Field evaluating system performance of a variable rate center pivot irrigation system

Jiusheng Li, Weixia Zhao

China Institute of Water Resources and Hydropower Research

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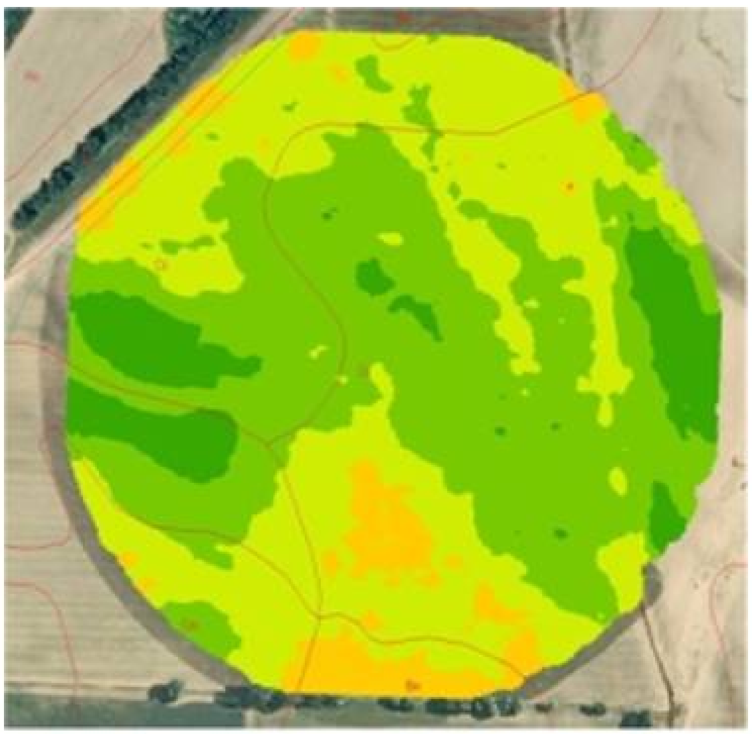
Introduction

- With the development of the intensive agriculture, the moving sprinkler irrigation systems are increasingly used in China.

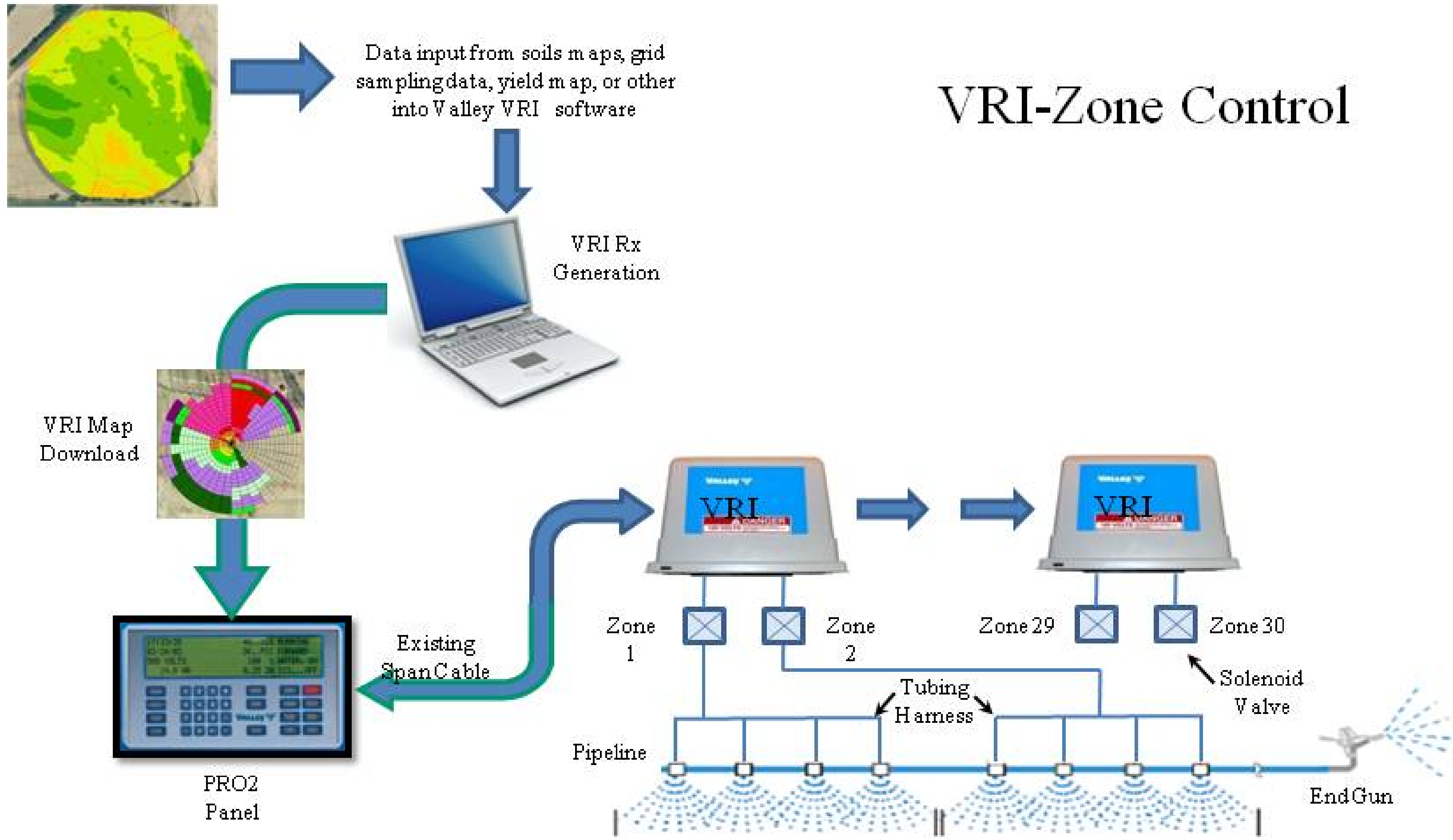
- According to the census in 2014, more than 14,000 center pivots were used, irrigating many crops, such as winter wheat, maize, soybean, and cotton.

Introduction

- Challenge: How can the system deal with within-field differences in soil texture, topography, and biotic stress through irrigation and fertilization in a relatively large coverage of center pivot systems?

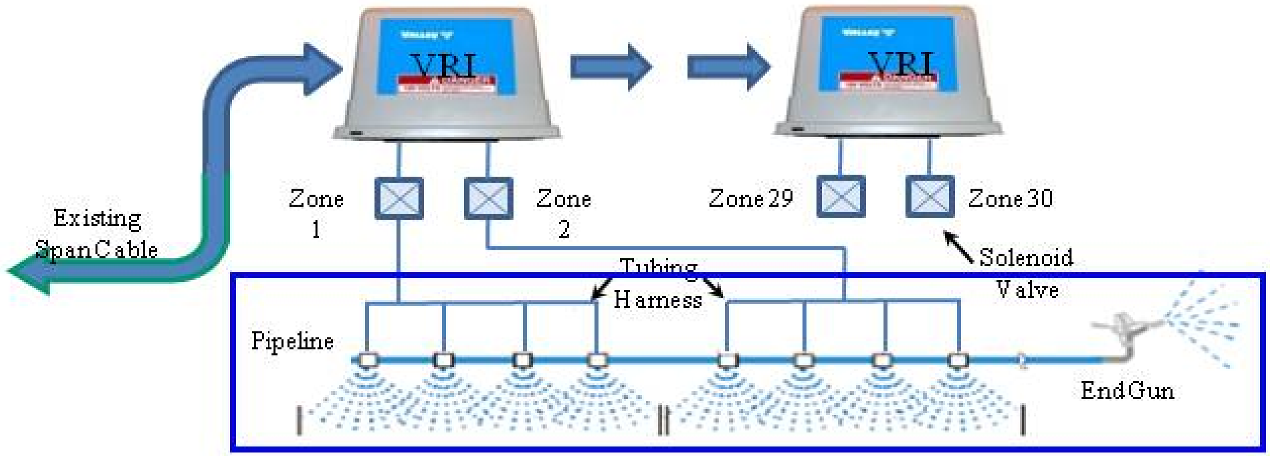


An alternative solution: VRI



- With the use of variable rate irrigation (VRI) systems, it is possible to apply variable amounts of irrigation along the irrigation lateral and in the direction of travel to meet site-specific crop water needs.

Introduction—Further concerns



For a URI system, the uniformity along the pivot radial direction and in the direction of pivot travel is about the same.

For a VRI system, the overlap distorted by the sprinklers from the adjacent zones may cause decreasing of application uniformity in a zone.

What is the profitability of the VRI system?

Objectives

- To investigate the influence of travel speed of center pivot and duty cycle of solenoid valves on applied depth, and to seek the method to reduce the control error between the target and applied depth for center pivot VRI system.

- To evaluate the profitability of VRI system on a highly variable alluvial flood plain field with winter wheat and summer maize in China.

Materials and methods

- **Variable rate irrigation (VRI) system**
- **A three-span (140 m) conventional center pivot system outfitted with 34 rotating sprinklers spaced at 4.2 m.**
- **Solenoid valve was equipped for each sprinkler.**
- **A control unit of geo recognizer designed with radio frequency identification technology was used for zones control in the direction of pivot travel.**

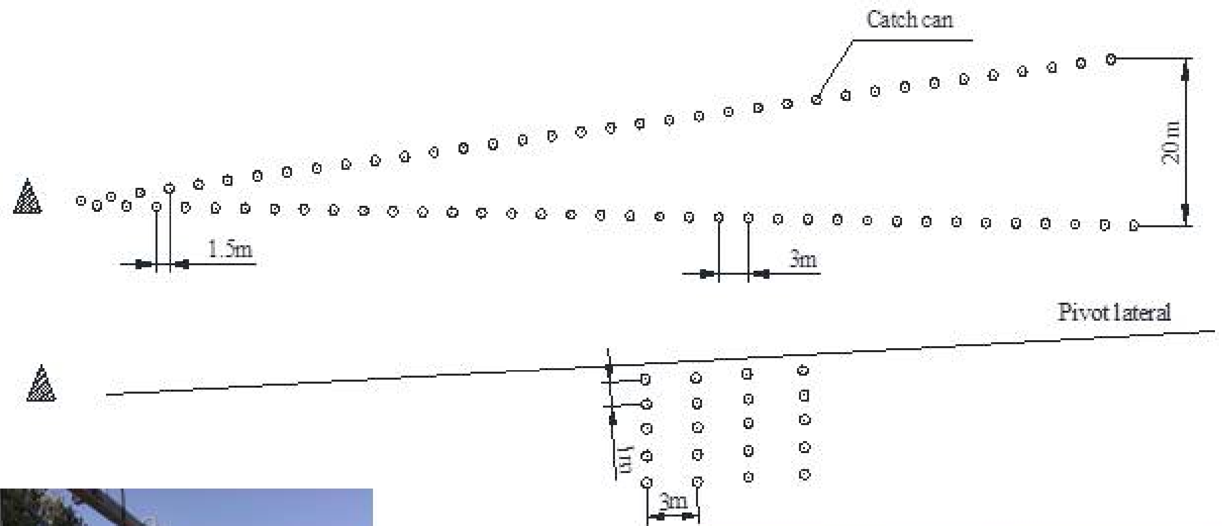
Materials and methods

Table 1 Experimental treatments for application depth testing of center pivot variable rate irrigation system.

Irrigation type	Treatments	Number of sprayer banks	Percent timer/%	Duty cycle of solenoid valve/%
Uniform rate irrigation	U1	1	20	100
	U2	1	40	100
	U3	1	60	100
	U4	1	80	100
	U5	1	100	100
Variable rate irrigation when partial sprinklers open	V1-1	3(8，10，16)	100	100，0，100
	V1-2	3(8，10，16)	100	0，100，0
	V1-3	4(8，6，15，5)	100	100，0，100，，0
	V1-4	5(6，7，7，6，8)	100	100，0，100，0，100
	V1-5	5(6，7，7，6，8)	80	100，0，100，0，100
	V1-6	5(6，7，7，6，8)	40	100，0，100，0，100
	V1-7	5(6，7，7，6，8)	100	0，100，0，100，0
	V1-8	5(6，7，7，6，8)	80	0，100，0，100，0
	V1-9	5(6，7，7，6，8)	40	0，100，0，100，0
	V1-10	6(6，6，6，6，6，4)	100	0，100，0，100，0，100
	V1-11	6(6，6，6，6，6，4)	100	0，100，0，100，0，100
Impulse type variable rate irrigation	V2-1	3(8，11，15)	30	100，80，50
	V2-2	4(8，9，6，11)	30	100，20，50，100
	V2-3	4(8，9，6，11)	30	100，20，100，50
	V2-4	4(8，9，6，11)	20	100，20，100，50
	V2-5	4(8，9，6，11)	50	100，20，100，50
	V2-6	5(8，9，6，6，5)	30	100，20，100，50，80
	CT=50 s	4(8, 9, 9, 8)	100	0, 20, 50, 80
	CT=50 s	4(8, 9, 9, 8)	50	0, 20, 50, 80
	CT=35 s	4(8, 9, 9, 8)	50	0, 20, 50, 80
	CT=30 s	4(8, 9, 9, 8)	50	0, 20, 50, 80
	CT=20 s	4(8, 9, 9, 8)	50	0, 20, 50, 80

Materials and methods

ANSI/ASAE S436.1 Test Procedure for Determining the Uniformity of Water Distribution of Center Pivot and Lateral Move Irrigation Machines Equipped with Spray or Sprinkler Nozzles



Materials and methods

- Irrigation depth for uniform rate irrigation (all sprinklers on)

$$h_{k\%} = h / K\%$$

  - *h* is irrigation depth when percent timer was set to 100%, mm
  - *K* is the percent timer setting

- It is assumed that the VRI control don't change the hydraulic performance of center pivot irrigation system, the irrigation depth for VRI was

$$h_{v-k\%} = m h_{k\%} = m \cdot h / K\%$$

  - *m* is the duty cycle of solenoid valve

Materials and methods

- The accuracy of irrigation depth for VRI was evaluated using

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|P_i - O_i\right|$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)$$

Results

Application depth under URI

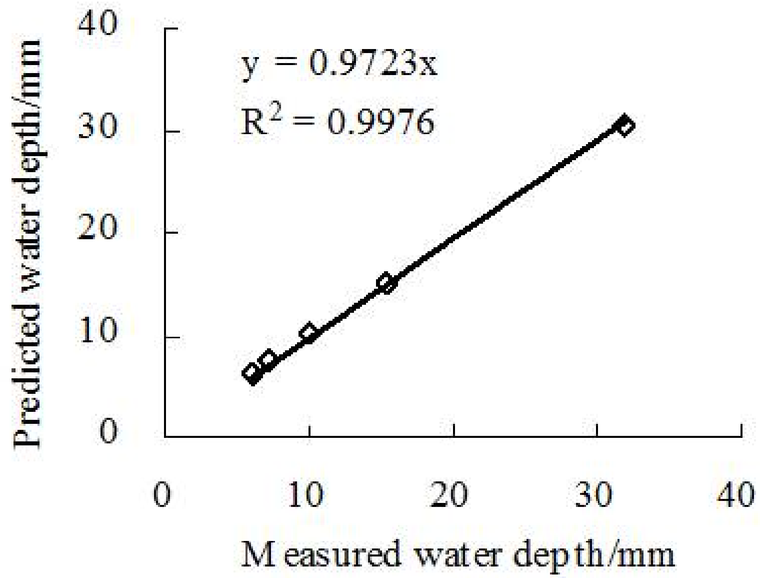


Fig. 1 Relationship between measured application depth and predicted value under uniform rate irrigation

- A target water application depth could be obtained accurately through setting a specific rotation speed of the pivot under uniform rate irrigation.

Application depth under VRI

Table 2 The mean absolute error and the mean bias error of application depth in different management zones when partial sprinklers opened.

Error	Management zone	V1-1	V1-2	V1-3	V1-4	V1-5	V1-6	V1-7	V1-8	V1-9	V1-10	V1-11	Average value
	2		0.42					0.54	0.59	1.45	0.38		
	3	0.41		0.56	0.41	0.5	2.61					0.56	
	4							0.41	0.69	1.23	0.41		
MAE	5				0.32	0.56	1.51					*	
(mm)	6										*		0.75
	2		-0.19					-0.24	-0.53	-0.88	0		
	3	-0.02		-0.39	-0.13	-0.18	-2.61					-0.39	
	4							-0.04	-0.3	-1.14	-0.09		
MBE	5				0.09	-0.16	-1.47					*	
(mm)	6										*		-0.48

- Both MAE and MBE indicated an increasing trend with the decreasing of pivot rotating speed.
- Averagely, the application depth was 0.48 mm underestimated.

Application depth under VRI

Table 3 The mean absolute error and the mean bias error of application depth for impulse type variable rate irrigation.

Error	V2-1	V2-2	V2-3	V2-4	V2-5	V2-6	Average value
MAE (mm)	2.89	0.88	0.55	1.85	2.45	0.83	1.57
MBE (mm)	-2.89	-0.86	-0.48	-1.85	-2.45	-0.21	-1.46

- The combination of impulse type on-off of solenoid valves and go-stop running mode of pivot increased the error of target application depth for impulse type variable rate irrigation.

Application depth under VRI

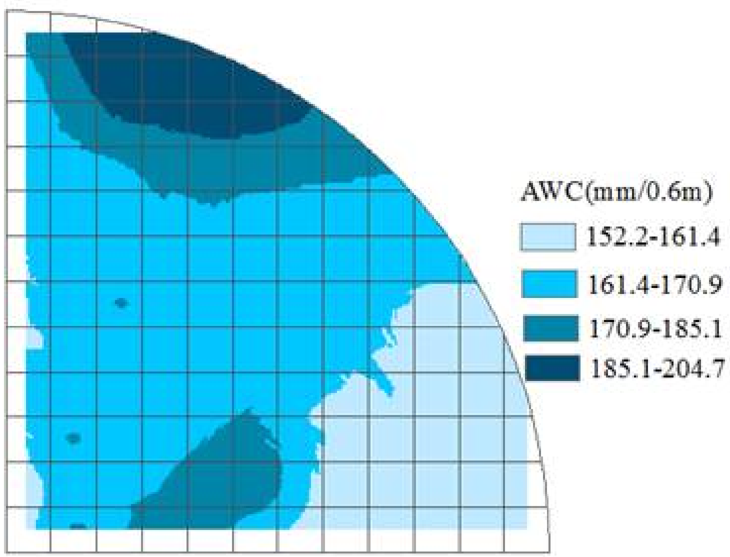
Table 4 Mean absolute error (MAE) and mean bias error (MBE) of water application depth for impulse type variable rate irrigation with different cycle times of solenoid valves.

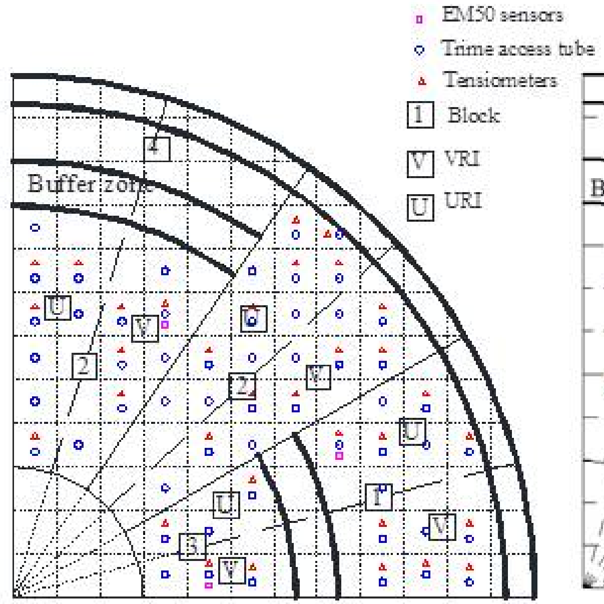
CT（s）	Percent timer (%)	MAE (mm)	MBE (mm)
50	100	0.37	-0.19
50	50	1.56	-1.56
35	50	1.59	-1.59
30	50	0.95	-0.92
20	50	2.24	-2.24

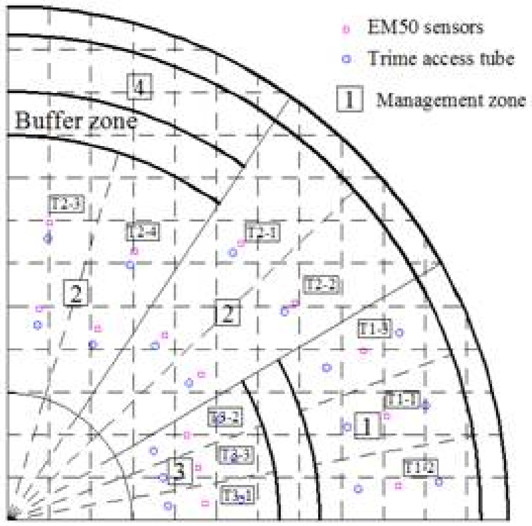
- An optimum cycle time might exist to minimize the error of application depth for impulse type variable rate irrigation.

Response of crop to VRI management

- **Identification of irrigation management zones**
- **Soil available water holding capacity (AWC)**







- The irrigation amount, soil water deep percolation, crop evapotranspiration rate, crop coefficient, yield, water use efficiency, and gross income of winter wheat and summer maize were compared between URI and VRI treatments.

The experiments were conducted in two years of 2014 and 2015:

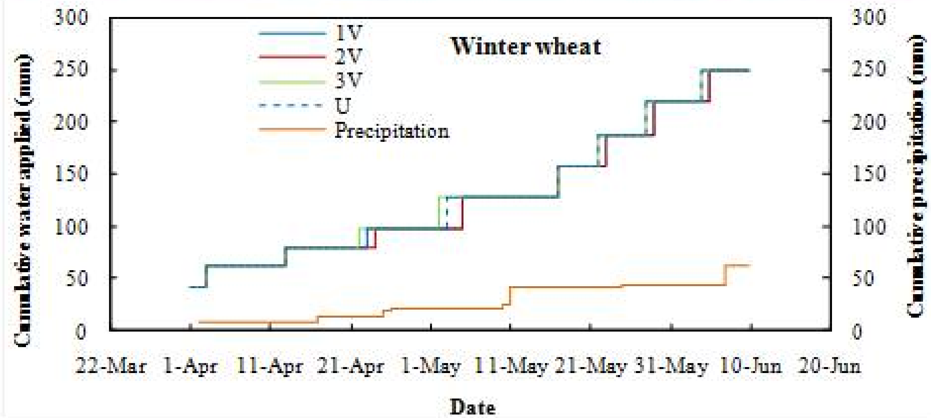
- In 2014, irrigation was triggered when soil water content within root zone was depleted to 0.45AWC.
- In 2015, each zone was divided into several subzones and a specified trigger point was adopted for each subzone to test the necessity of using different trigger points in different zones.

Photos of Experiments

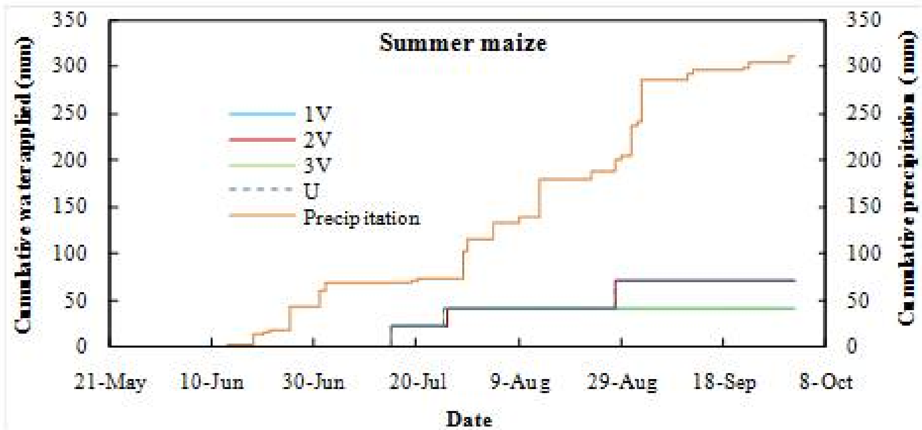
Winter wheat

Summer maize

Irrigation amount and precipitation



Wet season



Wet season

- The potential benefit of VRI management to saving water differed from crop types and weather conditions. Winter wheat under VRI received a seasonal irrigation amount similar to the URI; but the VRI saved 17.6% of irrigation water than the URI management for summer maize.

Deep percolation

Table 5 The mean and variation coefficient (CV) of modeled deep percolations for the URI and VRI treatments during winter wheat and summer maize growing seasons.

Crop type	Mean and variation coefficient	Development stage	Midseason stage	Late season stage	Whole growing season
	Mean for URI (mm)		2.0b*	7.2a	9.3a
	Mean for VRI (mm)		4.8a	4.3a	9.1a
	CV for URI		0.58	1.94	1.61
Winter wheat	CV for VRI		0.91	0.93	0.78
	Mean for URI (mm)	1.9a	6.2a	6.9a	15.0a
	Mean for VRI (mm)	1.2a	9.0a	7.1a	17.3a
	CV for URI	1.01	0.79	0.71	0.67
Summer maize	CV for VRI	1.25	0.82	0.77	0.66

- There was no significant difference in deep percolation between URI and VRI treatments, while the VRI decreased the spatial variability of deep percolation across the field when crop water consumption was mainly provided by irrigation water rather than precipitation.

Evapotranspiration rate

Table 6 Evapotranspiration rate and variation coefficient (CV) to the URI and VRI treatments during winter wheat and summer maize growing seasons.

Crop type	Mean or variation coefficient	Development stage	Midseason stage	Late season stage	Whole growing season
	Mean for URI (mm/d)		3.5a*	4.1a	3.8a
	Mean for VRI (mm/d)		3.2a	3.9a	3.6a
	CV for URI		0.23	0.23	0.12
Winter wheat	CV for VRI		0.22	0.23	0.18
	Mean for URI (mm/d)	3.4a	4.3a	1.1a	3.3a
	Mean for VRI (mm/d)	3.4a	3.8a	0.7b	3.0b
	CV for URI	0.24	0.18	0.64	0.12
Summer maize	CV for VRI	0.17	0.33	0.74	0.16

- The effect of VRI management on crop evapotranspiration rate was related to crop types. Significant difference in evapotranspiration rate for summer maize was observed between URI and VRI treatments but no difference was detected for winter wheat.

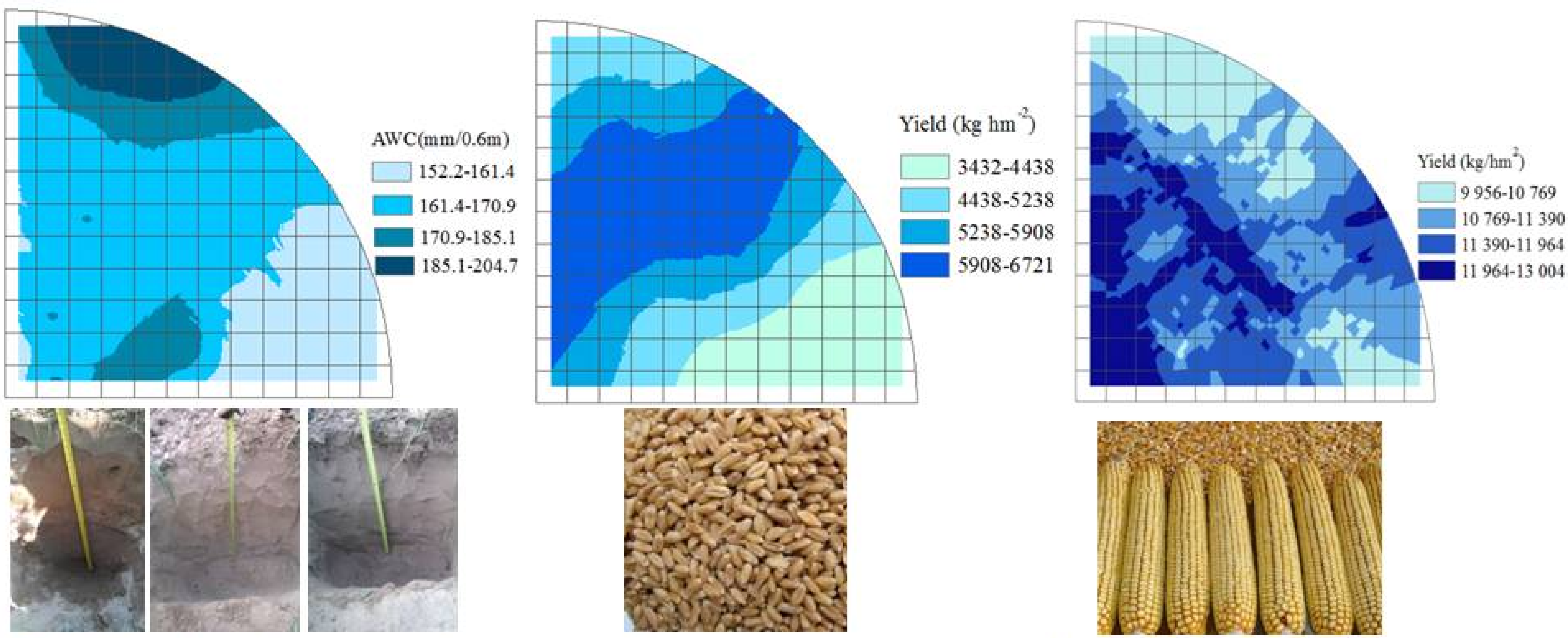
Crop coefficients

Table 7 The crop coefficients (Kc) for all management zones during growing seasons of winter wheat and summer maize.

Crop type	Growing stage	Average K_c	1V	2V	3V	1U	2U	3U
	Midseason	1.61	1.35c*	1.56bc	1.51bc	1.82ab	1.44bc	1.99a
Winter wheat	Late season	1.12	1.05b	1.41a	0.99b	1.18ab	1.44a	0.68c
	Development	0.97	1.00b	0.89b	0.95b	0.82b	0.92b	1.23a
	Midseason	1.28	1.10a	1.24a	1.21a	1.31a	1.37a	1.42a
Summer maize	Late season	0.50	0.41a	0.46a	0.34a	0.70a	0.66a	0.47a

- Significant difference in crop coefficients between the zones was detected for both winter wheat and summer maize. To improve the accuracy of prediction and facilitate variable rate irrigation implementation, the crop coefficient should be modified for each management zone.

Spatial distribution of yield



- The distribution of crop yield kept consistence with the AWC, demonstrating that AWC can be used as one of the parameters for zone identification in VRI management.

Yield

Table 8 Mean and variation coefficient (CV) of yield for all management zones during winter wheat and summer maize growing seasons.

Crop type	Parameter	Treatment		Yield for each Zone					
		VRI	URI	1V	1U	2V	2U	3V	3U
Winter wheat	Mean (kg/ha)	5229a	5325a	3928b	4251b	6209a	6236a	4024b	4023b
	CV	0.27	0.23	0.17	0.16	0.16	0.11	0.21	0.15
Summer maize	Mean (kg/ha)	11720a	11809a	10842a	11483a	12075a	11791a	11807a	12795a
	CV	0.16	0.18	0.07	0.22	0.18	0.16	0.16	0.20

- The responses of crop yield to VRI management were greatly dependent upon seasonal precipitation. Crop yield demonstrated decreasingly sensitive to irrigation management with an increasing precipitation.

Yield and WUE

Table 9 Yield and water use efficiency for winter wheat when managing VRI zones using a specific irrigation trigger point for each zone (2015 season).

Treatment	T1-1	T1-2	T1-3	T2-1	T2-2	T2-3	T2-4	T3-1	T3-2	T3-3
Trigger point	0.9Fc	0.8Fc	0.7Fc	0.8Fc	0.75Fc	0.7Fc	0.65Fc	0.8Fc	0.7Fc	0.6Fc
Yield (kg/ha)	2661a	2852a	3510a	5142AB	5656A	4428B	5062AB	4724a	3865ab	2195b
$I+P$ (mm)	284.5	304.5	254.5	304.5	324.5	284.5	254.5	434.5	304.5	254.5
ΔS (mm)	-42.4	-74	-102.7	-61.9	-69.1	-97.1	-89.5	-12.6	-104.5	-101.1
ET (mm)	326.9	378.5	357.2	366.4	393.6	381.6	344	447.1	409	355.6
WUE (kg/m^3)	0.81a	0.75a	0.98a	1.40A	1.44A	1.16B	1.47A	1.06a	0.94a	0.62a

Using a specified irrigation trigger point for each management zone was recommended to improve the WUE or to maximize the production potential of field.

Gross income

Table 10 The gross income of winter wheat under VRI and URI treatments for the 2014 season when managing all VRI zones at an equal irrigation trigger point.

Management zone	Area (ha)	URI management		VRI management	
		Application amount (m^3)	Yield (kg)	Application amount (m^3)	Yield (kg)
1	0.39	957.8	1640.9	957.8	1516.2
2	0.85	2123.9	5338	2123.9	5314.9
3	0.21	522.7	847.5	522.7	847.7
Total	1.45	3604.4	7826.4	3604.4	7678.8
Water charge ($)		98.8		98.8	
Income of yield ($)		3105.3		3046.8	
Gross income ($/ha)		-40.3			

Gross income

Table 11 The gross income of winter wheat under VRI and URI treatments for the 2014 season when managing VRI zones using a specific irrigation trigger point for each zone

Management zone	Area (ha)	URI management		VRI management	
		Application amount (m^3)	Yield (kg)	Application amount (m^3)	Yield (kg)
1	0.39	347.6	1354.9	347.6	1354.9
2	0.85	1027.7	3790.4	1370.3	4841.5
3	0.21	295.1	814.2	569.1	995.2
Total	1.45	1670.4	5959.5	2286.9	7191.6
Water charge ($)		45.8		62.7	
Income of yield ($)		2364.6		2853.4	
Gross income ($/ha)		324.8			

- ☐ The correct management method is critical for reasonably evaluating the VRI technology.

Summary

- When using the percent timer to control the application depth of VRI system, the accuracy is related to the duty cycle of solenoid valve and the traveling speed of irrigation system.
- The responses of crop yield to VRI management were greatly dependent upon AWC and seasonal precipitation. Crop yield demonstrated a decreasing sensitivity to irrigation management with an increasing seasonal precipitation.
- When managing the VRI zones with a specific irrigation trigger point for each zone, the significant difference was observed for water use efficiency and yield of winter wheat. The trend in gross income averaged across the field was $325/ha greater with VRI.
- Using a specified irrigation trigger point and crop coefficient for each management zone was recommended to improve the WUE or to maximize the production potential of field.

Thank You