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Maximizing water productivity of winter wheat by managing zones of variable rate irrigation at different deficit levels

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ABSTRACT

To determine the specific application rate for each management zone of a variable rate irrigation system, the yield and water use efficiency (WUE) of winter wheat were evaluated during two growing seasons at different deficit levels in the alluvial flood plain of the North China Plain. One 1.64-ha quadrant irrigated by a variable rate center pivot system was delineated into four management zones with available soil water holding capacity, and varied soil profiles were detected in these zones. Each zone was divided into several subzones to be irrigated at different deficit levels. In the 2016 season, each subzone was managed individually with irrigation trigger points of 55%, 65%, 75%, and 80% of field capacity along with a rain-fed treatment. In the 2017 season, all subzones were irrigated simultaneously with 0%, 33%, 67%, 100%, and 120% of the base application depth. For the two-season study, the rain-fed treatment produced significantly lower yield and WUE than the irrigated treatments, and both the maximum yield and the maximum WUE were obtained in zone 2, where a more uniform soil profile was detected. A linear crop water production function was determined for zones 1 and 3 in the 2017 season, while a quadratic equation fit the crop water production function well for other zones in the two seasons. The relationship between WUE and crop water use in the three zones can be represented by a curvilinear equation for both seasons. Taking the optimal application rate of maximizing WUE in zone 1 as a basis, 89% and 94% of the rate in zone 1 was recommended for zones 2 and 3, respectively, to achieve the maximum WUE in the entire field. Our results also suggested that the existing layered-textural soil profile can greatly influence crop productivity and should therefore be considered in mapping irrigation prescriptions.

1. Introduction

Irrigation is vital for agricultural production, and a substantially higher crop yield was obtained on irrigated land than on rain-fed land in China (Cao et al., 2015). However, available water resources for irrigation are increasingly limited. For example, the North China Plain, which has a semi-arid climate and produces nearly 75% of the wheat in China, has long been suffering from severe water shortages. The exploitation of groundwater accounts for 70% of the total water utilization, and 79% of the groundwater is pumped for irrigated agriculture (Zhang et al., 2013). Proper irrigation management to improve water use efficiency (WUE) is critical for sustainable crop production in this region (Cao et al., 2017).

Having the ability to allocate varied water amounts in different management zones, variable rate irrigation (VRI) systems provide the possibility and flexibility to enhance WUE by arraying spatially variable thresholds (O'Shaughnessy et al., 2015) or by varying water application depths across a field (O'Shaughnessy and Evett, 2010; Sui and Yan, 2017). However, it is not straightforward how to best manage irrigation with these systems and often the management does not save water or much water. It meant that VRI is of limited utility without precise irrigation scheduling (Howell et al., 2012). In recent years, extensive attention has been given to available soil water holding capacity (AWC) (Hedley et al., 2010) and electrical conductivity (LaRue, 2011; Sui and Yan, 2017) for developing management zones and prescription maps. Although the final conclusions about the irrigation date and amount in different management zones have not yet been determined, a common finding is that the management zone with a high AWC received a minor irrigation amount (Evans et al., 2013).

When the parameter of AWC was used to delineate the management zones, the AWC value in a specific location was the average value in the top 0-0.6 m depths where the majority root zone concentrated (Hedley et al., 2010; Zhao et al., 2017), and there was no consideration about the soil layers. In fact, layered soils inevitably exist in many fields as a result of geological processes. Numerous studies have shown that an interface exists in layered soils, whether fine-over-coarse or coarse-

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over-fine, limited downward water movement and increased soil water storage in the top layer soil (Jury and Horton, 2004; Li and Liu, 2011). These results suggest that the varied soil layers in a field might affect the prescription maps for VRI management based on the measurement of soil water content.

To generate the prescription map, knowledge about crop response (crop water production functions, WPFs) to variable water inputs is helpful (Evans et al., 2013). Although extensive research for several decades has indicated that WPFs have linear or quadratic functions (Musick et al., 1994; Shen et al., 1995; Schneider and Howell, 2001; Wang et al., 2006), WPFs are site specific because of the variability of soil and climatic conditions (Rajput and Singh, 1986; Sadler et al., 2002; Tolk and Howell, 2003). Even in an individual field, the variation in AWC has a substantial influence on the growth parameters, yield, and water productivity of crop. For example, through a two-season measurement of winter wheat response for a variable rate irrigation system with three management zones, Zhao et al. (2017) reported that the maximum yield was obtained in the zone with the medium AWC, rather than in the zones with the greatest AWC where layered-textural soil existed.

The objectives of this study were to (1) evaluate the effect of AWC and layered-textural soil on irrigation scheduling based on soil water content sensors, (2) verify the assumption that different water production potentials exist in management zones, and (3) generate an irrigation prescription map by means of WPFs in different management zones with the goal of obtaining the maximum WUE under a semi-arid climate.

2. Materials and methods

2.1. Experimental site

The study was conducted from October 2015 to June 2016 (referred to as the 2016 season) and from October 2016 to June 2017 (referred to as the 2017 season) during the growing season of winter wheat in Zhuozhou (39.45 °N and 115.85 °E), Hebei Province, China. This site is located in the Taihang mountain alluvial flood plain and experiences a warm and semi-arid climate, with an annual mean temperature of 11.6 °C and an annual mean precipitation of 563.3 mm.

The experimental area was one 1.64-ha quadrant controlled by a variable-rate, center-pivot irrigation system and the VRI control unit of the system was developed by the China Institute of Water Resources and Hydropower Research (Zhao et al., 2014). Weak topographic variations with an average slope of 0.18% and a 0.14-m elevation difference were found across the field. Prior to the experiments, the hydraulic performance of the VRI system was tested by field evaluation to guarantee control precision (Zhao et al., 2014).

Four management zones were delineated using AWC by soil sampling at 110 locations of a 12 m × 12 m grid. The AWC range was determined to be 152–161, 161–171, 171–185, and 185–205 mm within the top 1.0 m soil profile and the average field capacity calculated by the Wilcox method (Wilcox, 1962) was 0.21, 0.22, 0.23, and 0.25 $cm^3\ cm^{-3}$ within the 0.6 m soil profile for zones 1 (Z1), 2 (Z2), 3 (Z3), and 4 (Z4), respectively. Accordingly, the areas were 0.33, 0.76, 0.18, and 0.28 ha for Z1, Z2, Z3, and Z4, respectively. Varied soil profiles were detected in different management zones (Fig. 1). In Z1, the sand fraction largely increased with depth (57.8%–89.5%). Small ranges of the sand fraction (59.8%–65.8%) and clay fraction (4.6%–5.7%) were observed at different depths in Z2, showing a relatively uniform profile. A fine middle layer (47.9% sand and 8.6% clay) at the 0.2 to 0.4 m soil profile was found in Z3, suggesting a clearly layered-textural profile in the zone. In Z4, the mean sand and clay fractions in the 0-0.4 m soil layers were 55.4% and 7.4%, respectively. Lots of gravels were found below the 0.4 m depth after the burying of water pipelines. Therefore, Z4 was not included in this study since it loses its representativeness to the alluvial flood plain. More details about the soil parameters and management zones were described in Zhao et al. (2017).

2.2. Experimental design

According to the area of each management zone, Z1, Z2, and Z3 were equally divided into four, five, and four subzones, respectively. For each management zone, the subzones were randomly arranged in the zone, without reconsidering the variation of AWC within management zones. The first span of the center pivot was not used in this study due to its small area of coverage. To represent different deficit levels, the rain-fed treatment (Z1T0, Z2T0, and Z3T0, referred to as T0) and the treatments triggered at different irrigation trigger points of 55% (Z1T1, Z2T1, and Z3T1, referred to as T1), 65% (Z1T2, Z2T2, and Z3T2, referred to as T2), 75% (Z1T3, Z2T3, and Z3T3, referred to as T3), and 80% (Z2T4) of field capacity were scheduled in the 2016 season, resulting in a total of thirteen experimental treatment subzones in the field (Fig. 2a). Once the irrigation trigger point for a treatment was reached, the machine would pass through and apply an irrigation depth of 20 mm that was determined by considering the travel speed of the center pivot and the peak daily water use (O'Shaughnessy and Evett, 2010). Such a VRI management approach means that the duty cycle was set 100% (i. e., always "on") in the treatment, the other treatments did not receive any irrigation until the threshold for that subzone was reached.

In the 2017 season, the deficit irrigation levels in each management zone were applied by changing the irrigation rates to 0% (Z1T0, Z2T0, and Z3T0, referred to as T0), 33% (Z1T1, Z2T1, and Z3T1, referred to as T1), 67% (Z1T2, Z2T2, and Z3T2, referred to as T2), 100% (Z1T3, Z2T3, and Z3T3, referred to as T3), and 120% (Z2T4) of the base application depth. The base application depth was 20 mm before the flowering stage and 30 mm thereafter. The irrigation was triggered when the mean soil water content depletion in the Z1T3 subzone exceeded the threshold of 0.45 of the AWC, approximately 66% of the field capacity. The Z1 with minimum AWC was selected as the trigger zone of irrigation aimed at maximizing yield potential in the entire field (Zhao et al., 2017). Once irrigation was triggered, irrigation amounts delivered to all thirteen treatments were achieved by regulating the appropriate solenoid valves at duty cycles of 0%, 33%, 67%, 100%, and 120% of the base application depth.

A TDR Trime-tube system (Trime-T3, IMKO Ltd., Ettlingen, Germany) was used to monitor the soil water content. Six, ten, and three access tubes were installed approximately in the center of a 12 m × 12 m grid in each treatment of Z1, Z2, and Z3, respectively (Fig. 2b). These soil water content sensors were used in both 2016 and 2017 seasons. To determine the irrigation date, mean soil water contents in each irrigation treatment were measured daily at 0.2-0.4 m layer to approximately represent the average soil water content (Li et al., 2009; Gao et al., 2011) during the 2016 season. While daily measurement of soil water content in Z1T3 treatment to determine the irrigation date was extended to 0-0.4 m depths during the 2017 season. This change was aimed at avoiding triggering irrigation too frequently caused by layered-textural properties of soil in management zones, especially in Z3. During both irrigation seasons, in addition to determining the irrigation date, all access tubes in each subzone were measured in 0.2-m increments to a depth of 1.2 m every seven to ten days to evaluate the influence of deficit irrigation on water flux in different soil layers.

The rain forecast information of the following three days was considered in the two seasons to make full use of the rainfall. The water applied would be decreased by 0%, 20%, and 40% for light (less than 10 mm), moderate (between 10 mm and 25 mm), and heavy rain (more than 25 mm) (Wang et al., 2005) according to the forecast report from the National Meteorological Center of China Meteorological Administration. There was no additional application except for seedling emergence and aiding fertilization in the rain-fed treatments. An application of 20 mm irrigation was delivered for seedling emergence for all the

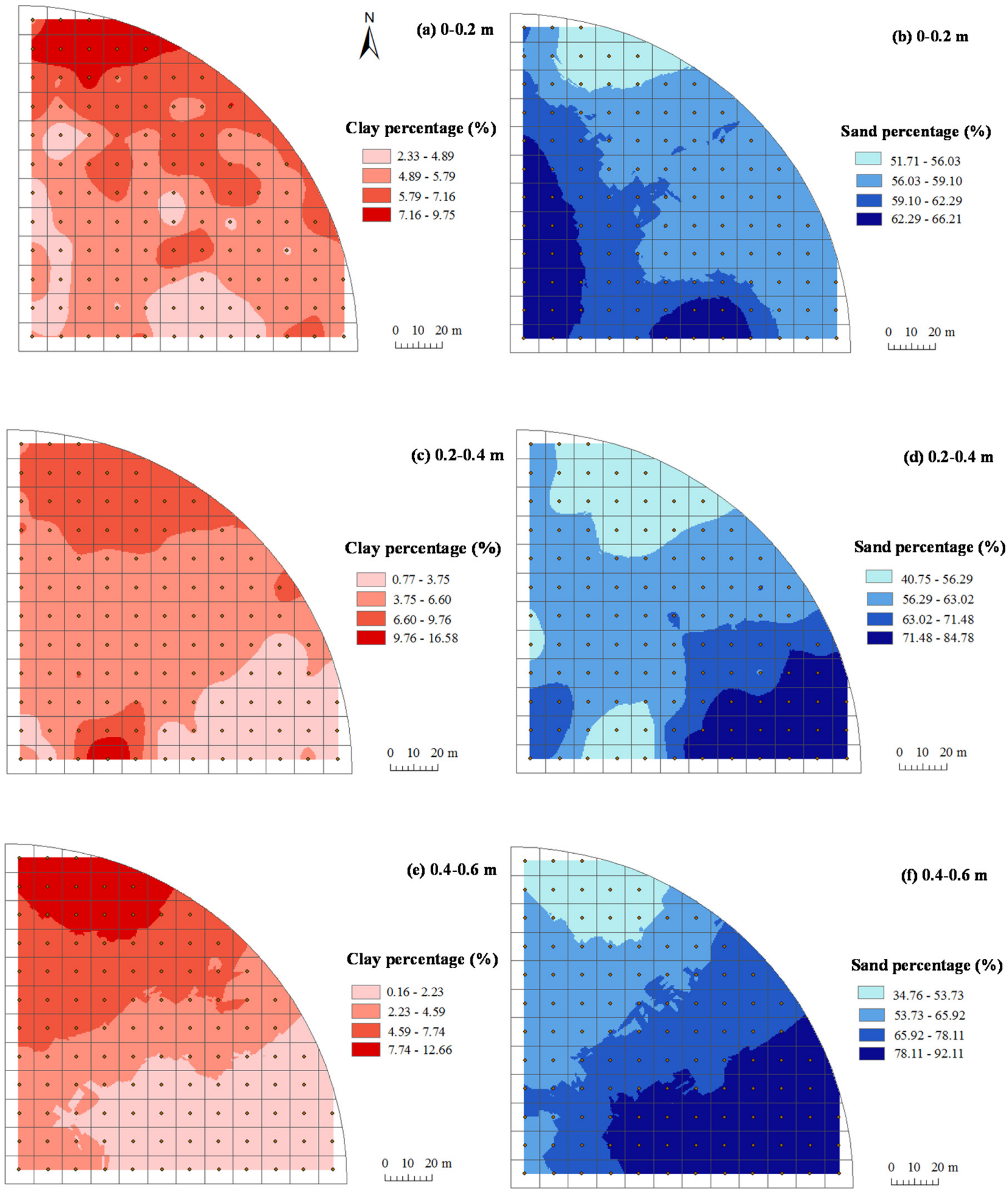

Fig. 1. Spatial distribution of clay percentages (a, c, e) and sand percentages (b, d, f) in soil profile.

treatments in both seasons.

Winter wheat (*Triticum aestivum* L, Jimai no. 22) was seeded on October 14, 2015, and on October 11, 2016, with rows 0.15 m apart, and the seeding rate was 375 kg ha^{-1}. All subzones were fertilized uniformly based on typical cultural practices for yield potential. Specifically, the total amounts of nitrogen, phosphorus (P_2O_5), and potassium (K_2O) applied were 175, 138, and 90 kg ha^{-1}, respectively. All phosphorus and potassium fertilizers and 54 kg ha^{-1} of nitrogen were applied as basal fertilizers. The remaining nitrogen was applied on March 15, 2016, and on April 2, 2017, and 20 mm of water was immediately applied after broadcast fertilization to enhance the fertilizer use efficiency.

2.3. Data collection and analysis

At harvest, seven rows of winter wheat of 1 m length (1.05 m^2) were harvested near the center of each grid. There were six, ten, and three replications in each treatment in Z1, Z2, and Z3, resulting in 86 sampling locations in total. In the 2016 season, winter wheat was harvested on June 3 in the rain-fed treatments and on June 12 in the irrigated treatments. In the 2017 season, it was harvested from June 1 to June 5 in the rain-fed treatments and on June 9 in the irrigated treatments to deal with the different maturation times. Grain yields were oven dried at 75 °C and corrected to 13% moisture. In addition, yield components (number of productive ears, ear length, number of grains per ear, and the 1000-grain weight) were measured to explain the differences in yield among the treatments.

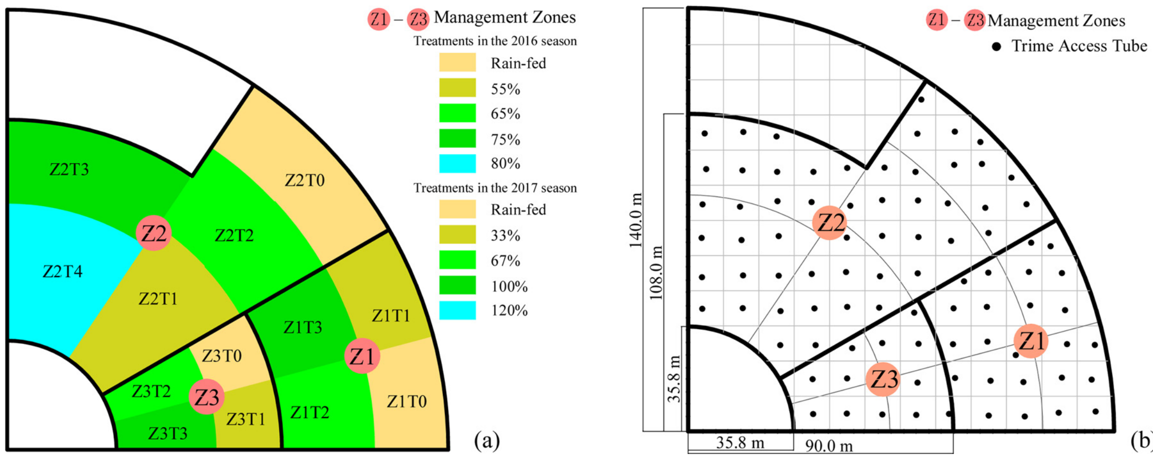

Fig. 2. Diagram of the management zones (a) and sensor layout (b) for different deficit irrigation levels with VRI in the 2016 and 2017 seasons.

The reference evapotranspiration (ET_0, mm) was calculated by the Penman-Monteith equation (Allen et al., 1998). The climatic parameters used in this equation and the total precipitation were collected from a weather station (Watchdog 2000, Spectrum Technologies Inc., USA) installed approximately 100 m away from the study field. The actual evapotranspiration (ET_a, mm) was calculated using the following water balance equation (Allen et al., 1998).

$$ET_a = I + P_e - D_p - R_{off} + \Delta S \quad (1)$$

where I is the irrigation applied (mm); P_e is the effective rainfall (mm), which was calculated by multiplying the total rainfall by the reduction coefficient (the coefficient is 0, 0.8, and 0.7 when the total rainfall is less than 5 mm, between 5 mm and 50 mm, and more than 50 mm, respectively); D_p is the deep percolation (mm), which was neglected because there was no obvious influence of irrigation and precipitation on soil water movement below the 0.6 m layer (this will be discussed in the following section); R_{off} is runoff caused by irrigation (mm), which was also ignored due to the weak topographic variations in this field and the low irrigation rate for each event (20–30 mm); and ΔS is the variation in soil water storage (mm) in the 0–1.2 m soil layers between the initial and terminal stages.

Water use efficiency (WUE) was calculated in each treatment by dividing the average crop yield by ET_a in each grid. The WUE values were reported in units of kg of grain per cubic meter of water received.

All data were analyzed using the statistical product and service solutions (SPSS) 16.0 software package (SPSS, 2007). One-way analysis of variance (ANOVA) was used to test whether the AWC or deficit irrigation had a significant effect on yield and WUE at the 0.05 probability level. Duncan's test was also performed on all management zones and irrigation levels at the 0.05 probability level.

3. Results and discussion

3.1. Climatic factors

The monthly climatic factors, such as the maximum air temperature (TMP), mean relative humidity (RH), cumulative solar radiation (SRD), and cumulative reference evapotranspiration ($C\text{-}ET_0$), during the two growing seasons of winter wheat are shown in Table 1. In both seasons, the lowest TMP and SRD were from December to February of the next year, meaning cold weather. After that, the TMP and SRD increased sharply until harvest. The maximum daily solar radiation was 39 MJ/m^2.d in the 2016 season and 24 MJ/m^2.d in the 2017 season, and the maximums were observed in late April and May, respectively. The variation of $C\text{-}ET_0$ was consistent with that of the SRD. The maximum daily ET_0 was approximately 7.3 mm, but it occurred in late April. The RH was less than 50% in most of the growing seasons; it ranged from 35% to 80% in the 2016 season and from 36% to 72% in the 2017 season. The monthly mean values of TMP, RH, SRD, and $C\text{-}ET_0$ were 23 °C, 52%, 323 MJ/m^2, and 74 mm in the 2016 season and 23 °C, 52%, 322 MJ/m^2, and 75 mm in the 2017 season, respectively. No obvious differences in these climatic factors were found between the two seasons.

Table 1
Main climatic factors during the 2016 and 2017 winter wheat growing seasons.

Month	2015-2016 season				2016-2017 season			
	TMP (°C)	RH (%)	SRD (MJ/m^2)	$C\text{-}ET_0$ (mm)	TMP (°C)	RH (%)	SRD (MJ/m^2)	$C\text{-}ET_0$ (mm)
Oct.	28	62	340	63	26	72	256	50
Nov.	20	80	112	18	15	64	202	22
Dec.	10	66	134	13	11	59	157	12
Jan.	7	39	162	14	8	49	165	18
Feb.	14	35	243	35	16	36	238	32
Mar.	25	37	346	77	20	43	368	74
Apr.	32	45	573	134	35	45	440	120
May	36	51	488	148	37	46	518	171
Jun.	39	56	507	162	39	55	556	173
Average	23	52	323	74	23	52	322	75

3.2. Rainfall and irrigation

The seasonal application amount and rainfall for different irrigation treatments in the 2016 and 2017 seasons are shown in Fig. 3. There were thirty-two precipitation events in total in the 2016 season, and all of them were light rain. In the 2017 season, twenty-five precipitation events occurred, of which twenty-one were light rains, and the remaining were medium. The seasonal rainfall was similar in the 2016 (80.1 mm) and 2017 (80.3 mm) seasons, being less than the long-term average of 126 mm (Zhang et al., 2002). A more uniform temporal distribution was found in the 2016 season than in the 2017 season.

To aid germination and fertilization, the rain-fed treatments received an additional irrigation amount of 46 mm in the 2016 season and 40 mm in the 2017 season. In the irrigation treatments, the responses of the seasonal irrigation amount to deficit irrigation levels were different among the three management zones in the 2016 season. In Z1, the seasonal irrigation amount ranged from 300 to 380 mm among the irrigation treatments, and the maximum value was obtained in the Z1T2 treatment with the medium irrigation trigger point. The widest variation in irrigation amount among the irrigation treatments was observed in Z2 (226 to 416 mm), where the minimum irrigation amount was obtained in the Z2T2 treatment and the maximum in the

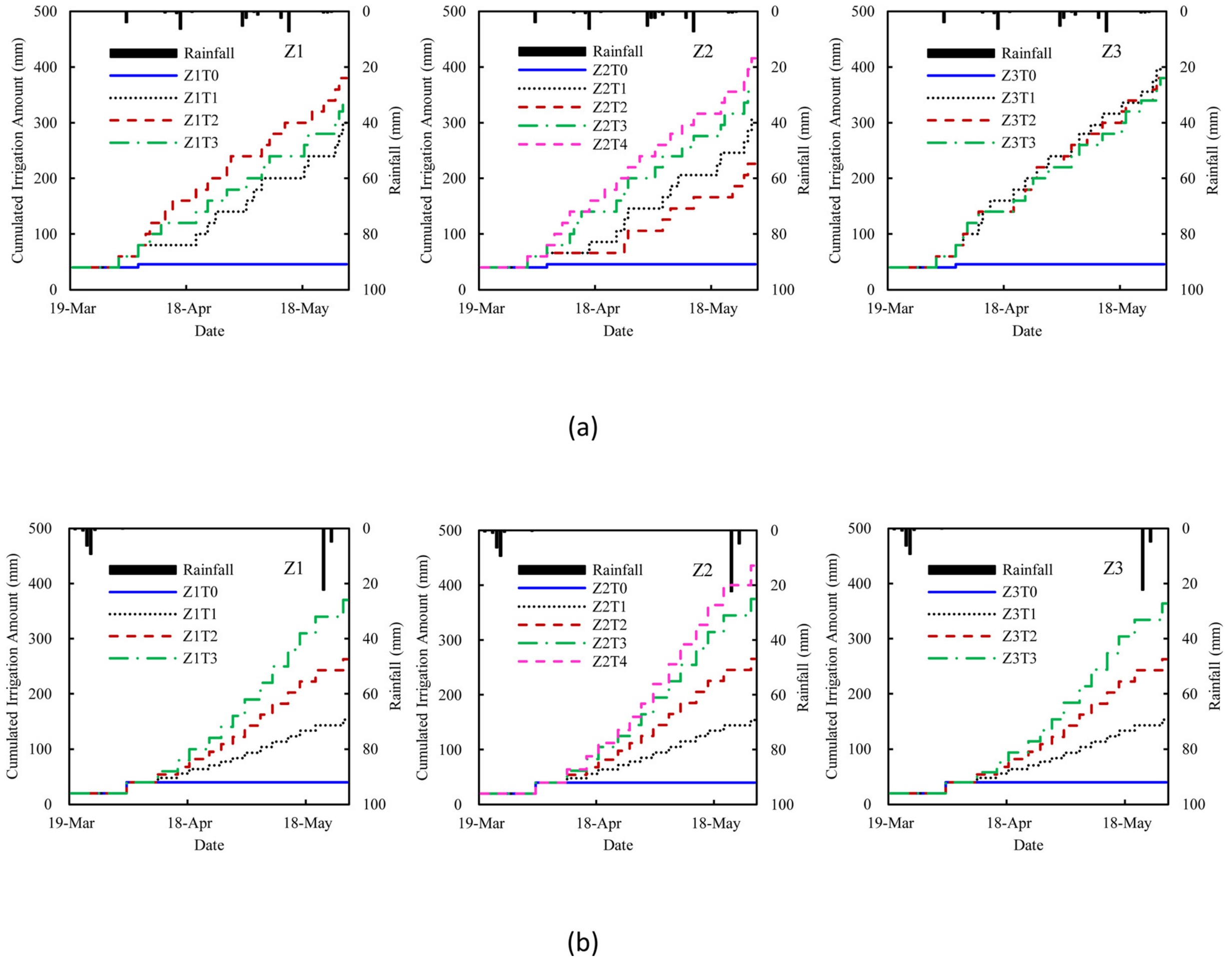

Fig. 3. Rainfall and irrigation applied to each treatment in the three management zones during the 2016 (a) and 2017 seasons (b).

Z2T4 treatment. In Z3, similar irrigation amount was received for all irrigation treatments (380 to 396 mm). The phenomenon that the irrigation amount did not fully increase with the increment of irrigation trigger points might be caused by different initial soil water content in the 0.2-0.4 m layer in various subzones (Fig. 4). Differing from the common view that a minor irrigation amount was received in the management zone with higher AWC, the mean irrigation amount in Z2 (234 mm) was 12% and 22% less than that in Z1 (267 mm) and Z3 (301 mm), respectively. This result could be explained by the seasonal change in soil water content in the 0–1.2 m layers in each treatment (Fig. 4). The hindrance of the existing interface between adjacent layers on the downward water flux in Z1 and Z3 resulted in a less depletion of soil water storage within the root zone in these zones, especially in Z3 (Fig. 4). For example, the average depletion of soil water storage for Z2 (34 mm) approximately doubled the value for Z1 (18 mm) and Z3 (14 mm) in the 2016 season. Then, a more frequent irrigation was triggered for Z1 and Z3 than for Z2. This suggests that VRI management based on soil water content measurement should carefully select the measurement depth when layered-textural soils exist. The soil water content sensors should not be positioned beneath the interface to capture the average status of soil water content within the root zone. In the 2017 season, the irrigation amounts of 153, 263, and 370 mm were applied at the 33%, 67%, and 100% treatment in each management zone, respectively. The seasonal change in soil water content in the 0–1.2 m layers decreased in most subzones (Fig. 5) compared with that in the 2016 season (Fig. 4). This was attributed to the higher terminal soil water content that resulted from the large rainfall at the end of the 2017 growing season (Fig. 3b). Similar to the 2016 season, a similar higher average depletion of soil water storage was obtained for Z2 (20 mm) than for Z1 (13 mm) and Z3 (12 mm) in the 2017 season.

3.3. Yield, yield components, and crop water production functions

The yield and yield components of winter wheat for all treatments during the 2016 and 2017 growing seasons are presented in Table 2. In the 2016 season, the lowest yield was obtained in the rain-fed treatments in each management zone. The variation in yield among the deficit irrigation treatments differed in the management zones. In Z1, the yield change was minor and ranged from 6370 to 6714 kg ha^{-1}, while slightly greater variations in yield were observed in Z2 (5508 to 7092 kg ha^{-1}) and Z3 (6083 to 7004 kg ha^{-1}). A statistically significant difference in yield among irrigation treatments was only observed in Z2. Furthermore, the maximum yield in Z2 was 6% and 1% higher than that in Z1 and Z3, respectively.

The minimum yield was again obtained in the rain-fed treatments in the 2017 season. Although the total water received (irrigation + rainfall) in the rain-fed treatments was similar in these two seasons, the mean yield in the 2017 season was obviously lower than that in the 2016 season due to the uneven temporal distribution of rainfall (Fig. 3) in the 2017 season. For the irrigation treatments in the 2017 season, the water delivered was equivalent at the same irrigation treatment in different management zones, while the yield at different deficit treatments ranged from 1644 to 7989 kg ha^{-1}, from 2482 to 8831 kg ha^{-1}, and from 1603 to 7078 kg ha^{-1} in Z1, Z2, and Z3, respectively. The maximum yield was again obtained in Z2 and was 11% and 25% higher than that in Z1 and Z3, respectively. This phenomenon that the maximum yield was obtained in Z2 was consistent with the results reported by Zhao et al. (2017) in the same field. For a given irrigation rate, no

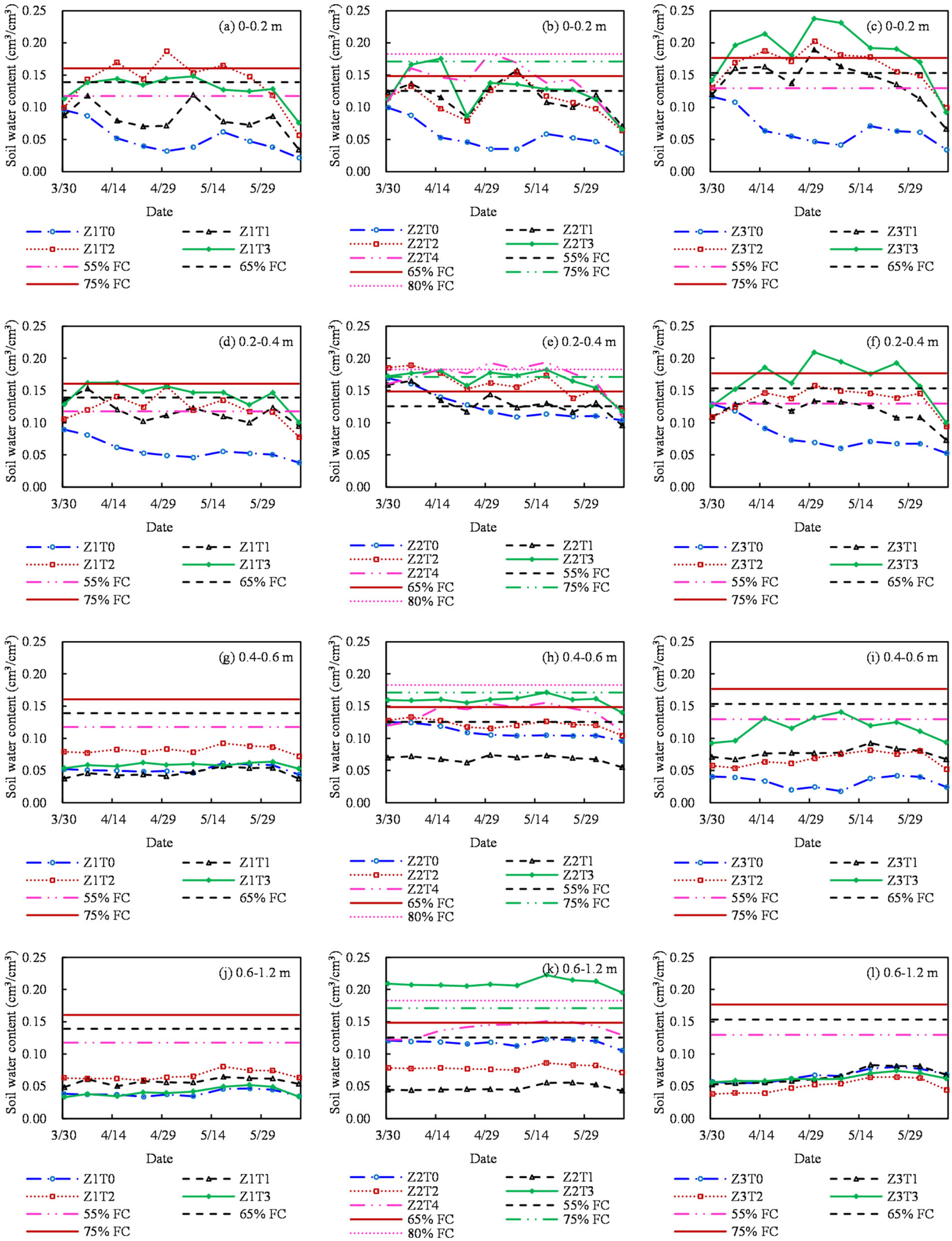

Fig. 4. Variations of soil water content with time in the 0–1.2 m layers during the 2016 growing season.

significant difference was observed among management zones; however, the percentage that the yield deviated from the mean value in different management zones varied from -16% to 30%, from -6% to 10%, and from -11% to 11% in the 2017 season in T1, T2, and T3 treatments, respectively. The difference in yield among management zones increased as crop suffered from more severe water deficit.

To obtain the WPFs in each management zone, the ET_a was calculated in each treatment. Based on the irrigation regimes mentioned above, the maximum infiltration depth of water was obtained in Z2, and no obvious variation in soil water content was observed at the 0.6–1.2 m layers during the winter wheat growing seasons (Fig. 4). Therefore, deep percolation was neglected during the calculation of ET_a

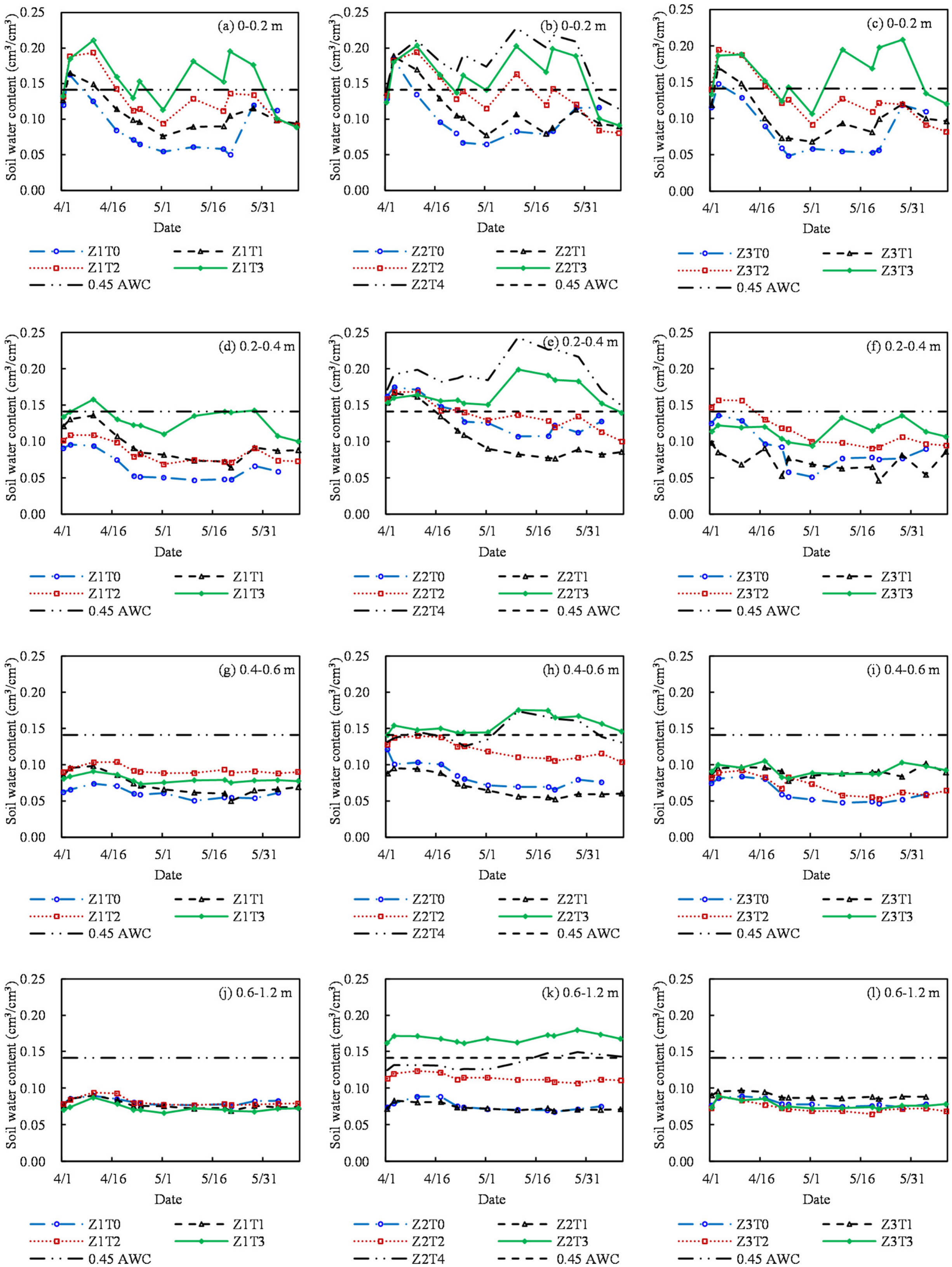

Fig. 5. Variations of soil water content with time in the 0–1.2 m layers during the 2017 growing season.

based on eq. 1. Similar to the variation pattern of irrigation applied, the lowest seasonal ET_a was obtained in the rain-fed treatment in both seasons. The greatest variation in seasonal ET_a was observed in Z2 among the three management zones in the 2016 season. For a given irrigation trigger point, ET_a ranged from 449 to 558 mm, from 356 to 539 mm, and from 479 to 526 mm in the T1, T2, and T3 treatments, respectively. Although similar irrigation was applied in each management zone in the 2017 season, the seasonal ET_a observed in Z2 (270 to 465 mm) was slightly higher than that in Z1 (258 to 464 mm) and Z3 (237 to 458 mm). For a given irrigation rate, the ET_a ranged from 237 to

Table 2
Mean crop yield and yield components for all treatments in the 2016 and 2017 seasons.

Treatment		Yield (kg ha^{-1})	No. of productive ears	Ear length (mm)	No. of grains per ear	1000-grain weight (g)	ET_a (mm)
2016 season							
Z1	T0	893d[a]	224d	38bc	7b	31b	226
	T1	6370abc	496bc	57a	25a	44a	467
	T2	6714ab	615a	62a	28a	43a	539
	T3	6530ab	535abc	56a	27a	44a	495
Z2	T0	1319d	426c	42b	10b	30b	188
	T1	6083bc	537abc	60a	27a	44a	449
	T2	5508c	515abc	57a	24a	44a	356
	T3	7092a	548ab	63a	29a	43a	479
	T4	6728ab	501abc	63a	29a	43a	546
Z3	T0	793d	273d	36c	6b	29b	227
	T1	6083bc	597ab	57a	26a	44a	558
	T2	7004ab	526abc	62a	29a	42a	534
	T3	6944ab	577ab	62a	28a	42a	526
2017 season							
Z1	T0	43e	6g	32g	2d	21f	158
	T1	1644d	323ef	58cde	14b	33de	258
	T2	6428c	456cd	69ab	26a	43a	367
	T3	7989ab	571bc	75a	29a	41ab	464
Z2	T0	108e	29g	50ef	10bcd	29e	151
	T1	2482d	432de	53def	14b	33cde	270
	T2	7325bc	653ab	70ab	27a	392abc	359
	T3	8831a	710a	68abc	28a	43a	465
	T4	8070ab	627ab	65bc	29a	43a	484
Z3	T0	74e	18g	46f	6cd	21f	116
	T1	1603d	286f	60bcd	11bc	36bcd	237
	T2	6247c	557bcd	61bcd	24a	42ab	373
	T3	7078bc	610ab	67abc	26a	45a	458

[a] Values followed by the same letter in a column in a given year are not significantly different at a probability level of 0.05.

270 mm, from 359 to 373 mm, and from 458 to 465 mm in the T1, T2, and T3 treatments, respectively, in the field.

The responses of grain yield to ET_a in each management zone are shown in Fig. 6. Compared to the 2017 season, the greater ET_a and yields for the T1 and T2 treatments were obtained in the 2016 season (Table 2). This was mainly caused by the greater irrigation amount delivered to these treatments in the 2016 season due to the nonuniform soil profile. Resultantly, the different yield to ET_a relationships were obtained in these two seasons. In the 2016 season, quadratic relationships were fitted to WPFs in Z1, Z2, and Z3. In the 2017 season, the grain yield was linearly related to seasonal ET_a for Z1 and Z3, while a quadratic relationship was fitted for Z2, mainly due to an extra application rate of 120% base irrigation depth.

3.4. Water use efficiency

The WUE for all treatments in the 2016 and 2017 seasons are shown in Table 3. Similar to the yield, the WUE varied within and among management zones. In the 2016 season, the rain-fed treatments produced the least yield and resulted in the lowest WUE. The WUE in the rain-fed treatment was significantly lower than that in any irrigation treatment, being 69%, 52%, and 72% lower than the average WUE value of the irrigation treatments in Z1, Z2, and Z3, respectively. In the irrigation treatments, no significant difference was observed among treatments in each of the three management zones. The values of WUE ranged from 1.25 to 1.36 kg m^{-3}, from 1.35 to 1.55 kg m^{-3}, and from 1.09 to 1.32 kg m^{-3} in Z1, Z2, and Z3, respectively. For a given irrigation trigger point, the percentage that the WUE deviated from the mean value (relative WUE) in different management zones ranged from -14% to 7%, from -9% to 13%, and from -4% to 8% in the T1, T2, and T3 treatments, respectively.

Similar to the 2016 season, the rain-fed treatments had the lowest WUE in the 2017 season (Table 3). In the irrigated treatments, a larger range of WUE at different deficit levels was observed, and a significantly lower WUE was obtained in the T1 treatment than in the T2 and T3 treatments in each management zone. The values of WUE ranged from 0.64 to 1.75 kg m^{-3}, from 0.92 to 2.04 kg m^{-3}, and from 0.68 to 1.68 kg m^{-3} in Z1, Z2, and Z3, respectively. Even with similar water application for a given irrigation rate, the relative WUE in different management zones ranged from -14% to 23%, from -8% to 12%, and from -10% to 10% in the T1, T2, and T3 treatments, respectively. A reduction in WUE but a broader WUE variation range among management zones was observed with decreasing irrigation water in both seasons, indicating that the influence of AWC on WUE increased as the water applied decreased (Tolk and Evett, 2015). The maximum WUE values in each management zone in both seasons were within the WUE range of 1.07 kg m^{-3} to 2.4 kg m^{-3} reported by Wang et al. (2006) in the North China Plain. The maximum WUE in Z2 was higher than that in Z1 and Z3, being 14% and 17% higher in the 2016 season and 17% and 21% higher in the 2017 season, respectively. Similar to the yield, the maximum WUE was obtained in Z2 with the medium AWC again in this study, and the same result was reported by Zhao et al. (2017) in this same field. It was confirmed that water productivity potentials were affected by not only AWC but also the soil profile characteristics.

The quadratic responses of WUE to ET_a in each management zone are illustrated in Fig. 7. This two-season study showed that WUE would decrease if the irrigation amount continued to increase under this experimental condition. The derivative of the fitting curve was calculated to determine the maximum WUE and the corresponding optimal ET_a in each management zone. In the 2016 season, the maximum WUE was 1.36, 1.51, and 1.67 kg m^{-3} and the corresponding ET_a was 459, 409,

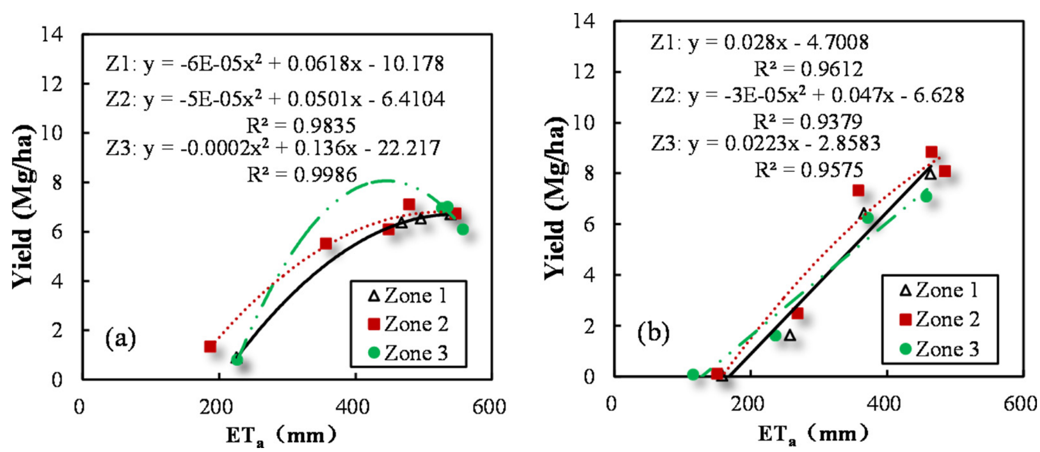

Fig. 6. Relationships between crop grain yield (y) and ET_a (x) in the 2016 (a) and 2017 seasons (b). R^2 is the determination coefficient.

Table 3
Mean water use efficiency for each treatment in the management zones in the 2016 and 2017 seasons.

Management zone	2016 season				2017 season			
	Treatment	I + P_e (mm)	ΔS (mm)	WUE (kg m^{-3})	Treatment	I + P_e (mm)	ΔS (mm)	WUE (kg m^{-3})
Z1	T0	81	145	0.40f[a]	T0	92	67	0.04d
	T1	335	132	1.36abc	T1	205	53	0.64c
	T2	415	124	1.25bcd	T2	315	53	1.75ab
	T3	375	120	1.32abcd	T3	422	42	1.72ab
Z2	T0	81	107	0.70e	T0	95	56	0.07d
	T1	341	108	1.35abc	T1	206	63	0.92c
	T2	261	95	1.55a	T2	317	42	2.04a
	T3	391	88	1.48ab	T3	426	38	1.90ab
	T4	451	95	1.23cd	T4	488	−4	1.67ab
Z3	T0	81	146	0.35f	T0	92	24	0.06d
	T1	431	127	1.09d	T1	205	32	0.68c
	T2	415	119	1.31abcd	T2	314	58	1.68ab
	T3	415	111	1.32abcd	T3	416	42	1.54b

[a] Values followed by the same letter in a column are not significantly different at a probability level of 0.05. I is the irrigation amount, mm; P_e is the effective rainfall during the growing season; and ΔS is the variation in soil water storage in the 0–1.2 m soil layer between the initial and terminal stage, mm.

and 427 mm for Z1, Z2, and Z3, respectively. In the 2017 season, the maximum WUE and the respective ET_a values were 1.84, 1.87, and 1.69 kg m^{-3} and 514, 431, and 522 mm for Z1, Z2, and Z3, respectively. In both seasons, the minimum optimal ET_a among the three management zones was found in Z2, but the difference in the optimal ET_a between Z1 and Z3 was minor. A comparison of the variation in AWC and the optimal ET_a among the three management zones revealed that the AWC varied in a substantially larger range (152–205 mm with a mean of 164 mm) than did the optimal ET_a (409–459 mm with a mean of 432 mm in the 2016 season). This suggests that there are additional factors to AWC that affect crop water use. The layered-textural profile in the studied field might be a contributing factor. The generation of prescription maps based on soil water content sensors needs to consider the dual effects of AWC and soil profile characteristics.

To generate a VRI prescription, the relationships between ET_a and seasonal irrigation amount (*I*) were derived for the zones selected in the 2016 and 2017 seasons (Fig. 8). These linear equations were significant at a probability level of $p < 0.01$ with high R^2 values. As shown in Fig. 8, the irrigation amount generated by the fitted linear equation corresponding to the optimal ET_a was 296, 276 mm, and 263 mm in Z1, Z2, and Z3, respectively, in the 2016 season. Accordingly, taking the optimal application rate in zone 1 as a basis, 93% and 89% of the rate in zone 1 was recommended for zones 2 and 3, respectively. Similarly, the optimal irrigation amount determined in the 2017 season was 423, 354, and 415 mm, and the application rates were 100%, 84%, and 98% for Z1, Z2, and Z3, respectively. The rates derived from the mean value of the two seasons were 100%, 89%, and 94% for Z1, Z2, and Z3, respectively. Then, these rates were used to determine the water savings of the VRI system compared to the uniform rate irrigation management based on the mean irrigation amount obtained from Z1 in the two seasons. It was found that 7% of irrigation water could be reduced by implementing the VRI strategies by multiplying the irrigation amount by the acreage in each management zone. The benefit of water-savings could be increased when the field is totally irrigated by a VRI system because the estimation of water savings was based on one-quadrant of the center pivot. It should be noted that the effects of AWC and layered-textural soil on yield and WUE were site-specific; the application rates proposed in the study might not be necessarily applied to other fields. While the application rates are a proof of concept on the method generating an irrigation prescription map by means of WPFs. Further works on various complex soils and climate conditions will be helpful for establishing a more general method of mapping irrigation prescription to serve the VRI technology.

4. Conclusions

Field experiments were conducted in the semi-arid region of the North China Plain, where an AWC range of 152–205 mm within the top 1.0 m soil profile was detected. The field was divided into four management zones based on the AWC and different water deficit levels were applied in each subzone with the VRI system. The yield, WUE, WPFs, and the relationship between WUE and crop water use in each zone were compared. The following conclusions are supported by this study:

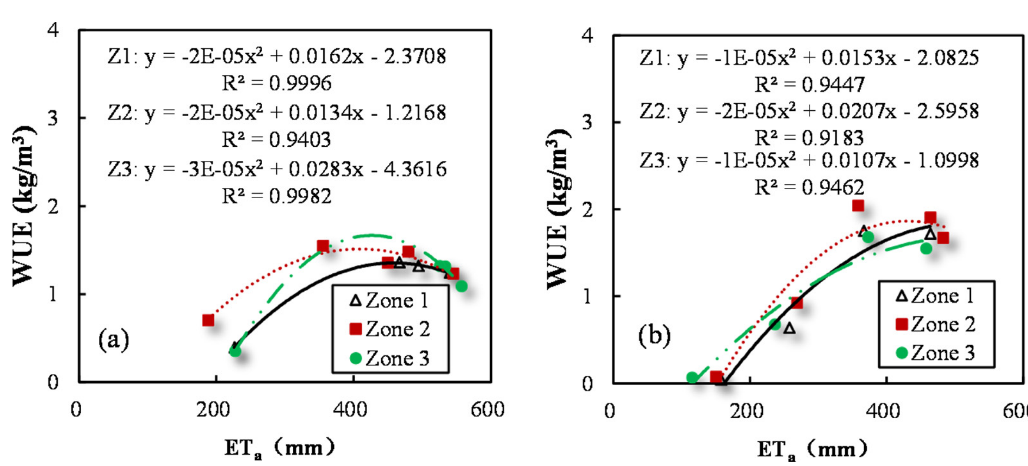

Fig. 7. Relationships between WUE and ET_a in each zone in the 2016 (a) and 2017 seasons (b). R^2 is the determination coefficient.

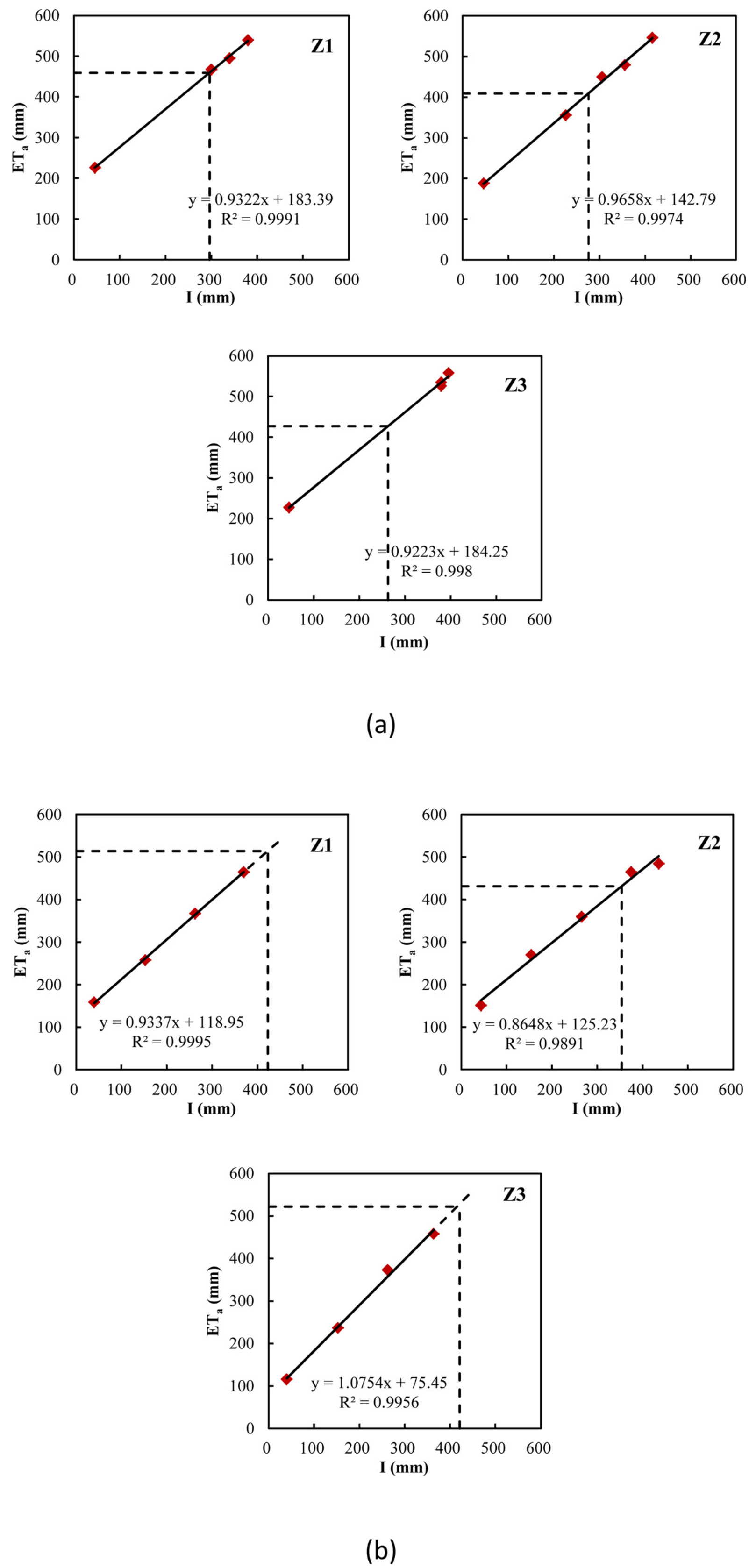

Fig. 8. Relationship between ET_a and the seasonal irrigation amount (*I*) in each management zone in the 2016 (a) and 2017 seasons (b). R^2 is the determination coefficient.

1) The management zone with a higher AWC does not always receive less seasonal irrigation. For the two seasons, zone 2 with a medium AWC and relatively uniform profile received 6 and 12% less irrigation water than zones 1 and 3, respectively, with clearly layered-textural soil profiles. When the irrigation scheduling for VRI was based on the measurement of soil water content, the depth of the interface in the layered soils relative to the buried location of soil water content sensor should be considered. Our results recommended that the sensors should be placed above the interface.
2) The different management zones had different WPFs and water productivity potentials. Compared with zones 1 and 3, the mean yield in zone 2 was 6 and 8% greater and the mean WUE was 18 and 25% higher for the two seasons, respectively.
3) A method for generating the irrigation prescription was provided with the goal to maximize the WUE of winter wheat in the entire field. When the optimal application rate of maximizing WUE in zone 1 was taken as a basis, 89% and 94% of the rate in zone 1 was recommended for zones 2 and 3, respectively, for VRI management in this semi-arid region.

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