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Plastic mulch decreases available energy and evapotranspiration and improves yield and water use efficiency in an irrigated maize cropland

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ABSTRACT

Plastic film mulch has been widely adopted in recent decades in the arid region of northwest China, and the practice changes the energy budget of the soil surface, crop water use and plant growth and yield. However, there are few studies that quantify differences in the energy balance, water use, plant growth and water use efficiency (WUE) with and without plastic film mulch. Energy components, crop evapotranspiration, plant growth and yield were measured in a mulched (M) and unmulched (NM) maize field in 2014 and 2015. The results showed that diurnal net radiation (R_n) was lower while soil heat flux (G) was higher for the M treatment than in the NM on typical sunny days. Diurnal pattern of G was the same as R_n but the maximum lagged by 0.5–2 h. For the M treatment, the duration of $R_n > 0$ was less than that of the NM for 96 days, i.e., 61% of the whole growth period. Plastic film mulch decreased daily R_n, as the linear regression of R_n with the R_n of unmulched treatment had a slope of 0.90. Plastic film mulch reduced ET as the available energy decreased. The total ET was 524 and 557 mm with daily mean values of 3.3 and 3.5 mm d^{-1} in 2014, and 550 and 575 mm with daily mean values of 3.5 and 3.7 mm d^{-1} in 2015 for M and NM, respectively. A better curvilinear relationship was found between ET for M and NM for two years, with R^2 of 0.95 and 0.90, respectively. The plastic film mulch decreased crop coefficient but accelerated plant growth and advanced maize maturity, and thus increased yield and WUE.

1. Introduction

Maize is one of main cereal crops in the arid region of northwest China, where water shortage is a major yield limiting factor. To reduce soil evaporation in the field and conserve water resources, soil surface mulched by plastic film has been widely adopted in recent decades in the region (Dong et al., 2009; Hou et al., 2010; Zhao et al., 2010). Many studies indicated that ground mulch can not only reduce water loss from soil evaporation, but also accelerate crop development during the early growth stage by increasing soil temperature and controlling weeds (Allen et al., 1998; Hou et al., 2010). By covering the soil surface, plastic film mulch can modify the energy exchange between the soil, mulch and atmosphere, thus the complexity of the process makes it important to analyze the effect of plastic film on the energy budget of the soil surface. Clear or white thin plastic mulch increases the albedo of the ground surface and such change would affect the crop microclimate environment and energy balance at the soil surface (Allen et al., 1998; Ding et al., 2013; Oebker and Hopen, 1974). Soil temperature and moisture regimes are the major determinant of the thermal microclimate of the soil and are related to the absorbed solar energy, and in turn the energy budget is controlled by both soil thermal and water conditions (Gong et al., 2015; Li et al., 2001; Kool et al., 2016).

Energy components under mulched conditions include net radiation (R_n), soil heat flux (G), latent heat flux (λET) and sensible heat flux (H). R_n represents the net flux density of radiation absorbed by the surface and depends on the surface reflectivity, absorptivity and temperature (Campbell and Norman, 1998). Spatial and temporal variability in G was found to be significant under the mulched condition (Giambelluca et al., 2009; Tarara, 2000). The previous studies indicated that plastic mulch could increase the shortwave reflectivity (Liakatas et al., 1986), reduce the shortwave absorptance (Ham et al., 1993), strongly affect the field temperature, soil heat flux, and net radiation, and thus have a direct effect on physiological characteristics of the plant (Decoteau et al., 1988). However, there are few studies that quantify the differences of energy balance and

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plant growth between with and without plastic film mulch in a side-by-side comparison.

The latent heat flux (evapotranspiration, *ET*) is a key variable connecting energy and water budget in cropland. *ET* is the largest term in the terrestrial water balance behind precipitation, and also a major component of the energy balance (Burba and Verma, 2005). There are numerous studies demonstrating that mulch would affect the two components of *ET*, i.e. soil evaporation (*E*) and crop transpiration (*T*), by reducing the soil water loss caused by evaporation, and thus leaving more water available in the soil for transpiration (Moitra et al., 1996), through increasing soil water storage and soil temperature (Chakraborty et al., 2010; Li et al., 2009; Ramakrishna et al., 2006; Sharma et al., 2011). However, it remains unclear whether there are significant differences in *ET* over the different growth stages between with and without plastic mulch, and whether plastic film can lead to higher yield with less *ET*, compared to that without-plastic mulch in northwest China.

In this study, energy budget components, crop evapotranspiration, plant growth and yield were measured in mulched (M) and unmulched (NM) seed maize field in an arid region of northwest China. The main objectives were to (1) quantify differences in energy balance components, crop evapotranspiration, yield and water use efficiency (WUE) in the two treatments, and (2) understand the mechanisms contributing to the possible differences in crop water use, yield and WUE in the mulched treatment.

2. Materials and methods

2.1. Experimental site and design

The experiment was carried out at Shiyanghe Experimental Station for Water-saving in Agriculture and Ecology of China Agricultural University located in Wuwei city, Gansu province of northwest China. (N 37°51′, E 102°52′, altitude 1581 m) from April to September in 2014 and 2015. The site is in a typical arid continental temperate climate zone, with abundant light and heat resources, a mean annual sunshine duration more than 3000 h, an average annual temperature of 8 °C, a frost-free period greater than 150 days. However the region is scare in water resources with a mean annual precipitation of 164 mm and mean annual evaporation from a free water surface of 2000 mm. The groundwater table is 30–40 m below the ground surface. The soil is sandy loam with mean soil dry bulk density of 1.40 g cm^{-3}, field capacity of 30% and permanent wilting point of 11%.

The experiment design was a complete random design comprising two treatments, with and without plastic film mulch (M, NM), and each treatment had three replicates with a plot of north-south length of 9 m and west-east length of 12.6 m. Soil surfaces were partly covered with strips of clear plastic film with a thickness of 0.04 mm and width of 140 cm and there were 4 rows of maize on each strip of mulch. The bare soil between plastic film strips was 20 cm. Maize seed was sown through 5.0 cm diameter holes in the plastic film with one-row male parents and five-row female parents, where the plant spacing was 25 cm and row spacing ~40 cm, and there was no maize plant in the bare soil (Fig. 1). Thus, actual ground-mulched fraction was ~0.7, which was defined as one minus the ratio of the summed surface areas of bare soil and holes to ground area. Seed maize was sown on 15 April and harvested on 20 September in 2014, and was sown on 17 April and harvested on 20 September in 2015.

Border-irrigation was applied to each plot through bare soil surfaces and holes in the plastic film, which made soil water evenly infiltration by the water re-distribution. The amount of water applied to each treatment was measured by turbine flow meters and recorded. Irrigation amounts were based on preceding *ET* estimated by crop coefficient method minus precipitation, and soil water deficit was determined by water balance. Soil water deficit was calculated as the difference of field capacity and observed soil water content (SWC) in the rootzone. Over the entire growing season in 2014, maize was border-irrigated four times on 13 June, 12 July, 31 July, and 21 August for mulched treatment, and 13 June, 7 July, 25 July, and 21 August for unmulched treatment with total irrigation water of 272.5 mm and 337.4 mm, respectively. In 2015, maize was border-irrigated six times for the two treatment on 8 June, 27 June, 19 July, 6 August, 20 August, and 2 September with total irrigation water of 425 mm and 475 mm for M and NM, respectively. In accordance with local practice, fertilizers were applied at the rate of 420 kg ha^{-1} N in 2014 and 390 kg ha^{-1} N in 2015. Meanwhile, 240 kg ha^{-1} P_2O_5 and 50 kg ha^{-1} K_2O were applied in each year. Entire dose of potassium and phosphate were applied as broadcast pre-plant but 50% of nitrogen as basal and the remaining 50% applied on the day of the first irrigation.

2.2. Energy balance measurements

Net radiation (R_n) was measured by two net radiometers (QTC-4, Jinzhou Sunshine Technology Co. Ltd, Liaoning, China) in the center of every representative plot of the M and NM treatments at a

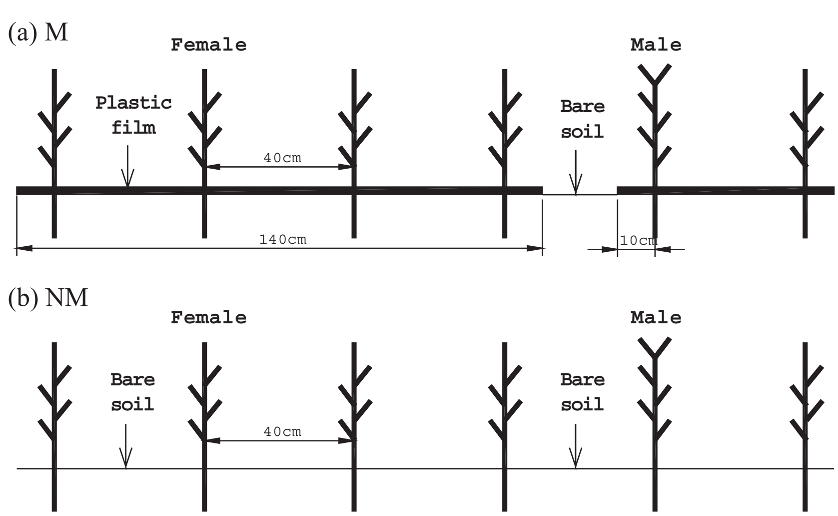

Fig. 1. The schematic diagrams of the mulch and planting configuration in both experiment years. (a) Soil surface partly mulched by clear plastic film (M), and (b) without mulch (NM). The proportion of male and female plants is 1:5.

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