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Simulation of soil water and heat flow in ridge cultivation with plastic film mulching system on the Chinese Loess Plateau

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ABSTRACT

A widespread measure for improvement of soil water use efficiency (WUE) in the semi-arid region of China is ridge cultivation with plastic film mulching system. However, the modification of soil water and heat flow under this management system is not well understood. The objective of this study was to understand soil water and heat coupling processes by monitoring and modeling of soil water and temperature dynamics in this system that is commonly used on the semi-arid Chinese Loess Plateau. Four treatments were investigated: conventional fertilization (CK, control), recommended fertilization (RF), straw mulching based on RF (SM), and straw mulching in furrows plus plastic film mulching on soil ridges based on RF (FM). Based on the field monitoring results, the process-based model HYDRUS-2D was calibrated to simulate the soil hydrothermal processes for the different treatments, each represented by specific boundary conditions at the soil surface. The model simulations have a good agreement with the field observation, showed that there are significant differences in soil water contents (5%) among the four treatments, with the FM treatment having the highest water storage and the highest WUE. While soil daily mean temperature was very similar, the daily temperature fluctuations were significantly higher under the plastic film mulching compared to the other treatments. The FM treatment performed better during the cold year than a warm year, improved crop production and water resource use through reduced evaporation and elevated transpiration. The modeling approach presented here is an efficient way to clarify the mechanisms of root-zone water and temperature dynamics under mulching and/or tillage that could be adopted for optimizing soil hydrothermal management in this region.

1. Introduction

With arid regions comprising about 45% of the earth's land surface, dryland farming systems may constitute the world's largest biome that will be indispensable for future food production (Schimel, 2010). Limited precipitation is the major constraints to crop production in semiarid regions, such as the Chinese Loess Plateau (Zhang et al., 2009; Liu et al., 2009). To overcome the shortage of water resources, mulching is being widely applied within this region (Dong et al., 2009). Particularly, ridge cultivation with plastic film mulching system (FM), which consists of alternate ridges and furrows, with the ridges covered with plastic film, was recently and intensively introduced to improve soil water storage and increase crop production (Li and Gong, 2002).

Historically, straw mulch has been well tested in northwestern China (Li et al., 2013), and plastic film mulch has been widely used since 1978 (Dong et al., 2009). Both mulch practices may greatly improve grain yields due to increased soil moisture (Liu et al., 2009) and reduced soil evaporation (Steiner, 1989), and increased or decreased topsoil temperatures depending on the growth period (Zhou et al., 2009). However, the decrease of grain yield was observed, primarily due to the over-consumption of plant available water during the first stage of wheat growth (Li et al., 2001a,b). The FM treatment was considered to be the most efficient mulching arrangement to increase water use efficiency (WUE) by maximizing the use of sparse rainfall (Li et al., 2013), however, the mechanisms behind are not clearly understood because soil micro-topography and mulching result in a non-uniform distribution of water and heat. To optimize mulching practices, it is essentially required to understand what extent the water and heat flow regime is modified in this system. In previous studies, soil moisture and temperature was compared among different mulching

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arrangements (e.g., ridge cultivation with plastic film mulching, full plastic film mulching or double-furrow cultivation with plastic film mulching) or mulching periods (e.g., mulching during whole growing season or before maturity) (Li et al., 2004; Zhou et al., 2009; Zhang et al., 2012). However, these studies did not distinguish the potential differences in soil water and temperature between plastic film-mulched ridges and bare furrows in the entire root zone, so water storage and WUE could not be established with certainty (Qi et al., 2016).

Water and heat flow in ridge and furrow systems are difficult to measure, but modeling can help to better understand the complex interplay between water and heat. A plastic film mulched ridge will direct runoff to the furrow (Filipovic et al., 2016), where water then infiltrates and redistributes into the subsurface soil of the ridge which is driven by lateral matric potential gradients. Whereas, an improperly designed ridge mulching system has disadvantages (e.g., greater deep water percolation and even nutrient leaching, less planting area, and lower WUE), an optimally designed ridge-furrow geometry should produce greater soil water storage and overall a higher WUE (Zhang et al., 2013a,b). In addition, the greenhouse-like effects introduced by the plastic film traps solar energy, and thus may result in increased air and soil temperature beneath the film. Alternately, the furrow may receive less direct solar energy because of the ridge shade that would likely result in lower rates of evaporation within the furrow. The coupled soil water and heat flow processes under a FM system are complex and not well understood from a quantitative perspective.

Several software packages are available to simulate soil water and heat flow based on Richards' equation, such as SVAT (Jansson and Halldin, 1980), SHAW (Flerchinger and Saxton, 1989), and HYDRUS-2D (Sejna et al., 2011). HYDRUS-2D is a Windows-based computer software program for simulating water, heat, and/or solute transport in a two-dimensional (2D) variably-saturated porous medium. The model has been used extensively to simulate water and/or heat flow in agricultural soils (Abbasi et al., 2004; Kandelous and Simunek, 2010). Understanding variables affecting soil water and temperature distribution through modeling is needed for optimized design and better mulching managements. 2D models are particularly suitable for such modeling studies because the spatial configuration of ridge-furrow cultivations can be explicitly taken into account. Dusek et al. (2010) evaluated the effects of model dimensionality (S1D and S2D models) on water flow in a drip irrigated plastic film mulched field. The HYDRUS-2D model have been proved to accurately simulate 2D soil water movement in ridge-furrow irrigation system (Zhang et al., 2013a,b), or under biodegradable plastic film mulch (Saglam et al., 2017). While those models have addressed key issues of water flow in a 2D complex system (Ruidisch et al., 2013), they did not account for soil heat flow which is an important variable that is affected by the mulching system. Based on our knowledge, there is very limited HYDRUS-2D application, in terms of fully coupled non-isothermal water and heat simulation in 2D (Wang et al., 2013).

In this study, our objectives are to: (1) test a modeling approach for a cross-sectional ridge-furrow configuration by calibrating and validating the physically-based HYDRUS-2D model, (2) simulate 2D moisture and temperature distributions under different treatments, and (3) clarify the interactions of soil water and temperature, associated with climate conditions, which may provide guidance for the efficient design of cultivation and mulching systems in the semiarid Chinese Loess Plateau.

2. Materials and methods

2.1. Experimental sites and treatments

The experiment was conducted for three cropping seasons (i.e., 2010–2011 for season 1, 2011–2012 for season 2, and 2012–2013 for season 3) at the Changwu Agricultural and Ecological Experimental Station (35.28 N, 107.88 E; 1,200 m a. s. l.), which is a typical dryland farming area on the Loess Plateau of China (Jiang et al., 2016). Dryland farming is dominated by monoculture cropping systems that are mainly comprised of winter wheat (*Triticum aestivum L.*). The area has a dry moderate inner-continental climate. The average annual precipitation from 1957 to 2012 was 582 mm, with 45% of the precipitation falling during the winter wheat growing season between October to June. The annual mean air temperature is 9.7 °C. The soils are Cumuli-Ustic Isohumosols with a silt loam texture according to the Chinese Soil Taxonomy (Gong and Zhang, 2007). The organic matter, total nitrogen, available phosphorus, available potassium, and inorganic nitrogen contents for the 0–20 cm soil depth at the beginning of the experiment are 11.8 g kg^{-1}, 0.87 g kg^{-1}, 14.4 mg kg^{-1}, 144.6 mg kg^{-1}, and 3.15 mg kg^{-1}, respectively.

In this experiment, four treatments were evaluated: (1) the flat cultivation with the conventional fertilization (CK, control), (2) the flat cultivation with the recommended (reduced) fertilization (RF), (3) the same with RF, plus straw mulching (100% surface coverage) with all straw (ca 4,500 kg ha^{-1}) harvested from the previous wheat (SM), and (4) the recommended fertilization plus straw mulching in furrows (30 cm width; 100% coverage) with impermeable transparent film mulching (0.008-mm-thick polyethylene) placed on the soil ridges (30 cm width and 10 cm height) (FM). Nitrogen in the form of urea (N 46%) was applied at a rate of 162 kg N ha^{-1} for the CK treatment prior to sowing, while the other three treatments received urea prior to sowing (112 kg N ha^{-1} broadcasting manually over the soil surface, and then plowed into the subsurface as a basal dressing) and a second time before reviving (and 38 kg N ha^{-1} using a hole-sowing machine following precipitation). A 105 kg phosphorus (P) ha^{-1} was applied as calcium superphosphate (P_2O_5 12%) and 80 kg potassium (K) ha^{-1} were applied as potassium sulfate (K_2O 45%) at the same time that the basal N fertilizer was applied to each plot.

Each treatment was replicated four times in a completely randomized block design with each plot size 22.0 m in length and 6.0 m in width. The distance between two adjacent plots was 1.5 m. A high-yielding wheat hybrid (*Changwu 521*) was selected for this study. Planting holes were spaced 15 cm apart with a 30-cm distance between plant rows, and furrow seeding was used in the FM treatment. In the SM plots, straw was homogeneously distributed on the soil surface after the sowing operation. In the FM plots, the plastic film was laid out by hand over the ridges, and the joints were secured by embedding the edges of plastic film into the soil. After harvest, the plastic film was kept in the field during the fallow season until the next planting at the end of September or early October, at which time the plastic film was cleared, wheat stalks removed and the plots were ploughed by spade. There was no irrigation applied during the wheat-growing season.

2.2. Field measurements

Before the measurements started in 2010, soil profiles were dug and FDR (frequency domain reflectometry) tubes (Theta probe PR2, Delta-T, Cambridge) were installed within each plot. The FDR sensors were used to manually record soil moisture at soil depths of 10, 20, 40, 60 and 100 cm, about once per week during the entire study. The sensors were site-specific calibrated in the field by comparing gravimetrically determined soil water contents with the readings. A paired *t*-test analysis was used to compare the soil properties for the different soil profiles which indicated no significant difference among the profiles (Table 1). Each FM cultivation included two FDR tubes (one measured the ridge under plastic film coverage: FM-R, and one measured the furrow under straw coverage: FM-F). The soil temperature at the 5 and 10 cm depths were recorded at 30-min intervals by TidbiT v2 tiny temperature recorder (Onset Computer Corporation, USA). Based on these measurements, growing degree day (GDD, °C) values (i.e., accumulated integral of soil temperature) were calculated using the following equation: