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Modeling soil water flow and quantification of root water extraction from different soil layers under multi-chemicals application in dry land field

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ABSTRACT

The combined application of different functional chemicals creates challenges both in modeling water flow in soil and quantification of water extraction by crops in dry land farming. In the present study, 2-year laboratory and field experiments were conducted in a typical dry land of northern China in order to: (i) develop a model to describe patterns of water flow in soil under two typical chemicals Superabsorbent polymer (SAP) and Fulvic acid (FA) combined applied in the soil-maize system and (ii) use the stable hydrogen and oxygen analysis method to further quantify the soil water extraction by crops as affected by SAP and FA. Two root water extraction (RWE) terms based on density of root length (DRL) and density of root nitrogen mass (DRNM), respectively, were established to describe the rate of RWE, demonstrating that the values simulated from DRNM were verified to be closer to measured values. A particular model was further developed to simulate flow of water in different soil layers, and its authenticity was confirmed for describing the patterns of soil water flow under multi-chemicals application. The results of hydrogen and oxygen isotope abundance estimated from multi-source mass balance method (IsoSource model) suggested that main depth of water extraction as affected by multi-chemicals decreased first and then increased, and mainly concentrated in the shallow soil layers, 0–20 cm soil layer for jointing stage, 20–40 cm soil layer for heading stage, 0–20 cm soil layer for grain filling stage. Combined application of SAP and FA played a synergistic role in promoting the rainfall WUE of maize.

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1. Introduction

The rapid growth of human beings has made the demand for agricultural production greatly increased. Meanwhile, the prosperity and development of economic and social inevitably requires more water resources and arable land resources (Lotzecampen et al., 2008; Srinivasan et al., 2012). In recent years, the challenges of water resources and limited arable land resources have seriously restricted the sustainable development of agriculture, causing a profound impact on the future of mankind (Spiertz, 2010; Damien et al., 2017). The common problem faced by researchers all over the world is how to use the limited land and water resources to produce enough food to feed the growing human beings, as well as continuously improve the quality of human life (Pereira et al., 2002; Du et al., 2015; Vico and Porporato, 2011). The effective method to address this problem is formulating scientific water resources management strategies to promote the water use efficiency (WUE).

Root water extraction (RWE) is an essential link for water transport in soil-crop system, and the rate of RWE determines the WUE, due to soil water with nutrient is extracted by the roots and then transported to the aboveground part of crop to support normal physiological growth and form dry matter (Moura et al., 2012; Geerts and Raes, 2009; Ferchaud et al., 2015). In dry land farming, application of chemicals to regulate RWE is a widely recognized agricultural water-saving technology (Fallahi et al., 2016; Liao et al., 2012; Gao et al., 2013). Currently, some typical chemicals such as Superabsorbent polymer (SAP) and Fulvic acid (FA) are commonly combined employed to enhance the utilization ability of crop to soil water and nutrient, by taking advantage of their respective properties. Extensive previous reports suggested that the use of chemicals,

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Table 1
Soil physical and chemical properties.

Soil depth cm	Soil particle size USDA classification			FC	BD	Soil texture	
	Sand (%)	Silt (%)	Clay (%)	cm^3/cm^3	g/cm^3		
0–45	52.4	36.1	11.5	25.88	1.28	sandy loam	
45–100	48.3	42.8	8.9	24.56	1.37	loam	
Soil depth	*TN*	*AN*	*TP*	*AP*	*TPO*	*APO*	*OM*
cm	*g/kg*	*mg/kg*	*g/kg*	*mg/kg*	*g/kg*	*mg/kg*	*g/kg*
0–45	1.06	47.20	0.74	26.45	18.65	106.00	10.85
45–100	0.59	25.50	0.53	7.73	21.00	97.35	3.19

BD: bulk density; FC: field capacity; TN: total nitrogen; AN: alkaline nitrogen; TP: total phosphorus; AP: available phosphorus; TPO: total potassium; APO: available potassium; OM: organic matter.

such as PAM, FA, krilium, super slurper, SAP etc., could effect on soil physical and chemical properties, crop photosynthesis, root growth etc, thus regulating transport of water in soil-crop system (Qusdtel, 1953; Kirkham and Runkles,1952; Letey, 1975; Hemyari and Nofziger, 1981; Cooke, 1996; Abrol et al., 2013; Koupai et al., 2008; Hüttermann et al., 2009; Anjum et al., 2011; Benhur et al., 2015). The cost for using these chemicals is US\$560–800 hm^{-2}, which is nearly as cost as fertilizer (US\$536–953 hm^{-2}) applied for field crop or fruit in each year. And adding chemical can greatly improve the fertilizer use efficiency by 18.72–27.06% (Huang et al., 2002), thus making it possible to reduce application of fertilizer, as well as environmental pollution caused by fertilizer. Moreover, compared to the application of a single chemical, the combined application of multi-chemicals has a synergistic effect, which is better in improving WUE and crops yield. The mechanism for this synergistic effect was preliminary explored to reveal that multi-chemicals controlled the release of the endogenous hormones in crops, ensuring effective use of soil water resources (Liao et al., 2018). Liao et al. (2015) applied SAP and FA combined to maize and the results indicated a significant yield increase of 21% compared to the treatment without chemicals. However, other studies reported by Zhuang et al. (2008) and Han et al. (2004) pointed out that single SAP applied to winter wheat can achieve a yield increase of 10.14%, and single FA applied to apple can get a yield increase of 4.88% to 7.32%, respectively. Impressively, Han et al. (2005) and Li et al. (2011) combined use SAP and FA to wheat and apple, and their results demonstrated that the application of multi-chemicals took more beneficial effects than any single chemical, on soil moisture and crop yield. Therefore, it is of great significance to study the mechanism of SAP and FA combined effect on water extraction. Disappointedly, the previous studies mainly focus on application modes of chemicals, lacks of in-depth analysis on its effect mechanism.

Besides, it is unreliable to develop soil water flow model based on the traditional soil hydraulic parameter system and root response system under SAP application because SAP's unique characteristics of repeated absorption and release of water produces unstable effects on soil physical and chemical properties and root growth (Li et al., 2014; Han et al., 2010; Guilherme et al., 2015). Many previous researches have also verified this view. In a laboratory experiment, Bai et al. (2010) found SAP will reduce soil bulk density with the alternation of wetting and drying cycles in soil, and the greater the amount of SAP application, the lower the bulk density. Zhou et al. (2012) applied SAP to maize in a field experiment and found that maize roots became shorter and had larger surface areas. In the process of developing model to describe water movement under SAP application, Han et al. (2013) also pointed out that SAP produced time-varying effects on soil hydraulic parameters, which made the established model based on traditional soil hydraulic parameter system invalid in simulating soil water movement. In addition, the response mechanism of crop root growth to multi-chemicals application was still unclear, which also created challenge for developing a soil water flow model.

In this study, 2-year laboratory and field experiments were carried out to model water flow in soil and further quantify soil water extraction by crops as affected by SAP and FA combined application. Two RWE terms based on density of root length density (DRL) and density of root nitrogen mass density (DRNM), respectively, were established to simulate the rate of RWE. Then a soil water flow model was developed to describe the patterns of water flow in soils. The mechanism of SAP and FA effects on RWE of maize was explored, and the value of water extraction by maize from different soil layers was quantified by employing stable isotope mixing models

2. Materials and methods

2.1. Experimental site

The laboratory and filed experiments were conducted in the International Seed Industry Park (39°43′23.7″ N 116°40′47.1″ E), Yujiawu town, Tongzhou Distric, Beijing. The annual mean temperature is 11.3 °C and annual precipitation is about 600 mm. The experimental position and accessories were displayed in Fig. 1 and physical and chemical properties of experimental soil were shown in Table 1.

2.2. Materials

The SAP selected in this study is a cross-linked polyacrylamide/polyacrylate copolymer ($(C_3H_5ON)_m(C_3H_4O_2)_{n-m}SiO$, 0–4.0 mm in particle size) provided by DYHY New Material Co., Ltd. (Shandong, China); The FA selected in this study is a kind of antitranspiration agent ($C_{14}H_{12}O_8$, the molecular weight is 308, brown liquid) provided by HTHDL Humic Acid Co., Ltd. (Xinjiang, China); The test crop selected in this study is summer maize (*Zea mays* L.), whose growth period average lasts 100 days; The experimental soil column selected in this study is made of PVC (58 cm in height and 26 cm in diameter). Main performance parameters of SAP and FA are list in Table 2.

2.3. Treatments and experimental methods

Two water-controlled experiments in column and field, a water-uncontrolled (rain fed) in field experiment were combined conducted. The design treatments were shown in Table 3. The water-controlled column experiment (**E1**) was employed to research the response of root growth to multi-chemicals application, and establish RWE source/sink for development of soil water flow model; the water-controlled field experiment (**E2**) was applied to model patterns of water flow in different soil layers; the rain fed field experiment (**E3**) was used to further study the mechanism of multi-chemicals effects on soil water flow and quan-

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