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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