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Effect of straw incorporation on the temporal variations of water characteristics, water – use efficiency and maize biomass production in semi-arid China

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ABSTRACT

Field experiments were conducted in 2008–2010 in the Loess Plateau of China to study the effects of straw incorporation on maize growth and biomass water use efficiency (WUE) under semi-arid condition in dark loessial soil. Low (LS 4.5 t ha^{-1}), medium (MS 9.0 t ha^{-1}), and high (HS 13.5 t ha^{-1}) levels of straw were incorporated into the surface soil combined with fixed levels of inorganic fertilizers (CK) as control. Straw incorporation compared with CK significantly improved biomass yield at the tasseling–maturity stage of maize and WUE at the jointing–ten leaf collar and the tasseling–grain filling stages. WUEs with LS and MS treatments were significantly lower than that with CK at the ten leaf collar–tasseling stage, although the WUEs with MS and HS treatments were significantly higher in the whole growth period. HS treatment compared with LS treatment significantly increased biomass yield at the ten leaf collar–maturity stage and WUE at the jointing–tasseling stage. Meanwhile, MS and HS treatments compared with LS treatment significantly increased the biomass yield at the late grow period. Straw incorporation significantly improved WUE at the sowing–jointing stage and soil organic carbon relative to CK. Biomass yield at the ten leaf collar stage and WUE in whole growth period with LS treatment were significantly higher compared with CK. WUE at the ten leaf collar–tasseling and the grain filling–maturity stages were significantly higher with HS treatment compared with CK. In the long term, the rational straw incorporation level in improving maize biomass yield and WUE was 9.0 t ha^{-1}.

1. Introduction

Water deficiency is a main factor limiting the improvement of agriculture productivity in semi-arid areas (Mupangwa et al., 2008). Since the crop growing season is inconsistent with the rainy season there, drought will occur at the critical growth stages (Wang et al., 2012a). Recycling of crop residues is an effective practice as it can reduce the application of mineral fertilizers (Wang et al., 2013), maintain soil fertility (Bertora et al., 2009; Gami et al., 2009), improve soil biophysical properties (Singh et al., 2007) and soil water (Zhao et al., 2009), and support sustainable crop production(Zhang et al., 2009) in cropping systems. In addition, straw complement will reduce the atmospheric pollution due to open-field straw burning. Wang et al. (2012b) recommended the deep plough incorporated with straw and fertilizers after harvest in autumn and then direct sowing spring maize in spring without any soil cultivation.

Despite many field trials on straw incorporation, most of these studies focus on soil properties and crop yield. As reported, straw incorporation significantly improved grain yield in the second fertilization year (Xu et al., 2010). Maize straw incorporation utmost improved the potential soil respiration, although it did not significantly affect soil organic carbon or microbial biomass (Monaco et al., 2008). Wheat straw incorporation improved infiltration rate and organic carbon in the soil, although it reduced pH and soil bulk density (Karami et al., 2012). The effects of inorganic fertilizer application on carbon sequestation in surface soil mainly depended on the return regime of straw residue (Lou et al., 2011).

However, the maize growth and biomass water-use efficiency (WUE) especially the temporal variations affected by straw complement under dryland farming have not been well documented. Hence, the present study was undertaken to (1) evaluate the effects of straw incorporation combined with

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inorganic fertilizer on maize biomass yield, water properties and WUE at different growth stages of maize in a semi-arid agro-ecosystem; (2) investigate the correlations of WUE among different growth stages and the relationship between WUE and biomass yield. The results provide scientific support on how to optimize agro-management practices for saving water, improving WUE, and obtaining high-yield maize cultivation.

2. Materials and methods

2.1. Site description

Field experiment with maize was conducted on dark loessial soil (sand 26.83%, silt 41.91%, and clay 21.03%) between 2008 and 2010 at the Ganjing Research Station of the Northwest A&F University, Heyang, Shaanxi, China (35°24′N, 110°17′E; 850 m altitude). The mean annual temperature was 9–10 °C. The experimental site was characterized by low and erratic rainfall with drought occurring at different growth stages of maize. The long-term mean annual rainfall was 571.9 mm and the mean annual evaporation was 1832.8 mm. Most of the rainfall occurred from July to September. From 2008 to 2010, the rainfall during the maize growth period was 350.8, 379.1 and 422.3 mm, respectively (Table 1). Analysis of soil samples taken from the same experimental area in April 2007 showed that the top 20 cm of soil was characterized as follows: pH 8.1, soil organic carbon 8.3 g kg^{-1}, total nitrogen (N) 0.8 g kg^{-1}, total phosphorus (P) 0.5 g kg^{-1}, total potassium (K) 8.4 g kg^{-1}, available N 46.5 mg kg^{-1}, available P 9.0 mg kg^{-1}, and available K 106.2 mg kg^{-1}.

2.2. Experimental design

A completely randomized block design was used in the field experiment with four treatments, three replicates, and 4 × 6 m plots. The four treatments were: application of straw at low level (4.5, LS), medium level (9.0, MS), and high level (13.5, HS) t ha^{-1} in combination with chemical fertilizers; application of chemical fertilizers only (CK). The chemical fertilizers contained 255 kg ha^{-1} N and 90 kg ha^{-1} P. The N and P fertilizers were applied separately as basal fertilizers before sowing the maize, at levels of 102 and 90 kg ha^{-1}, respectively. Additional N fertilizer was applied at a level of 153 kg ha^{-1} at the ten leaf collar stage (late July). The maize straw contained 6.0 g N kg^{-1}, 0.6 g P kg^{-1}, and 13.7 g K kg^{-1}. The maize straw at the experiment plots removed after harvest. The removed maize straw was cut into 15 cm long segments, uniformly covered to the experimental plots according to the experimental design and then tilled by a conventional method into 20 cm soil at the end of September. The maize variety was Shendan 16. In each year, maize was planted at a level of 49,500 plants ha^{-1} in mid-April and harvested in mid-September. No irrigation was used in any year.

2.3. Sampling and analysis methods

Soil water content was measured gravimetrically (drying method, w/w) to a depth 200 cm at 20 cm increments before sowing and at different growth stages. Three random locations in each plot were taken to measure soil water storage.

Soil water storage was calculated as follows:

$$S_{W_i} = h \times d \times b_i\% \times 10 \ (\mathrm{i} = \mathrm{sowing, jointing, tenleafcollar, tasseling, grainfilling, maturitystagesofmaize}) \quad (1)$$

where S_W (mm), the soil water storage; h (cm), soil depth; d (g cm^{-3}), soil bulk density; b%, the gravitational water content. Soil water storage was calculated at 0–60 cm soil profile (the active layer of soil water), while that for calculating evapotranspiration was at 0–200 cm soil profile.

Evapotranspiration (ET, mm) was calculated as follows:

$$\mathrm{ET_j} = P_j - D_j - R_j - \Delta S_j - E_{ij} \ (\mathrm{j} = \mathrm{sowing - jointing, jointing - tenleafcollar, tenleafcollar - tasseling, tasseling - grainfilling, grainfilling - maturitystagesofmaize}) \quad (2)$$

where P (mm) is the precipitation, D (mm) the downward drainage outside the root-zone where the crop root spread, R (mm) the surface runoff, ΔS (mm) the change in soil water storage and E_i (mm) is evaporation from intercepted rainfall. In this study, D was ignored because the groundwater was contributed from a water table 50 m below the surface, and the drainage outward the root-zone could not be considered in this area. R was zero because the topography was flat, and E_i was neglected because it was quite constant and accounted for a very small proportion of the water balance compared with other terms (Zhang et al., 2007). ΔS can be either positive or negative. Therefore, Eq. (2) was simplified into:

$$\mathrm{ET_j} = P_j - \Delta S_j (\mathrm{j} = \mathrm{sowing - jointing, jointing - tenleafcollar, tenleafcollar - tasseling, tasseling - grainfilling, grainfilling - maturitystagesofmaize}) \quad (3)$$

WUE (kg ha^{-1} mm^{-1}) was calculated as follows (Hemmat and Eskandari, 2004):

$$\mathrm{WUE_j} = \mathrm{DMY_j/ET_j} \ (\mathrm{j} = \mathrm{sowing - jointing, jointing - tenleafcollar, tenleafcollar - tasseling, tasseling - grainfilling, grainfilling - maturitystagesofmaize}) \quad (4)$$

where DMY (kg ha^{-1}) is the dry matter yield of the maize.

Dry matter yields were measured at different growth stages. All the samples of maize were first dried in an oven at 105 °C for 1 h and then dried at 75 °C to constant weight. Five maize plants were collected per plot and were used (and thus, destroyed) for each measurement at each growth stage. Two 3 m row lengths of maize

Table 1
Rainfall at different growth stages of maize in 2008–2010.

Years	Rainfall (mm)					
	Sowing–jointing stage	Jointing–ten leaf collar stage	Ten leaf collar–tasseling stage	Tasseling–grain filling stage	Grain filling–maturity stage	Whole growth stage
2008	57.7	96.9	27	123.4	45.8	350.8
2009	71.5	111.8	46.6	30.9	118.3	379.1
2010	75.9	37.2	92.4	114	102.8	422.3