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Gravel-sand mulch thickness effects on soil temperature, evaporation, water use efficiency and yield of watermelon in semi-arid Loess Plateau, China

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ABSTRACT

Mulch thickness is one of the important factors affecting soil moisture and temperature. Two field experiments were conducted at Gaolan, Gansu, China, to investigate the influence of gravel-sand mixture mulch thickness on soil temperature, evaporation, evapotranspiration, water use efficiency (WUE) and yield. There were 5 levels of gravel-sand mulch thickness in Experiment 1 (3, 5, 7, 9 and 11 cm; without crop) and 4 levels of gravel-sand mulch thickness plus 80% plastic film mulch in Experiment 2 (3, 5, 8 and 11 cm; cropped to watermelon). There was a close negative relationship between mulch thickness and soil evaporation, with exponential function. Mulch decreased soil evaporation up to a thickness of 7 cm. The soil temperature from 11:00 to 18:00 was slightly lower with mulching compared to no mulching and, as a result, mulch not only decreased the temperature difference between day and night, but also it had a lag. In addition, the peak soil temperature at 5 cm depth was reduced and the soil temperature at night was raised with increased mulch thickness. Mulch had no further effect on soil temperature when thickness is greater than 7 cm. With 80% plastic film mulch, a significant effect on watermelon yield and WUE was detected among the different treatments used in this study, with the highest yield and WUE obtained with the 8 cm mulch thickness treatment. Therefore, 7–8 cm of mulch thickness appears to be the most appropriate option for gravel-sand mulch to sustain high watermelon yield and WUE.

1. Introduction

Gravel and sand mulch is a traditional water conservation technique that has been used for hundreds of years in the loess area of northwestern China. Recently, this technique has expanded its usage, due to the lack of water sources and high irrigation costs. In parts of this region, irrigating fields have almost been replaced by the use of gravel-sand mulch on dry land. Extensive research and practical experience have proved that gravel-sand mulch could markedly reduce soil evaporation and increase soil temperature at night as well as reduce soil temperature fluctuations ([1–5]). Nachtergaele et al. (1998) determined that gravel mulch causes a significant increase in the soil temperature measured at two soil depths (mean increase of 1.0 °C and 1.5 °C at 3 and 10 cm soil depth, respectively) in vineyards of southern Switzerland. Chen et al. [6] and Xie et al. [5] studied the effect of gravel size on soil evaporation, and showed a positive linear relationship between gravel size and soil evaporation. Also, gravel size impacted the porosity of mulch layer and the process of hydraulic transfer and thermal conduction [7].

Besides gravel size, however, there has been little research reported in the literature with respect to mulch thickness as another important factor affecting hydraulic transfer and thermal conduction. Tsutomu et al. [8] measured the influence of mulch thickness on soil evaporation resistance. His results showed that soil evaporation resistance can exponentially increase with the increase of mulch thickness. In China, the mulch thickness effect on soil temperature was only mentioned in reference to the ballast embankment and revetment along the Tibet-Qing railway [9]. However, the purpose of using mulch is totally different between the revetment of an embankment and mulching of farm land. In addition, gravel-sand mulch is a high-cost technique under conservation tillage (no-tillage) and its thickness is a considerable factor when linked with the total cost. Thus, it is essential to determine the impact of mulch thickness on soil evaporation and temperature, in order to optimize the structure of the gravel-sand layer to preserve maximum soil temperature and moisture at the minimum cost. Therefore, the objective of this study was to investigate the influence of mulch thickness on soil temperature and evaporation (Experiment 1, without crop), and to determine the relationship between mulch

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thickness and evapotranspiration, water use efficiency (WUE) or yield (Experiment 2, cropped to watermelon, *Citrullus lanatus*).

2. Materials and methods

2.1. Climate and soil

This study was conducted at the Gaolan Research Station of Ecology and Agriculture, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences. The station is located in the Northwest Loess Plateau (Gaolan County, Lanzhou, Gansu Province; 36°13′N, 103°47′E) at an altitude of approximately 1800 m asl. Based on 30 years of records, the mean annual rainfall totals 263 mm, of which nearly 70% falls between May and September. Average annual pan evaporation is 1786 mm. The region's mean annual temperature is 8.4 °C, with a maximum of 20.7 °C in July and a minimum of –9.1 °C in January. The depth to groundwater is more than 120 m, which is far too deep for this water to be accessible to plants. The soil is a silt loam (sand, 123 g kg^{-1}; silt, 669 g kg^{-1}; clay, 208 g kg^{-1}) of loess origin, which belongs to the Haplic Orthic Aridisols. Soil moisture content at field capacity and permanent wilting point averaged 24.5 and 9.0% by weight, respectively. The bulk density for the top 1.6 m of soil averaged 1.33 g cm^{-3}.

2.2. Experimental design

2.2.1. Experiment 1

The field experiment was conducted without crop to examine the response of soil temperature or evaporation to mulch thickness of gravel-sand mixture in 2006, 2007 and 2008. We designed five levels of mulch thickness: 3, 5, 7, 9 and 11 cm. Mixed layer was consisted a 30% of 0.3–2 cm fine sand, a 40% of 2–4 cm medium gravel and a 30% of coarse pebble. Bare plot was control. The treatments were arranged in a randomized complete block design (RCBD), with 3 replications. The area of plot was 4.5 m^2 (1.5 m × 3 m). In this experiment, there was no plastic film mulch since no crop was cultivated. Soil temperature was measured at 5, 10, 15 and 20 cm depths, respectively, in gravel mulch, gravel plus plastic film mulch and bare plot. Daily soil temperature variation was observed in two typical days (cloudy and sunshine) in 2009.

2.2.2. Experiment 2

The field experiment with watermelon was conducted in a gravel-sand mixture mulched field from 2006 to 2008. Gravel size, combined with mulch thickness, was considered in this experiment. There were 2 sizes of gravel (0.3–1 and 1–2 cm diameter) and 4 levels of mulch thickness (3, 5, 8 and 11 cm). The eight treatments were arranged in an RCBD with 3 replications. Watermelon ('Xinong-8' variety) was seeded at an in-row spacing of 1.0 m, in rows that were 0.6 m apart. After planting, 80% of the area of each plot was mulched using plastic film 0.012 mm in thickness to reduce water loss throughout the watermelon growth period. Plastic film was applied and removed every year. Gravel-mulch was applied and left intact from 2006 to 2008 (no-tillage). Mulch layer was swept up by a small board during fertilizer application and covered back after fertilization. Manure (30,000 kg ha^{-1}), oil cake fertilizer (1500 kg ha^{-1}), as well as inorganic fertilizer were applied directly in the rows to provide 150 kg N, 90 kg P_2O_5, and 99 kg K_2O ha^{-1} to the experimental field. Hole seeding was used with a 2 cm soil plus 1 cm sand cover and then plastic film mulched entirely. After seedling emergence, a hole was punched into the plastic above each seedling [3].

2.2.3. Measurements

Two micro-lysimeters were installed in each plot (Experiment 1 only), to measure soil evaporation. Measurements of soil evaporation were made using micro-lysimeters containing undisturbed samples [10]. The micro-lysimeter casing and the pipe lining the holes, in which the micro-lysimeters were mounted, were both constructed from un-plasticized polyvinyl chloride (PVC) pipe. The dimension of the micro-lysimeters was 11 cm internal diameter and 15 cm in length. The liner tube was 12 cm internal diameter and 15 cm in length. The weight loss was recorded using an electronic scale (sensitivity is 0.01 g), and then put into the liner tube. Both tubes were put into the hole where undisturbed soil had been taken. Lysimeters with undisturbed soil were weighed each day at 8:00 a.m. To minimize the difference of soil core and its soil surrounding, an undisturbed soil core was renewed every four days under normal conditions, but it was immediately done after rainfall [4].

Soil temperature was measured, using a geothermometer, from two locations in each plot (Experiment 1 only) at the 5, 10, 15 and 20 cm depths, starting from the original soil surface (0 cm) prior to adding mulch. Measurements were taken 3 times a year (May to September), within 10 consecutive days each time.

Gravimetric soil water content was measured at 10 cm intervals in the top 40 cm of soil and at 20 cm intervals from the 40 to 160 cm depth, at four randomly selected locations in each plot, every 10 days between planting and harvesting. These samples were oven-dried at 105 °C for 24 hours.

We used a standard rain gauge to record the amount of rainfall. Evapotranspiration (ET) was determined using the following formula:

$$ET = P - D - \Delta W$$

where P is the total precipitation during the watermelon growing season, D is the drainage, and ΔW is the variation in water content of the soil profile (all values in mm) between planting and harvesting or between growth stages. Sixty percent of rainfall provided less than 5 mm of rain, and 79% of the rainfall intensities were less than 5 mm h^{-1} at the experimental site. The experimental area was level and no surface runoff occurred. The soil moisture measurements indicated that drainage (D) at the study site was negligible [3,4].

Water-use efficiency (WUE) was calculated as the watermelon yield (kg fresh weight ha^{-1}) divided by total ET. All data were subjected to analysis of variance (ANOVA) using SPSS10.0, and means were tested for significance by least significant difference ($LSD_{0.05}$) procedure for each experiment.

3. Results

3.1. Effect of mulch thickness on soil evaporation

Mulch thickness had a significant impact on soil evaporation, and there was a close power-series relationship between the two factors (Fig. 1). When the mulch thickness was less than 7 cm, the evaporation sharply decreased as mulch thickness increased, and evaporation was greater for coarse than for fine gravel. However, when the mulch thickness was >7 cm, the evaporation decreased slowly with increasing mulch thickness, and there was little difference between coarse gravel and fine gravel.

3.2. Effect of mulch thickness on soil temperature

Figure 2 shows the trends of daily soil temperature at 5 and 10 cm depths for mulch thickness treatments. The daily soil temperature in the 11 cm mulch thickness treatment was very similar to 9 cm mulch thickness treatment. The results indicated that the soil temperature at 5 and 10 cm depths was higher for all mulched treatments than for the non-mulched ones from 23:00 (night) to 8:00 (morning), and increased slightly with increased thickness of mulch (Fig. 2). However, soil temperature between 11:00 and 18:00 was