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Optimization of irrigation scheduling for spring wheat with mulching and limited irrigation water in an arid climate

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ABSTRACT

Combining mulch and irrigation scheduling may lead to an increase of crop yield and water use efficiency (WUE = crop yield/evapotranspiration) with limited irrigation water, especially in arid regions. Based on 2 years' field experiments with ten irrigation-mulching treatments of spring wheat (*Triticum aestivum* L.) in the Shiyang River Basin Experiment Station in Gansu Province of Northwest China, a simulation-based optimization model for deficit irrigation scheduling of plastic mulching spring wheat was used to analyze optimal irrigation scheduling for different deficit irrigation scenarios. Results revealed that mulching may increase maximum grain yield without water stress by 0.4–0.6 t ha^{-1} in different years and WUE by 0.2–0.3 kg m^{-3} for different irrigation amounts compared with no mulching. Yield of plastic mulching spring wheat was more sensitive to water stress in the early and development growth stages with an increase of cumulative crop water sensitive index (CCWSI) by 42%, and less sensitive to water stress in the mid and late growth stages with a reduction of CCWSI by 24%. For a relative wet year, when irrigation water is only applied once, it should be at the mid to end of booting growth stage. Two irrigations should be applied at the beginning of booting and heading growth stages. The irrigation date can be extended to the beginning of jointing and grain formation growth stages with more water available for irrigation. For a normal or a dry year, the first irrigation should be applied 5–8 days earlier than the wet year. The highest WUE of 3.6 kg m^{-3} was achieved with 180 mm of irrigation applied twice for mulching in a wet year. Combining mulch and optimal deficit irrigation scheduling is an effective way to increase crop yield and WUE in arid regions.

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1. Introduction

Water shortage is a frequent occurrence in arid and semiarid regions, which is a limiting factor for crop growth in these regions. Therefore, it is important to use limited water resources more efficiently to increase crop yield and water use efficiency (WUE = crop yield/evapotranspiration (ET)). At a cropland scale, this may be achieved by a combination of management (such as optimal irrigation scheduling) and agronomic (such as plastic or straw mulch) measures under a specific irrigation method.

Appropriate irrigation scheduling to allocate limited irrigation water properly in time and space is an effective way to balance water-saving and high crop yield by improving the marginal benefit produced by per unit water (Fereres and Soriano, 2007). For this purpose, appropriate optimization method or simulation-based optimization method (Singh, 2012, 2014a; Allam et al., 2016) can be used.

Optimization methods applied to deficit irrigation usually aims to maximize an objective function such as crop yield, net benefit, or WUE under several constraints (Garcia-Vila et al., 2009; Akhtar et al., 2013; Garg and Dadhich, 2014; Leite et al., 2015). Traditional optimization methods mainly include linear (Anwar and Clarke, 2001; Lu et al., 2011), nonlinear (Benli and Kodal, 2003; Ghahraman and Sepaskhah, 2004), and dynamic programming (Prasad et al., 2006; Jin et al., 2012). In recent years, some new methods have been used in irrigation scheduling, including genetic algorithms (GA) (Wu et al., 2007; Moghaddasi et al., 2010), an effective global random search method, and simulated annealing algorithms (Brown et al., 2010), a probabilistic technique for approximating the global optimum. However, pure optimization methods usually over-simplified the impact of irrigation on cropland ET, field water balance, and crop growth and yield, and can find the optimal irrigation amount in a growth stage or time

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interval that is not readily available for irrigation water management (Mao and Shang, 2014).

To solve this problem, simulation-based optimization methods were used in water resources allocation (Safavi et al., 2010; Sedki and Ouazar, 2011; Singh, 2014b) and irrigation scheduling (Shang, 2005; Shang and Mao, 2006; Soundharajan and Sudheer, 2009) for its advantages of determining the irrigation time accurately. The simulation-based optimization method integrates the superiority of simulation models in describing the ET process and crop yield and optimization algorithm in finding the optimal solution. Therefore, it is appropriate to be used in irrigation scheduling by fully considering the complex relations of irrigation with ET and crop yield.

Mulching is an important agronomic practice to improve WUE and crop yield for its effect of reducing soil water evaporation (*E*), conserving soil water, increasing soil temperature, and aiding in weed control (Allen et al., 1998; Igbadun et al., 2012). It was reported to be suitable for most crops, such as spring wheat (Li et al., 1999; Xie et al., 2005), maize (Li et al., 2013; Fan et al., 2016), and vegetables (Moreno and Moreno, 2008; Yaghi et al., 2013). However, some studies have also found that mulch would cause a higher ET than non-mulch because increased leaf area index (LAI) in mulching field significantly increased crop transpiration (*T*) (Xie et al., 2005; Chen et al., 2015). Consequently, inappropriate irrigation scheduling may cause a more severe water stress in some growth stages and result in a yield reduction for mulching cropland. Du et al. (2003) indicated that the mulch might even lead to a lower yield in cases of low initial soil water or long-time mulch in semiarid area. Therefore, the impact of mulching on ET and yield should be further studied.

Deficit irrigation, defined as the application of water below full irrigation (Fereres and Soriano, 2007), was also combined with mulch technology to reduce irrigation water use and to attain a higher crop yield. The effects of different irrigation scheduling and mulch on yield and WUE of various crops was investigated, such as wheat (Humphreys et al., 2011; Ram et al., 2013), tomato (Kere et al., 2003; Mukherjee et al., 2012), and other economic crops (Nayak et al., 2015; Kaur and Brar, 2016). Most of those studies designed the irrigation scheduling based on different irrigation frequency or irrigation amount of each application, which is usually sub-optimal irrigation water management and not applicable to cases with limited irrigation water.

Therefore, appropriate combination of optimal irrigation scheduling and mulching can be an effective way to increase crop yield and WUE in arid regions with limited water for irrigation. The main objectives of the current study were to develop a daily scale simulation-based optimization model for optimal irrigation scheduling to study optimal irrigation scheduling at different deficit irrigation scenarios for spring wheat (*Triticum aestivum* L.) in an arid region of Northwest China.

2. Material and methods

2.1. Simulation-based optimization method for irrigation scheduling of mulching cropland

Simulation-based optimization method applied to optimize crop irrigation scheduling with limited water and plastic mulch is composed of three parts, field water balance model, crop yield simulation model, and optimization method for irrigation scheduling (Fig. 1). First, for a specified irrigation scheduling (B2 in Fig. 1), the dynamic process of ET (B8) can be attained based on simulation of field water balance (B3-B8). Second, the relationship between crop ET and yield can be expressed by a crop-water production function (B11), where the crop water sensitivity index (CWSI, B10) was

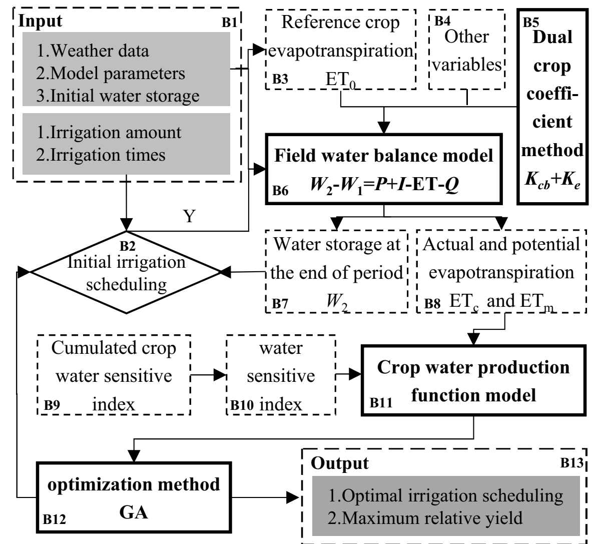

Fig 1. Schematic diagram of crop simulation-based optimization model for irrigation scheduling.

estimated from a cumulative crop water sensitive index (CCWSI, B9). Third, the optimal irrigation scheduling for maximum yield can be achieved by the optimization model (B12) for a given available irrigation amount (B1). The input (B1) of the method mainly includes weather data, model parameters, initial soil water storage, total irrigation amount and irrigation times, which are then used to attain an optimal irrigation scheduling and maximum relative yield as model output (B13).

2.1.1. Field water balance model

Field water balance model depicts the balance of input, output and change of soil water storage (SWS) in the effective root zone. As shown in Fig. 1 (B6), the water balance in the crop root zone can be expressed as (Shang, 2005)

$$W_{i+1} - W_i = P_i + I_i - \mathrm{ET}_i - Q_i - \mathrm{R_i} \tag{1}$$

where W_{i+1} and W_i are the SWS at the beginning of the (*i+1*)th and *i*th day (mm), respectively; P_i, I_i, ET_i, Q_i, and R_i are precipitation, irrigation, evapotranspiration, water flux at the bottom of root zone, and runoff at the *i*th day (mm), respectively. P_i can be measured at weather station, I_i is the controlled variable in field experiment or decision variable in irrigation scheduling, R_i can be assumed to be zero because of the little precipitation in arid regions. Consequently, major tasks in field water balance simulation are calculations of ET and *Q*.

(1) Calculation of crop ET

Considering different influences of film mulching on *E* and *T*, a proper dual-source method for ET calculation (Kool et al., 2014) should be adopted. The dual crop coefficient method (Allen et al., 1998, 2005) recommended by FAO is adopted in this study for its advantages of simple calculation and less parameters (Kool et al., 2014). Using this method, ET can be calculated from:

$$\mathrm{ET_c} = K_\mathrm{c}\mathrm{ET_o} \tag{2}$$

$$K_\mathrm{c} = K_\mathrm{s} K_\mathrm{cb} + K_\mathrm{e} \tag{3}$$

where $\mathrm{ET_c}$ is the actual crop ET (mm), $\mathrm{ET_o}$ is the reference ET (mm), K_c is the crop coefficient, K_s is the water stress coefficient dependent on available soil water, K_cb is the basal crop coefficient representing the transpiration component, and K_e is the soil water evaporation coefficient representing the evaporation component. The $\mathrm{ET_o}$ can

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