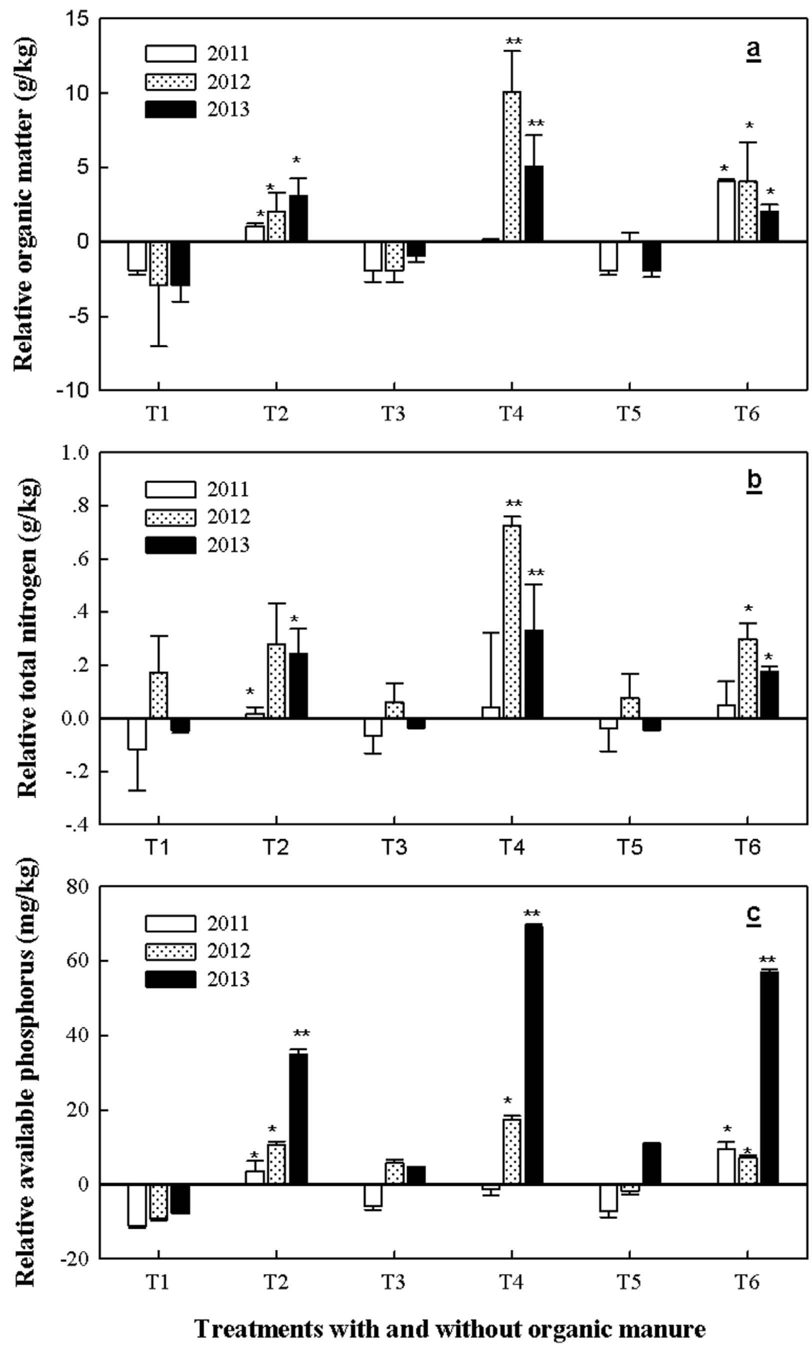

Fig. 4. Relative increments (or Reductions) in SOM (a), total N (b) and available P (c) contents in topsoil measured after each harvest from 2011 to 2013 compared to the original contents measured prior to seed sowing in April 2011. Positive values mean the quantity of increase and negative ones mean the quantity of decrease. Bars with * ($P < 0.05$) and ** ($P < 0.01$) show significant differences between treatments with and without organic manure applications under the same planting density.

4. Discussion

4.1. Soil properties improved with organic manure application

In the present study, SBD at depth of 0–20 cm decreased by 6.9, 12.3 and 7.7% in low, medial and high planting densities after four consecutive manure application years compared to that in spring of 2011 (Fig. 3). Edmeades (2003) reported that organic manure or chemical fertilizer benefitted only soil productivity and not soil quality. Accumulation of soil nutrients, particularly P and N, could arise from the long-term use of manure, relative to the use of fertilizers. However, stable production positively relied on the improvement of both soil productivity and soil quality. Furthermore, organic manure not only decreased SBD at a 0–30 cm soil layer, but also reduced soil water penetration resistance at depth of 0–50 cm in Mediterranean soil compared with the use of mineral fertilizer (Lithourgidis et al., 2007; Celik et al., 2010). Decrease of SBD was associated with the increase of soil organic matter and higher porosity. A consequence of the increase in soil organic matter is that some soil chemical and biological properties were improved (Edmeades, 2003; Celik et al., 2010), which benefitted soil water storage in a dryland farming region of China (Hai et al., 2010; Hou et al., 2012).

Our results show that SWC in the depth of 0–50 cm was maintained at about 25% over four years (Fig. 2). SWC in the depth of 50–150 cm under organic manure application decreased,

Table 2
Harvest index (HI) for different treatments in four years.

Harvest index (kg kg^{-1})												
Planting Density (Plants ha^{-1}) (D)	2011			2012			2013			2014		
	Organic manure (t ha^{-1}) (O)		Average	Organic manure (t ha^{-1})		Average	Organic manure (t ha^{-1})		Average	Organic manure (t ha^{-1})		Average
	0 (T1, 3, 5)	52.5 (T2, 4, 6)		0 (T1,3, 5)	52.5 (T2,4, 6)		0 (T1, 3, 5)	52.5 (T2, 4, 6)		0 (T1, 3, 5)	52.5 (T2, 4, 6)	
60,000	0.33aB	0.32aB	**0.33 B**	0.41aB	0.41aB	**0.41 B**	0.40aB	0.41aB	**0.41 B**	0.34aA	0.41aA	**0.38 A**
75,000	0.33aB	0.34aB	**0.34 B**	0.47aAB	0.46aAB	**0.47 AB**	0.47aAB	0.53aA	**0.50 A**	0.38aA	0.38aA	**0.38 A**
90,000	0.42aA	0.42aA	**0.42 A**	0.49aA	0.53aA	**0.51 A**	0.51aA	0.49aA	**0.50 A**	0.39aA	0.40aA	**0.40 A**
Average	**0.36 a**	**0.36 a**		**0.46 a**	**0.47 a**		**0.46 a**	**0.48 a**		**0.37 a**	**0.40 a**	
Source of variation	**O: NS D: * O × D: ***			**O: NS D: * O × D: ***			**O:NS D: * O × D: ***			**O: NS D: * O × D: NS**		

* Significant at $P < 0.05$; NS, non-significant
The mean values followed by different letters (a, b and c) within a row indicate significant difference between with and without organic manure at $P < 0.05$, n = 3; the mean values followed by different letters (A, B and C) within a column indicate significant difference among three planting densities at $P < 0.05$, n = 3.

Table 3
Average grain yield for different treatments in four years.

Grain Yield (Mg ha^{-1})												
Planting Density (Plants ha^{-1}) (D)	2011			2012			2013			2014		
	Organic manure (t ha^{-1}) (O)		Average	Organic manure (t ha^{-1})		Average	Organic manure (t ha^{-1})		Average	Organic manure (t ha^{-1})		Average
	0 (T1, 3, 5)	**52.5 (T2, 4, 6)**		**0 (T1, 3, 5)**	**52.5 (T2, 4, 6)**		**0 (T1, 3, 5)**	**52.5 (T2, 4, 6)**		**0 (T1, 3, 5)**	**52.5 (T2, 4, 6)**	
60,000	8.4aC	8.9aC	**8.7 C**	11.4aB	12.1aB	**11.8 B**	12.4aB	13.4aB	**12.9 B**	11.8aB	11.7aC	**11.8 B**
75,000	9.6aB	10.7aB	**10.2 B**	11.9aAB	12.9aB	**12.4 AB**	13.3bAB	14.5aAB	**13.9 B**	12.9aAB	13.5aB	**13.2 AB**
90,000	11.7aA	12.6aA	**12.2 A**	12.6bA	14.7aA	**13.7 A**	14.8aA	15.9aA	**15.4 A**	13.7aA	14.9aA	**14.3 A**
Average	**9.9 a**	**10.7 a**		**12.0 b**	**13.2 a**		**13.5 a**	**14.6 a**		**12.8 a**	**13.4 a**	
-CN≥ Source of variation	O: NS D: ** O × D: *				O: * D: * O × D: *			O: NS D: * O × D: *		O: NS D: * O × D: *		

* Significant at $P < 0.05$, ** Significant at $P < 0.01$; NS, non-significant
The mean values followed by different letters (a, b and c) within a row indicate significant difference between with and without organic manure at $P < 0.05$, n = 3; the mean values followed by different letters (A, B and C) within a column indicate significant difference among three planting densities at $P < 0.05$, n = 3.

Table 4
evapotranspiration (ET) and crop water productivity (WP) of different treatments in four years.

ET (mm)												
Planting Density (Plants ha^{-1}) (D)	2011			2012			2013			2014		
	Organic manure (t ha^{-1}) (O)		Average	Organic manure (t ha^{-1})		Average	Organic manure (t ha^{-1})		Average	Organic manure (t ha^{-1})		Average
	0 (T1, 3, 5)	52.5 (T2, 4, 6)		0 (T1, 3, 5)	52.5 (T2, 4, 6)		0 (T1,3, 5)	52.5 (T2,4, 6)		0 (T1, 3, 5)	52.5 (T2, 4, 6)	
60,000	364	362	**363**	372	380	**376**	457	491	**474**	412	420	**416**
75,000	360	354	**357**	380	387	**384**	452	481	**467**	418	440	**429**
90,000	361	358	**360**	359	378	**369**	486	483	**485**	410	423	**417**
Average	**362**	**358**		**370**	**382**		**465**	**485**		**413**	**428**	
Source of variation	**O: NS D: NS O × D: NS**			**O: NS D: NS O × D: NS**			**O: NS D: NS O × D: NS**			**O: NS D: NS O × D: NS**		
WP (kg mm^{-1})												
60,000	23.2aC	24.6aC	**23.9C**	31.3aB	32.3aB	**31.8 B**	27.1aB	27.4aB	**27.3 B**	28.3aB	27.8aC	**28.1C**
75,000	29.3bB	31.5aB	**30.4 B**	32.7aB	33.3aB	**33.0 B**	29.4aAB	30.1aAB	**29.8 AB**	30.7aAB	30.6aB	**30.7 B**
90,000	32.4bA	35.3aA	**33.9 A**	35.9bA	37.4aA	**36.7 A**	30.5aA	32.8aA	**31.7 A**	33.3bA	35.2aA	**34.3 A**
Average	**28.3 b**	**30.5 a**		**33.3 a**	**34.3 a**		**29.0 a**	**30.1 a**		**30.8 a**	**31.2 a**	
Source of variation	**O: * D: ** O × D: ***			**O: NS D: * O × D: ***			**O: NS D: * O × D:***			**O: NS D: ** O × D: ****		

* Significant at $P < 0.05$, ** Significant at $P < 0.01$; NS, non-significant
The mean values followed by different letters (a, b and c) within a row indicate significant difference between with and without organic manure at $P < 0.05$, n = 3; the mean values followed by different letters (A, B and C) within a column indicate significant difference among three planting densities at $P < 0.05$, n = 3.

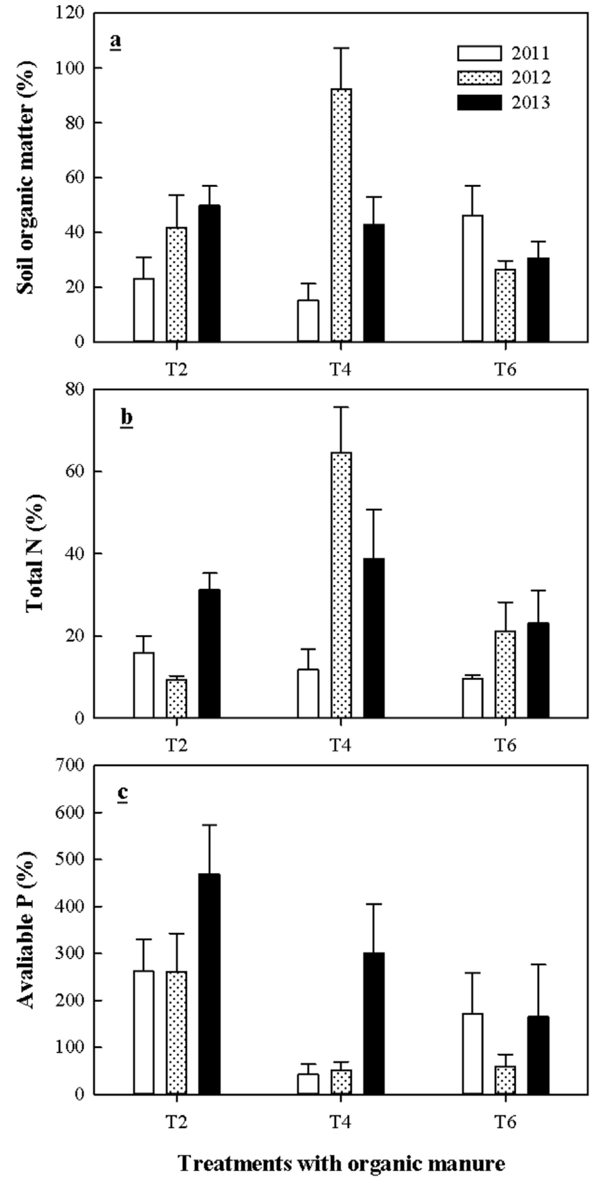

Fig. 5. Relative increments (%) of SOM (a), total N (b) and available P (c) contents in topsoil measured after each harvest from 2011 to 2013 with organic manure applications (T2, T4 and T6) compared to non manure input at respective planting densities.

especially in the dry year of 2014. Consequently, consecutive organic manure input improved soil water uptake in 50–150 cm soil profile and maintained stable SWC in the depth of 0–50 cm and below 150 cm. These results were partly consistent with previous studies on the alleviation of soil water stress by organic manure in dry land farming (Eldardiry et al., 2013; Gajri et al., 1994; Dalal et al., 2011). Addition of organic matter to soil improved both soil water infiltration and water holding capacity, through incorporation of plant residues or manures (Celik et al., 2010; Parija and Kumar, 2013). Notably, the positive effects of organic manure on soil water retention should be in consideration of soil quality, which contributes to sustainable production in the dry land farming region of China.

Long term application of chemical fertilizer resulted in soil compaction, acidification and microbial diversity loss which were the major causes of soil degradation (Gong et al., 2009; Hou et al., 2012). Degraded soil had lower soil organic matter and higher nutrients loss (Gong et al., 2009; Celik et al., 2010). In the present research,

Table 5
Increment rate of grain yield and water productivity (WP) of the organic manure treatments (T2, T4 and T6) compared to non organic manure treatments (T1, T3 and T5) at the respective planting density.

Treatments	Grain yield (%)					WP (%)				
	2011	2012	2013	2014	Mean	2011	2012	2013	2014	Mean
T2	5.3	6.39	8.57	0.78	**5.26**	6.01	5.02	1.07	1.95	**3.51**
T4	11.78	1.42	9.04	4.78	**6.77**	7.4	1.71	2.52	0.43	**3.02**
T6	7.86	16.34	6.88	8.94	**10.00**	8.97	9.75	7.44	5.59	**7.94**

decrease of N, P and SOM in topsoil with only chemical fertilizer application over four years indicated a consistent result of soil fertility deterioration. However, when organic manure was applied in consecutive years, N, P and SOM in the topsoil significantly increased which not only resulted from manure composition but also from organophilic nutrient accumulation (Fig. 4). Over four years, manure helped maintaining stable N, P and SOM in topsoil. With soil organic matter increasing in a long-term organic manure project, soil quality and fertility were simultaneously improved, which provided a solid foundation for sustainable soil productivity (Hou et al., 2012; Dunjana et al., 2012), through prevention of soil nutrients leaching out and locking residual compounds into the topsoil after rapid mineralization (Celik et al., 2010; Pinitpaitoon et al., 2011), then optimizing soil microorganism diversity and enzymatic activity (Edmeades, 2003; Eldardiry et al., 2013). These results also suggested the potential of organic manure for replacing synthetic fertilizer input in a semi-arid farming region (Gong et al., 2009; Liu et al., 2013). According to our results, SOM and N increased by 22.9 and 24.7% over three years, organic manure replacing synthetic fertilizer as an alternative could be feasible, but P increase by 137% suggested that synthetic P input should decrease by 20–90% when extra organic manure is applied, especially in a wet year (2013) and at a lower planting density. Li et al. (2013) indicated that soil P availability depended on soil properties and regional climate variations, the most fundamental of which were soil pH and rainfall distribution.

4.2. Organic manure had a potential for harvest index (HI) increase

Organic manure improved Soil environments e.g. soil physical and chemical properties which favored maize root growth (Zhao et al., 2009; Efthimiadou et al., 2010). A further research about the effects of organic manure on biomass accumulation indicated that favorable root growth caused a large increase in the dry weight of shoots and grains (Maddonni and Otegui, 1996; Jena et al., 2013), and final crop yield (Jokela, 1992; Chen et al., 2012). In the present study, organic manure application showed a great potential for HI increase, which also depended on planting density and consecutive years of manure application (Table 2). Organic manure application for high yield primarily affected root-shoot ratio and then HI (Mohsin et al., 2012; Muhumed, 2014). The insignificant differences of HI in our results possibly related to planting density (Valentinuz and Tollenaar, 2006), the amount of manure input and duration of manure release of nutrients (Abera et al., 2013).

4.3. Grain yield and WP increased under organic manure application

In our results, organic manure treatments generally obtained higher maize grain yield at the three planting densities, even though the effect of organic manure on grain yield was insignificant compared with only chemical fertilizer input treatments. Long term manure application stably increased yield and WP by 7.4 and 4.8%, respectively, over four years (Table 3). It was likely that organic manure improved the soil permeability (Liu et al., 2014; Zhao, 2014), or improved field-saturated hydraulic conductivity (Uzoma et al., 2011), and stimulated root physiological function and adjusted soil water distribution for higher WP (Zhou et al., 2012; Mkhabela and Materechera 2013). It also appears that additional manure application would alleviate the inconsistency between scarce water resources and high water demand for substantial yield (Smaling et al., 1992; Ge et al., 2011). Wang et al. (2010) reported that the combination of organic manure and chemical fertilizer increased the sustained supply of soil nutrients, while reduced the nutrient enrichment of synthetic fertilizer in soil environments. Meanwhile, organic manure benefitted the infiltration of rainwater into the soil and enhanced soil water retention for high crop production and WP (Parija and Kumar, 2013), through improving soil physico-chemical properties (Uzoma et al., 2011). However, Edmeades (2003) reported that there was no significant difference between chemical fertilizer and manure in the long-term effects on crop production, and organic manure might only improve the vegetative organs during crop development (Bilalis and Karamanos, 2010). Therefore, organic manure involved in modern agriculture was vital for achieving higher yield and WP, particularly in dry land farming regions (Gong et al., 2009).

At the three different planting densities, grain yield increased by 5.3%, 6.8% and 10.0%, and WP by 3.5%, 3.0% and 7.9% with organic manure compared to non-organic manure treatments (Tables 3 and 5). This was probably because organic manure optimized photosynthate allocation and root capacity to an efficient extent in different planting densities (Zhou et al., 2012; Gao, 2014). Higher WP under extra manure was mostly attributed to restricted topsoil water evaporation and enhanced rainwater infiltration (Liu et al., 2013), which could have caused the increase in yield and WP at high planting density. Finally, organic manure improved soil water retention, and mineralization or immobilization of soil nutrients when the fertilizer input exceeded crop uptake (Jokela, 1992; Perry, 2011). Application of organic manure would be an alternative strategy for semi-arid farming because it could increase soil water and nutrient storage (Wang et al., 2013).

5. Conclusion

A sustainable and stable increase in yield and WP was observed with consecutive application of organic manure at three planting densities over four years. The stable increase in grain yield under organic manure application was due not only to optimize soil water use but also to the residual soil nutrients retained from previous growing seasons. Organic manure application optimized the water use in 50–150 cm soil layer and enhanced rainwater infiltration from soil surface into deeper soil layer. Correspondingly, organic manure could increase SOM and subsequently decrease SBD, which benefits mineralization and immobilization of residual N and P in topsoil. The findings indicate a better soil environment for maize development, the stable increase of yield and WP over four seasons. Our findings suggest that, for a higher yield and resource use efficiency, farmers could adopt the rational combination of organic manure with appropriate low P and N input at low and medium planting densities.

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