IRRIGATION AND DRAINAGE
Irrig. and Drain. **(2018)**

VARIABLE RATE PRECISION IRRIGATION TECHNOLOGY FOR DEFICIT IRRIGATION OF PROCESSING TOMATO[†]

SÁNDOR TAKÁCS[1]*, TIBOR BÍRÓ[2], LAJOS HELYES[1] AND ZOLTÁN PÉK[1]

[1]Szent István University, Faculty of Agriculture and Environment, Institute of Horticulture, Gödöllő, Hungary
[2]National University of Public Service, Faculty of Water Sciences, Institute of Hydraulic Engineering and Water Management, Baja, Hungary

ABSTRACT

Centre pivot machines, with a variable rate irrigation (VRI) package that provides individual sprinkler control systems (VRI iS), are not common. This research focuses on how uniform the water distribution is under VRI control, and on the size of over- and under-irrigated areas and volumes. Moreover, we wanted to know how wide transition zones are. We conducted different uniformity measurements using common rain gauges for measuring water application depths. Besides grid shape and radial direction measurements for uniformity, perpendicular measuring lines to borders were set to evaluate transition zones. In a processing tomato deficit irrigation experiment, we investigated how different plant properties react to different water depths. Results showed that very good uniformity is achievable both in the IR100 and IR50 application rates, but the former showed higher uniformity. CU_C ranged from 91.8 to 92.9% and 88.8 to 90.8% in the IR100 and IR50 rates respectively. The highest RMSE was 2.65 mm. The amount of over- and under-irrigation was not significant. Transition zones were not equally wide; 9 m was enough for transition widthways between the IR100 and IR50 rates, but was wider longitudinally. This technology is suitable for conducting deficit irrigation experiments, but consideration of transition zones is important at plant sampling. © 2018 John Wiley & Sons, Ltd.

KEY WORDS: VRI; VRI iS; transition zone; irrigation uniformity; over-irrigation; under-irrigation

Received 7 March 2018; Revised 22 August 2018; Accepted 22 August 2018

RÉSUMÉ

Les machines de pivots centraux, avec le package d'irrigation à taux variable (VRI) qui assure des buses d'irrigation à commande individuelle (VRI iS), ne sont pas encore répandues. Cette étude caractérise l'uniformité de la distribution en eau avec le contrôle VRI iS, la taille des zones sur-irrigué et sous-irrigué et les volumes. Au-delà, on voulait également déterminer le largueur des zones de transition. Diffèrentes mesures d'uniformité ont été effectuées par des pluviomètres communs pour mesurer la quantité d'eau appliquée. En dehors des mesures d'uniformité suivant une grille et des directions radiales, des lignes de mesure perpendiculaires aux bordures ont été mise en place pour évaluer les zones de transition. On a étudié dans une expérience d'irrigation déficitaire de tomates, comment les différentes caractéristiques de la plante réagissent à différentes doses d'eau. Selon les résultats, une très bonne uniformité a été obtenue sur les deux modalités IR100 et IR50, mais la parcelle IR 100 a montré une plus grande uniformité. Les valeurs de CUc variaient de 91.8 à 92.9% et de 88.8 à 90.8% dans les taux IR100 et IR50 respectivement. La plus grande RMSE mesurée était de 2.65 mm. Le niveau de sur-irrigation et de sous-irrigation n'était pas significatif. La largeur des zones de transition n'étaient pas égale; 9 m de largueur semblait suffire pour la zone de transition entre IR100 et IR50, mais plus large longitudinalement. Cette technologie est appropriée pour mener des expériences d'irrigation déficitaire, mais pour l'échantillonnage des plantes il faut prendre en compte les zones de transition. © 2018 John Wiley & Sons, Ltd.

MOTS CLÉS: VRI; VRI iS; zone de transition; uniformité; sur-irrigation; sous-irrigation

---

*Correspondence to: Mr Sándor Takács, Szent Istvan Egyetem Mezogazdasag- es Kornyezettudomanyi Kar—Institute of Horticulture. Páter Károly street 1. Godollo 2100, Hungary. E-mail: takacs.sandor@mkk.szie.hu

[†] Technologie d'irrigation de précision à débit variable pour l'irrigation déficitaire de la tomate en traitement.

Contract/grant sponsor: Ministry of Human Capacities of Hungary; contract/grant number: Higher Education Institutional Excellence Program
Contract/grant sponsor: European Union; contract/grant number: EFOP-3.6.1-16-2016-00016 and EFOP-3.6.3-VEKOP-16-2017-00008
Contract/grant sponsor: Ministry of Human Capacities; contract/grant number: New National Excellence Programme ÚNKP-17-3-I/SZIE-1

INTRODUCTION

The amount of precipitation in the Carpathian basin, central Europe, varies year by year, together with increasing temperature trends (Spinoni *et al.,* 2015). The most important agricultural production areas are situated on the Great Plain (its area spreads to five countries). In many years when precipitation was very low in the growing season, drought caused lots of damage to growers (Szalai, 2009). Even if the amount of precipitation is enough, its distribution can be unfavourable and long dry periods can occur in the growing season. These problems cause unpredictable agricultural production in the region and irrigation becomes a must-do especially with high-value crops such as processing tomato.

The area equipped for irrigation is nearly 300 000 ha in Hungary; nevertheless, the actual irrigated area is just above 100 000 ha on average (Food and Agriculture Organization of the United Nations (FAO), 2016). Sprinkler systems are widely used in Hungary. Centre pivots are starting to spread in the country, operating on 7% of the irrigated area, while the most common irrigation machines are hose reel systems, with travelling guns mostly (16%) and lateral move pivots (linears) on 69% of the entire irrigated area (Marosán, 2017). Hose reel systems need much more pressure for proper operation than centre pivots or lateral move pivots. Large parts of lateral move pivots were constructed decades ago, so ageing will cause more and more problems if farmers do not renew these systems.

In Hungary, accessibility to irrigation water is good in general especially where growers have access to a constructed surface water distribution system. Moreover, there are endangered subsurface aquifers in the country where growers cannot cover their irrigation water needs from surface water and water saving is a priority in these areas (Biró *et al.,* 2011). In addition, reducing irrigation costs, avoiding secondary salinization or improper irrigation are important in every case. Water and energy conservation with a positive impact on crop water productivity and the environment is achievable with site-specific irrigation (Evans *et al.,* 2013). Over-irrigation will lead to deep percolation or surface runoff, moreover it can also cause ponding on the surface (Fiebig and Dodd, 2016). These factors are the basis of soil degradation, nutrient leaching and reduction of water use efficiency (O'Shaughnessy *et al*., 2016).

It certainly affects plants as well, not just the soil. Since tomato is one of the most significant horticultural crops in the world and its production (FAO, 2018) is only effective —in most of its production area—when proper irrigation is provided, hence knowledge about its reaction to irrigation is very important. As has been observed, over-irrigation induces growth inhibition in tomato (Fiebig and Dodd, 2016). Under-irrigation negatively affects the plant's biomass and yield production. Utilization of potential maximum yields is not feasible without satisfying the crop's water demand. However, under-irrigation is a potential way to enhance the quality of processing tomato (Pék *et al.,* 2017). Deficit irrigation is a water-saving concept where irrigation water does not cover 100% of crop evapotranspiration. This is a good way to maximize crop production per unit water consumed (Fereres and Soriano, 2007). This method reduces potential biomass and yield, but the improved quality and the amount of water saved may be more beneficial (Patanè *et al.,* 2011). Other water-saving solutions, such as partial root zone drying in processing tomato (Battilani *et al*., 2009), are not feasible for sprinkler irrigation.

During the configuration of a modern irrigation management system, one must consider the varying soil types and different species or growth stages of a plant within a field. Precision irrigation is also very new to growers and only a few irrigation machines are operating in Hungary that are capable of site-specific irrigation which can be achieved through speed and zone control of pivots. The speed control can vary the speed of the travelling system to achieve higher or lower application depths (ADs). Zone control modulates the duty cycle of sprinklers (or groups of sprinklers), so they provide different ADs along the pivot (Kranz *et al.,* 2012).

Moreover, with precision devices, another very important challenge is to operate these devices adequately for the task. For this approach, one must know how diverse their field is (infiltration, relief, soil water-holding capacity etc.) (Yari *et al.,* 2017). To create maps with different information that is relevant for programming the operation of a precision irrigation machine, a detailed survey is needed. But the more detailed the survey, the more money it costs. First of all, farmers should know how detailed these maps must be. It is not economical if one acquires a high-resolution map, but the machine is not able to follow it successfully. Between the different adjacent zones we find transition zones because of sprinkler overlap (O'Shaughnessy *et al.,* 2013). The size of these transition zones will determine how we must mark the boundaries of zones, which has to be considered with small field plots (Sui and Fisher, 2015). Daccache and coworkers (Daccache *et al.,* 2015) also warn of the problems of defining too small irrigation management zones, as sprinkler overlap may cause high variation in the scheduled AD.

In areas with different desired ADs or with deficit irrigation experiments that are performed with sprinkler irrigation systems, it is not acceptable if the system cannot provide proper uniformity, or water application differs from the ADs aimed at. This is not an easy task due to the lack of a standard procedure to examine variable rate irrigation (VRI) systems. Former studies showed that neither travelling speed nor sprinkler cycling rate affected uniformity (Perry *et al.,* 2003; Dukes and Perry, 2006), but different nozzle types influenced application uniformity (Dukes and

Perry, 2006). Old worn-out sprinkler systems and windy conditions negatively affect a centre pivot's application uniformity (Yari *et al.,* 2017).

The main goal of this study was to evaluate how precisely one must mark off the shape of polygons with different irrigation water application on the prescription map of a precision irrigation machine (defining VRI zones). Our experiments partly focused on to evaluate how long a transition zone (overlap between zones) between differently irrigated areas is. Moreover, another goal was to see how uniform is the irrigation in the polygons with different ADs and what this uniformity means when we examine the over- and under-irrigated areas. We also examined the yield, soluble solids content (SSC) and water stress level of processing tomato—that was cultivated in the experimental area—to reveal how these plant properties react to deficit irrigation provided by a VRI system.

MATERIALS AND METHODS

Description of the irrigation system

The irrigation system used in this research consists of two spans of Valley 8120 and an 800c corner. The machine is equipped with a VRI iS system (Valmont Irrigation, Valley, Neb.) which provides VRI sprinkler by sprinkler on the fixed spans, not just with multi-sprinkler management zones as in simpler VRI systems. The length of the three spans is 180.86 m in total. VRI controlled length is 98.26 m. Maximum AD is 7.6 mm day^{-1}. Nelson R3000 D8 rotator sprinklers can be found on the VRI controlled spans with Valley Regulator PSR-2 (1.03 bar). Sprinklers are hung from the pipes at approximately 2.4 m height above the ground. The sprinklers' dispersion radius is around 6–7 m. Sprinkler spacing is mostly 5.73 m but differs in the several sprinklers around the tower. Operating pressure was around 1.8 bar at the centre which was measured by an inbuilt gauge. The constant pressure was provided by a frequency changer connected to the pump. The machine's movement is controlled by a GPS driving system. To reach different ADs on the site the valves must turn on and off from time to time above areas with different application rates (ARs). This pulsing operation is provided by magnetic valves.

Description of measurements and the experimental area

The measurements were conducted at Szarvas, south-east Hungary, on the experimental farm of Szent István University, Tessedik Campus (GPS coordinates: 46°53′11.5″ N, 20°31′58.6″ E). The location is 84 m asl. The area is bordered by the backwater of the river Körös to the east and north-east with a line of trees and shrubs alongside it and an arboretum with forest vegetation in the south. The western borders are dams of fishponds and a road. The area is characterized by temperate climate with continental, oceanic and Mediterranean effects. Szarvas belongs to the warm and dry part of the country with usually less than 500 mm annual precipitation (Hungarian Meteorological Service, 2018). The different measurements were processed from May to August over a deficit irrigation experiment that was set on ~0.4 ha (38 × 104 m) area, on clay-loam soil. This field was divided into three similar plots (rectangular shape) and irrigated with 0, 50 and 100% of the water application (Figure 1). These rates were determined according to the water demand of the tomato plants (calculated with AquaCrop). Soil properties or elevation were not considered by the configuration of the application zones: 0% works as a rain-fed control and the 100% AR represents the well-irrigated plot with no water stress. 50% AR is between these two end values which results in moderate water stress, which can raise the SSC in tomato, which is an important parameter for the processing tomato industry, but does not reduce the yield very much (Patanè *et al.,* 2014). Valley VRI 8.46 software was used

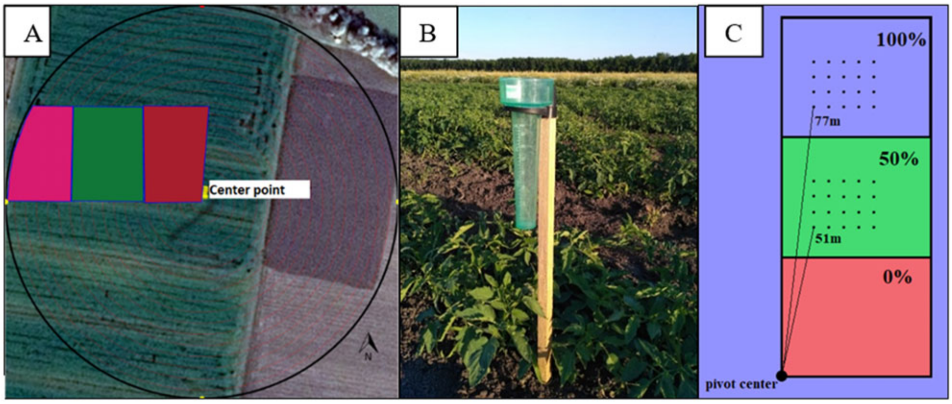

Figure 1. (A) Designed VRI plots under the centre pivot (red: 0%, green: 50%, pink: 100% application rate), (B) a rain gauge that we used for measuring depths, (C) experimental design of grid shape measurements. [Colour figure can be viewed at wileyonlinelibrary.com]

to plan the polygons with different ADs. We registered meteorological data over the whole season with a meteorological station, installed near the field. Wind speed was measured at 10 m above the surface, but we transformed wind speed to 2 m height, using a logarithmic wind profile. Mean wind speed ranged between 0.24 and 2.53 m s^{-1} during the catch-can measurements. To determine the borders of these application zones on the field initially, for the first measurement we installed the measuring cans in a row perpendicular to the expected lines between the polygons.

We used common rain gauges (mm scale) for measuring the applied irrigation water. These were installed on a wooden rod (Figure 1). We used uniform measuring heights for the respective measurements. They were 60 cm in general, but we had to raise it to 90 cm in the late season because of greater plant heights. After this we attempted to evaluate the distribution uniformity (Kruse, 1978) and Christiansen uniformity coefficient (CU_C) (Christiansen, 1941) of the two irrigated plots. For these measurements, we placed the cans in a 4 × 5 grid into the two parcels where the distance between cans was 3 m and they were placed at 60 cm height. These grids were placed inside the plots, so transition zones could not affect the measured values. The nearest rain gauge in the 50% rate zone (IR50) was 51 m from the pivot centre and 77 m in the100% rate zone (IR100). It was replicated four times. To evaluate how close the measured depths were to the prescribed depths and to reveal the accuracy of the irrigation, we calculated mean absolute error (MAE) and root mean square error (RMSE).

The second type of measurement was conducted according to a standard, developed by the American Society of Agricultural Engineers (American Society of Agricultural Engineers (ASAE), 1997), for determining a centre pivot's water distribution uniformity. Thus we arranged the cans in two straight rows radiating from the pivot centre. The distance between cans was 3 m and they were at 60 cm height. The nearest rain gauge was 36 m from the centre, because we eliminated the 0% rate zone (IR0) completely from the measurement. The third type of measurement was to determine how long is the transition zone between zones with different ARs. For this, we placed straight lines of the cans perpendicular to the borders of zones. This time we used 1 m spacing between cans and raised them to 90 cm height because of the developed vegetation. The arrangement of the catch cans is displayed on Figure 7 with coloured lines. We placed 14 cans on the blue line, 14 cans on the orange line, 11 on the yellow line and 9 on the red line. This measurement was conducted on 29 July, and average wind speed was 2.27 m s^{-1} during the irrigation. For monitoring evaporation during the measurements, we placed three cans containing 10 mm water, but there was no appreciable decrement during the measurements, so it was not necessary to correct any values. Most irrigation tests and measurements were performed through the night and the values were checked in the early morning. We could not calculate the effect of irrigation water losses occurring between the sprinkler and catch cans, but according to the review of Schneider (2000) it ranges between 1 and 2% of water application by spray irrigation. The machine headed forward in every case. The catch-can tests were always part of the irrigation schedule, not an additional extra above the calculated water demand.

Evaluation of data

For the evaluation, the Christiansen uniformity coefficient (CU_C), distribution uniformity (DU) and the Heerman and Hein formula (CU_{HH}) were used.

CU_C (Christiansen, 1941):

$$\mathrm{CU_C} = 100\left[1 - \frac{\sum_{i=1}^{n} |V_i - \overline{V}|}{\sum_{i=1}^{n} V_i}\right] \tag{1}$$

where

Vi = the individual collector measurement (mm)
$\overline{V}$ = the average volume of water over all collectors (mm)

Distribution uniformity (Burt *et al.,* 1992, 1997):

$$\mathrm{DU} = \frac{\textit{Average}\ \text{low quarter depth of application (mm)}}{\textit{Overall}\ \text{average depth of application (mm)}} \tag{2}$$

The Heerman and Hein formula (American Society of Agricultural Engineers (ASAE), 1997):

$$CU_{HH} = 100\left[1 - \frac{\sum_{i=1}^{n} S_i |V_i - \overline{V}_p|}{\sum_{i=1}^{n} V_i S_i}\right] \tag{3}$$

where

$\mathrm{CU_{HH}}$ = Heerman and Hein uniformity coefficient
n = number of collectors
i = *i*th collector
V_i = volume of water collected in the *i*th collector (mm)
S_i = distance of the *i*th collector from the pivot point (m)

$\overline{V}_p$ = weighted average of volume of water caught (mm). It was determined as

$$\overline{V}_p = \frac{\sum_{i=1}^{n} V_i S_i}{\sum_{i=1}^{n} S_i} \tag{4}$$

Determination of over- and under-irrigation was based on the grid shape measurements. 3D surfaces were created from the measured grid data and flat levels created according to the prescribed ADs applied at the given irrigation test. One purpose was to visualize the water distribution models belonging to the computed uniformity values. Furthermore, to calculate over- and under-irrigation volumes we subtracted the flat surfaces from the surfaces that show the water distribution (Figure 2). The modified Shepard method was used for gridding. This interpolator uses an inverse distance weighted least squares method. It differs from the similar inverse distance to a power since it uses local least square that eliminates or reduces the 'bull's eye' appearance of the generated models. It can be either an exact or a smoothing interpolator (Shepard, 1968; Franke and Nielson, 1980; Renka, 1988). We chose this method from among many interpolators that are available in Surfer and visually showed results that are adaptable for the spraying pattern (inverse distance to a power, kriging, local polynomial, minimum curvature, modified Shepard method, radial basis function, triangulation with linear interpolation). We chose for the test of interpolators the IR100 AR of test 4 (8 June), because it presented both under- and over-irrigation. Afterwards, we made the grids and computed the residuals and summed the absolute residual values of the different interpolations. The residuals represent the difference between the measured and estimated values. The least summed value was 0.0125 for the modified Shepard method, so we decided to use this interpolator for the further examinations. The results we gained were expanded to hectare scale. The 3D surface modelling and volumetric subtractions were performed in Surfer 11 (Golden Software, Inc, Golden, Colorado).

Deficit irrigation experiment

Plants are the best indicators of different irrigation treatments. Therefore, a deficit irrigation experiment with processing tomato (UG812J F1 hybrid) on clay-loam soil was conducted. The shape and area of the plots are described above. AquaCrop v5.0 (Steduto *et al.,* 2012) was used to determine the plants' water demand. Reference evapotranspiration (ET) was calculated by software according to the FAO Penman–Monteith method, corrected by the crop coefficient (K_c) (Allen *et al.,* 1998). Daily minimum and maximum temperature, rain, wind and mean relative humidity data were used for the calculation. These data were gathered by a meteorological station installed near the field (Figure 3). Thus, the two differently irrigated plots were the IR100 (100% of evapotranspiration), IR50 (50% of IR100) and there was a rainfed control (IR0). Irrigation was performed twice a week and was ended 19 days before harvest. Plants were transplanted on 9 May (2017) to single-row style (140 × 20 cm). Harvest date was 17 August when 10 plants were sampled from every treatment in three replications. We measured above-ground fresh biomass, total fruit yield and SSC (°Brix). Soil moisture was also monitored during the experiment in the upper 15 cm

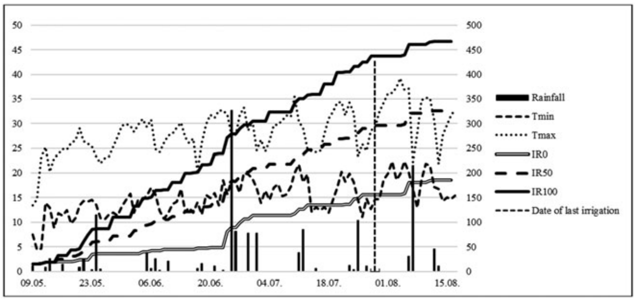

Figure 3. Meteorological and irrigation data.

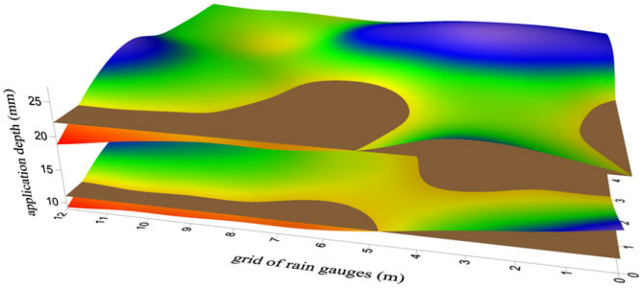

Figure 2. Water distribution pattern of the 100% (upper) and 50% (lower) application rate of the second irrigation test (brown flats shows the prescribed depths). [Colour figure can be viewed at wileyonlinelibrary.com]

level with a Trime-fm PS3 soil moisture probe (IMKO Micromodultechnik GmbH, Ettlingen, Germany). Crop water stress index (CWSI) was also calculated from leaf surface temperature data collected with a FLIR One for Android thermal cam (FLIR Systems, Wilsonville, Oregon, USA). This was only measured in July (27 days). Dry and wet reference surface temperatures were used to calculate CWSI (Jones, 1999) as follows: $(T_{leaf} - T_{wet})/(T_{dry} - T_{wet})$. Thermal images were processed by FLIR Tools 6.3. Statistical tests were performed in R ×64 3.4.3 (R Core Team, 2017) with R Commander (Fox and Bouchet-Valat, 2018). The Shapiro–Wilk test was used to check normality. We tested for homogeneity of variances with Bartlett's test. To reveal differences between treatments we used ANOVA and Tukey as post-hoc tests.

RESULTS AND DISCUSSION

Processing tomato yield, Brix, water productivity (WP)

The amount of total yields and SSC yield showed the expected increasing trend as the applied irrigation water was greater. Tomato yields showed the difference between VRI zones very well. The amount of water was 186 mm in IR0, 326 mm in IR50 and 467 mm in the IR100 plot. Mean temperature was 21.9°C and the mean relative humidity was 64.1% in the season. Total rainfall was 146 mm.

The three groups differed significantly in the case of total yields and SSC. These values demonstrate perfectly the effect of different water applications. Irrigation water raised yields by 65.1 and 133.7% in the IR50 and IR100 treatments, respectively. But when we examine SSC yields, there was no difference between IR50 and IR100, even if the soluble solids produced in the IR100 were almost 25% higher than in the IR50 treatment. As the result shows, irrigation water had the same level of efficiency in the two irrigated plots (Table I). Water use efficiency was highest in the unirrigated plot (29.4 kg m^{-3}) and lowest in the IR100 plot (24.6 kg m^{-3}). This trend of WP is agreed by other researchers (Patanè *et al.,* 2011; Biswas *et al.,* 2015). Besides deficit irrigation, VRI technology supported by supervisory control and data acquisition systems was also a good way to enhance WP (O'Shaughnessy *et al.,* 2016).

Heat stress measurements

Tomato plant heat stress values followed the rising water dosage according to the crop water stress index (CWSI) computed from leaf surface temperature data (Figure 4). By contrast, when we used the simpler stress degree day (SDD) index, we could not differentiate the irrigated plots. It is important to note that there is a relatively big variance among CWSI values in the IR100 treatment.

Soil moisture data

The soil moisture lines of different treatments differed clearly throughout the season (Figure 5). Soil moisture can be an important factor for setting VRI zones and huge water savings can be achieved if the zones are designed according to the differing soil moisture levels (Hedley and Yule, 2009). In addition, soil moisture is a dynamic variable, changing day by day, so a dynamic response is needed throughout the season (Vellidis *et al.,* 2016).

There are some occasions where the line of rain-fed plots reach, or cross, the line of irrigated plots. This happened at the end of June, because of heavy rainfall in the last week of the month. Later, at the beginning of August, the lines of the irrigated plots show a reducing tendency due to the termination of irrigation at the end of July.

Water distribution uniformity, volumetric and planar calculations

Grid measurements. These measurements performed in a grid shape were suitable for investigating water distribution uniformity and additionally volumetric and planar calculations of over- and under-irrigation.

Two of these four ADs were similar (12.2 and 12.7 mm) and the other two were higher (22.1 and 25.1 mm) (Table II). In the case of Christiansen's uniformity, the

Table I. Results of tomato yield (different lower case letters (a, b, c) means differencies found by the Tukey post-hoc test: $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$, ns – not significant)

Treatment	Total yield (t ha^{-1})	SSC (°Brix)	SSC yield (t ha^{-1})	WP (kg m^{-3})
IR0	45.9 ± 2.8^{c}	6.1 ± 0.1^{a}	2.8 ± 0.2^{b}	29.4 ± 1.8^{a}
IR50	75.8 ± 7.9^{b}	5.4 ± 0.1^{b}	4.1 ± 0.3^{a}	25.6 ± 2.7^{a}
IR100	107.3 ± 6.9^{a}	4.7 ± 0.1^{c}	5.1 ± 0.3^{a}	24.6 ± 1.6^{a}
IR0-IR50	*	*	*	ns
IR0-IR100	**	**	**	ns
IR50-IR100	*	*	–	ns
IR0-IR50-IR100	**	***	**	ns

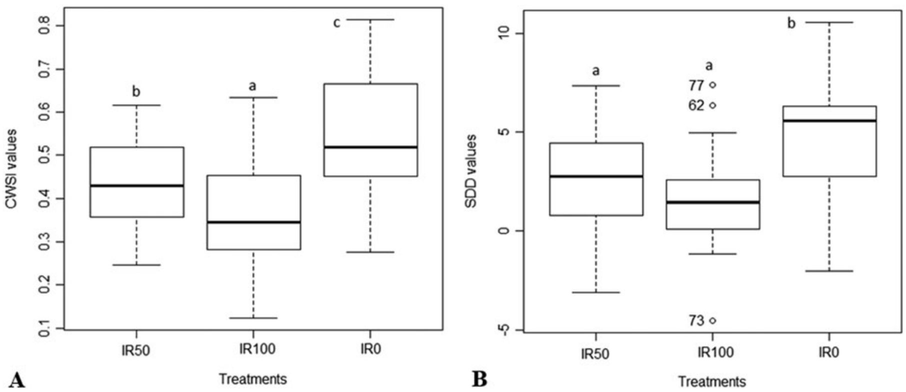

Figure 4. Heat stress indices computed from thermal cam data. CWSI data are shown on (A), SDD data on (B). Lowercase letters mark the results of the Tukey test ($n = 27$; $P < 0.05$).

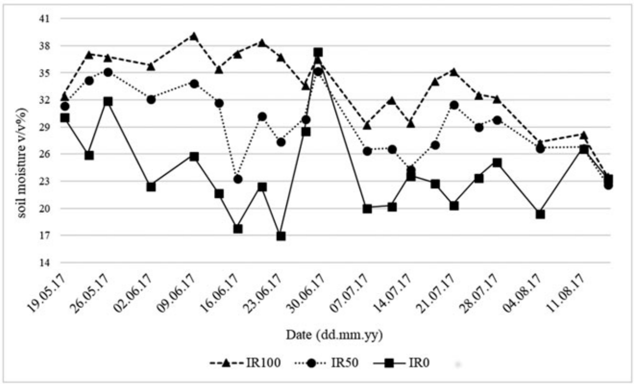

Figure 5. Soil moisture changing during the season.

results were consistent. The values mostly reached at least 90%. Two values—89.3 and 88.8% (IR50 AR)—were under that, but over 86%, which is considered a limit value for uniform irrigation (Yari *et al.,* 2017). Both CU_C and DU values were lower in the deficit irrigated area. The lower limit of uniform irrigation of DU is 80% (Irmak *et al.,* 2011). The computed values were always above this limit with this particular centre-pivot irrigation machine. Student's t-test showed that there was a difference ($P < 0.05$) in the uniformity of these two rates. Dukes and Perry (2006) evaluated a centre pivot and a linear move with NELSON R3000 sprinklers and registered 0.95 DU and 95% CU_C for the 100% sprinkler rate and 0.91 and 0.92 DU, together with 93 and 94% CU_C when the system movement speed was 7 and 11% respectively. These are higher than our results. Similar grid measurements were conducted with different ADs (19.1, 25.4 and 31.7 mm) under windy conditions where high CU_C values (90.4–94.4%) paired with high deviation from prescribed depth, because of high wind speeds (Yari *et al.,* 2017). Every measurement was conducted under low-wind conditions; the highest wind speed was 1.18 m s^{-1} during the measurements (Table III).

Table II. Water distribution uniformity values according to grid measurements and the computed over- and under-irrigation volumes and areas

Irrigation test	Application rate	Application depth (mm)	Uniformity		Volumetric calculation (m^3 ha^{-1})			Planar calculation (ha ha^{-1})	
			CU_C (%)	DU (%)	Over-irrigation	Under-irrigation	Difference	Over-irrigated area	Under-irrigated area
Test 1: 29 May	IR100	25.1	91.8	88.7	14.1	11.8	2.3	0.51	0.48
	IR50	12.6	90.8	86.2	5.6	5.2	0.5	0.43	0.57
Test 2: 3 June	IR100	22.1	92.8	90	15.8	1.1	14.8	0.83	0.17
	IR50	11.6	88.8	85.1	4.1	3.6	0.5	0.48	0.52
Test 3: 6 June	IR100	12.2	92.3	88.7	6.1	4	2.1	0.53	0.47
	IR50	6.1	89.3	86.7	6.7	0.1	6.7	0.93	0.07
Test 4: 8 June	IR100	12.7	92.9	89.5	6.4	1.4	5	0.67	0.33
	IR50	6.35	90.7	86.4	5.9	0.5	5.3	0.85	0.15

According to MAE and RMSE, the accuracy of irrigation was better when the ADs were 12.2 and 12.7 mm. The average MAE in the 50% AR zone was 0.97 mm and 1.44 mm in the 100% zone. Average RMSE values were 1.1 and 1.82 mm in the 50 and 100% zones respectively. Researchers also found <3 mm of RMSE, measured both in the travel direction and along the pivot (O'Shaughnessy *et al.,* 2013). To calculate the irrigated water proportion to IR100 of VRI, we considered the means of water recorded in the catch cans. As the lower AR was 50%, the results found were around 50% of irrigation water compared to IR100. The biggest deviation occurred on 6 June, when plus 5.4% were irrigated above the planned 50%.

The quantity of over- and under-irrigation varied with the different tests and ARs. Test 3 is shown as an example of this examination (Figure 2). The highest over-irrigation was 14.1 and 15.8 m^3 ha^{-1} when we applied more than 20 mm irrigation water. In other cases, the amount of over-irrigation was in the 4.1–6.7 m^3 ha^{-1} range. The mean of the modelled over-irrigation was 8.1 m^3 ha^{-1}. Under-irrigation was lower according to the grid measurements, with the highest amount of 11.8 m^3 ha^{-1} when 25.1 mm was irrigated. In other tests a minimum 0.1 and maximum 5.2 m^3 ha^{-1} water were missing from the field in the under-irrigated area. The mean of under-irrigated quantities was 3.46 m^3 ha^{-1}. When under-irrigation was subtracted from over-irrigation we got very different results. When the ADs were over 20 mm we recorded the smallest differences with the 50% AR (0.5 m^3 ha^{-1} with both tests). We experienced the highest difference in test 2 with 100% AR. The highest amount of over-irrigation was registered with a low amount of under-irrigation.

Examining the over- and under-irrigated areas, it shows that even if the over-irrigated volumes are greater in every case, there are two occurrences of the opposite. These happened under the 50% AR in tests 1 and 2.

Radial measurements. It is important to note that there was an overlapping zone between the two different ARs. Therefore, we had to remove the values of this zone, so we could compute CU_{HH} uniformity. Additionally, this measurement provided information about how wide the overlapping zone was.

The problem is that the measuring line is not perpendicular to the border of the two zones, because it was set radially. We experienced the worst uniformity with test 4 in the 50% AR zone. The best uniformity value was also in that zone with test 3 (Table IV). We recorded high uniformity values with every test. All the measured values were over or near to 90%. Since the rain gauges were installed with 3 m distance between each of them, we cannot see exactly how wide the overlapping zone was. As an example, we show the measurements of test 3 on Figure 6. In this case, the overlapping zone starts at ca. 69 m from pivot centre and ends at 78 m. Similar measurements was conducted by Zhao *et al.* (2014) and they concluded that a maximum 4 m buffer zone is enough between adjacent irrigation zones when $CU_{HH} \geq 85\%$ uniformity is satisfactory. There is an outlier on line II, but on line I the recorded irrigation depth fits exactly with the desired depth. The outlier on line II could be caused by dripping from the sprinkler when it passed right above the rain gauge. Sui and Fisher (2015) tested a centre pivot with a VRI zone control package (10 control zones) for uniformity. Average CU_{HH} was 83.1% in the 50% AR zone and 88.7% in the 100% rate zone. These represent lower uniformity than in the case of the machine investigated by us.

The width of overlap zones. On Figure 7 we illustrate the gradual transition between the two zones irrigated at different rates. The colour code helps to identify the given measuring lines.

The two measurements widthways were similar. In these two cases, both the 0–100% and 50–100% lines showed that

Table III. Accuracy of grid shape measurements

Irrigation test	Appli-cation rate	Prescribed depth (mm)	Mean of wind speed (m s^{-1})	MAE (mm)	RMSE (mm)	Mean (mm)	Irrigation water proportion to IR100 (%)
Test 1: 29 May	IR100	25.1	0.94	2.1	2.7	24.7	–
	IR50	12.6		1.2	1.7	12.4	50.4
Test 2: 3 June	IR100	22.1	0.61	1.7	2.3	23.1	–
	IR50	11.6		1.2	1.6	11.2	48.4
Test 3: 6 June	IR100	12.2	1.18	1	1.2	12.4	–
	IR50	6.1		0.8	0.1	6.9	55.4
Test 4: 8 June	IR100	12.7	0.24	0.9	1.2	12.9	–
	IR50	6.35		0.7	1.1	6.9	53.3

Table IV. Water distribution uniformity values according to ASAE Standard measurements (ASAE Standards, 1997)

Irrigation test	Application rate	Mean of wind speed (m s^{-1})	Prescribed application depth (mm)	Uniformity	
				CU$_{HH}$ (%)	Mean (mm)
Test 1: 12 June	IR100	1.3	14.2	90.2	14.3
	IR50		7.1	91.1	6.8
Test 2: 16 June	IR100	2.53	19.3	90	19.4
	IR50		9.7	89.5	9.3
Test 3: 19 June	IR100	0.46	15.7	90	16.6
	IR50		7.9	92.4	7.4
Test 4: 23 June	IR100	1.32	20.4	90.2	22.6
	IR50		10.2	87.8	10.8

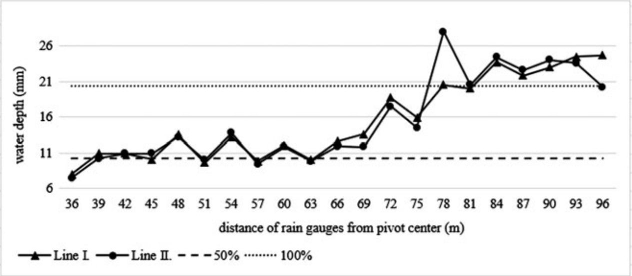

Figure 6. The values measured in test 3 with the prescribed application depth.

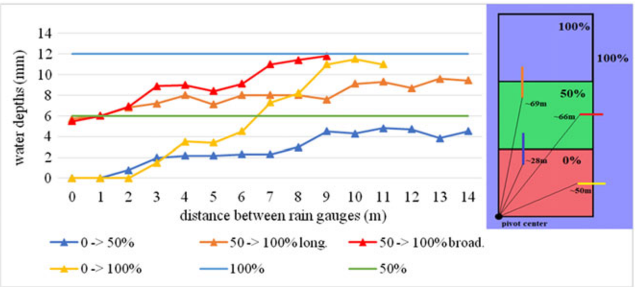

Figure 7. Measurement of the overlap zones with explanatory figure of the measuring lines. [Colour figure can be viewed at wileyonlinelibrary.com]

the overlap ceased within 9 m. The width of overlap zones is hard to define with the longitudinal measuring lines. Neither the 0–50% nor the 50–100% reached the desirable depth. On the 0–50% line, the measured depth reached 75% of the desirable depth (6 mm) in 9 m and 80% of the desirable depth in 11 m but did not go above this limit along the 14-m long measuring line. On the 50–100% line, the measured depth reached 75% of the desirable depth (12 mm) in 10 m and 80% in 13 m but did not go above that along the 14-m long measuring line. Wind speed was 1.64 m s^{-1} during the measurement. Other authors have reported significantly impacted uniformity for a 3 m wide zone for the first three spans and 6–9 m for last two spans of a six-span centre pivot (O'Shaughnessy *et al.,* 2013). That machine provided a shorter transition than the one we used for our experiment.

CONCLUSION

In countries where farmers have preferred linears in the past, centre pivots are not popular at the moment. It is very important to introduce centre pivots to farmers, and which can be installed and operated more easily and since corners are available they can be adjusted better to irregular shaped fields. Water- and energy saving of VRI technology adds more reasons to this. This kind of approach that we conducted in this study which evaluates over- and under-irrigation at a given AD, paired with distribution uniformity measurements of VRI iS irrigation, is a novelty, especially on individual sprinkler-controlled VRI systems. The processing tomato experiment showed that yields, SSC and water stress represented the expected differences between 100 and 50% ARs. Uniformity was measured at the same time, under the same circumstances at the 100 and 50% AR, so the DU and CU$_C$ were comparable. Both irrigated plots showed excellent uniformity in general, and in addition we revealed that there were no significant over- and under-irrigated water amounts on a hectare scale. Evaluation of the width of transition zones around the adjacent zones showed that one must calculate with at least 9-m wide transition zones, which can go up to more than 14 m when very precise water application is necessary. In conclusion, we established that centre pivots with individual sprinkler control VRI systems are suitable for conducting deficit irrigation experiments concerning over- and under-irrigation and water distribution uniformity, but one must consider at least a 9-m wide transition zone at plant sampling, because samples from that zone would not represent the desired water application.

ACKNOWLEDGEMENTS

This study was supported by the ÚNKP-17-3-I/SZIE-1 New National Excellence Programme of the Ministry of Human Capacities. The publication is supported by the EFOP-3.6.3-VEKOP-16-2017-00008 and EFOP-3.6.1-16-2016-00016 projects. These projects are co-financed by the European Union and the European Social Fund. This research was supported by the Higher Education Institutional Excellence Programme awarded by the Ministry of Human Capacities within the framework of water-related research of Szent István University.

REFERENCES

Allen RG, Pereira LS, Raes D, Smith M, Ab W. 1998. Crop evapotranspiration—guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. Rome; 1–15. https://doi.org/10.1016/j.eja.2010.12.001.

American Society of Agricultural Engineers (ASAE). 1997. Test procedure for determining the uniformity of water distribution of center pivot and lateral move irrigation machines equipped with spray or sprinkler nozzles St. Joseph, MI. ASAE Standards 932–938.

Battilani A, Solimando D, Jensen CR, Plauborg FL, Andersen MN, Sandei L. 2009. Water saving irrigation strategies for processing tomato. *Acta Horticulturae* **823**: 69–76.

Biró S, Apáti F, Szőllősi L, Szűcs I. 2011. Az öntözésfejlesztés gazdasági összefüggései. In Biró S, Kapronczai I, Szűcs I, Váradi L (eds). *Vízhasználat és öntözésfejlesztés a magyar mezőgazdaságban*. Agrárgazdasági Kutató Intézet: Budapest, Hungary; p 45–74.

Biswas SK, Akanda AR, Rahman MS, Hossain MA. 2015. Effect of drip irrigation and mulching on yield, water-use efficiency and economics of tomato. *Plant, Soil and Environment* **61**(3): 97–102. https://doi.org/10.17221/804/2014-PSE.

Burt CM, Clemmens AJ, Strelkoff TS, Solomon KH, Bliesner RD, Hardy LA, Howell TA, Eisenhauer DE. 1997. Irrigation performance measures: efficiency and uniformity. *Journal of Irrigation and Drainage Engineering* **123**(6): 423–442. https://doi.org/10.1061/(ASCE)0733-9437(1997)123:6(423).

Burt CM, Walker RE, Styles SW. 1992. *Irrigation System Evaluation Manual. Irrigation Training and Research Center, California Polytechnic State University*: California, USA.

Christiansen EJ. 1941. The uniformity of application of water by sprinkler systems. *Agricultural Engineering* **22**(3): 89–92.

Daccache A, Knox JW, Weatherhead EK, Daneshkhah A, Hess TM. 2015. Implementing precision irrigation in a humid climate—recent experiences and on-going challenges. *Agricultural Water Management* **147**: 135–143. https://doi.org/10.1016/j.agwat.2014.05.018.

Dukes MD, Perry C. 2006. Uniformity testing of variable-rate center pivot irrigation control systems. *Precision Agriculture* **7**(3): 205–218. https://doi.org/10.1007/s11119-006-9020-y.

Evans RG, LaRue J, Stone KC, King BA. 2013. Adoption of site-specific variable rate sprinkler irrigation systems. *Irrigation Science* **31**(4): 871–887. https://doi.org/10.1007/s00271-012-0365-x.

Fereres E, Soriano MA. 2007. Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany* **58**(2): 147–159. https://doi.org/10.1093/jxb/erl165.

Fiebig A, Dodd IC. 2016. Inhibition of tomato shoot growth by over-irrigation is linked to nitrogen deficiency and ethylene. *Physiologia Plantarum* **156**(1): 70–83. https://doi.org/10.1111/ppl.12343.

Food and Agriculture Organization of the United Nations (FAO). 2016. *Global Map of Irrigation Areas* (*GMIA*). http://www.fao.org/nr/water/aquastat/irrigationmap/HUN/index.stm

Food and Agriculture Organization of the United Nations (FAO). 2018. *Production Quantities of Tomatoes by Country*. Rome, Italy: FAOSTAT.

Fox J, Bouchet-Valat M. 2018. Rcmdr: R Commander. R package version 2.4–4. Available at: https://cran.r-project.org/web/packages/Rcmdr/citation.html

Franke R, Nielson G. 1980. Smooth interpolation of large sets of scattered data. *International Journal for Numerical Methods in Engineering* **15**(11): 1691–1704. https://doi.org/10.1002/nme.1620151110.

Hedley CB, Yule IJ. 2009. Soil water status mapping and two variable-rate irrigation scenarios. *Precision Agriculture* **10**(4): 342–355. https://doi.org/10.1007/s11119-009-9119-z.

Hungarian Meteorological Service. 2018. *Climate of Hungary—General Characteristics*. Budapest, Hungary. https://www.met.hu/en/eghajlat/magyarorszag_eghajlata/

Irmak S, Odhiambo LO, Kranz WL, Eisenhauer DE. 2011. Irrigation efficiency and uniformity, and crop water use efficiency. *Biological Systems Engineering: Papers and Publications* **451**: 8. https://doi.org/10.13031/trans.59.11331.

Jones HG. 1999. Use of infrared thermometry for estimation of stomatal conductance as a possible aid to irrigation scheduling. *Agricultural and Forest Meteorology* **95**(3): 139–149. https://doi.org/10.1016/S0168-1923(99)00030-1.

Kranz WL, Evans RG, Lamm FR, Peters RT. 2012. A review of mechanical move sprinkler irrigation control and automation technologies. *Applied Engineering in Agriculture* **28**(3): 389–397.

Kruse EG. 1978. Describing irrigation efficiency and uniformity. *Journal of the Irrigation and Drainage Division ASCE* **104**(1): 35–41.

Marosán Á. 2017. *Öntözésjelentés*. Budapest, Hungary: Agrárgazdasági Kutató Intézet.

O'Shaughnessy SA, Evett SR, Andrade MA, Workneh F, Price JA, Rush CM. 2016. Site-specific variable-rate irrigation as a means to enhance water use efficiency. *Transactions of the ASABE* **59**(1): 239–249. https://doi.org/10.13031/trans.59.11165.

O'Shaughnessy SA, Urrego YF, Evett SR, Colaizzi PD, Howell TA. 2013. Assessing application uniformity of a variable rate irrigation system in a windy location. *Applied Engineering in Agriculture* **29**(4): 497–510. https://doi.org/10.13031/aea.29.9931.

Patanè C, La Rosa S, Pellegrino A, Sortino O, Saita A. 2014. Water productivity and yield response factor in two cultivars of processing tomato as affected by deficit irrigation under semi-arid climate conditions. *Acta Horticulturae* (1038): 449–454.

Patanè C, Tringali S, Sortino O. 2011. Effects of deficit irrigation on biomass, yield, water productivity and fruit quality of processing tomato under semi-arid Mediterranean climate conditions. *Scientia Horticulturae* **129**(4): 590–596. https://doi.org/10.1016/j.scienta.2011.04.030.

Pék Z, Daood HG, Neményi A, Helyes L, Szuvandzsiev P. 2017. Seasonal and irrigation effect on yield parameters and soluble solids content of processing cherry tomato. *Acta Horticulturae* **1159**: 45–49. https://doi.org/10.2478/s11535-013-0279-5.

Perry C, Pocknee S, Hansen O. 2003. A variable rate pivot irrigation control system. In Stafford J, Werner A (eds). *Precision Agriculture*. Wageningen Academic Publishers: p 1–6. https://doi.org/10.3920/978-90-8686-814-8.

R Core Team. 2017. *R: a Language and Environment for Statistical Computing*. R Foundation for Statistical Computing: Vienna, Austria.

Renka RJ. 1988. Multivariate interpolation of large sets of scattered data. *ACM Transactions on Mathematical Software ACM* **14**(2): 139–148. https://doi.org/10.1145/45054.45055.

Schneider AD. 2000. Efficiency and uniformity of the lepa an spray sprinkler methods: a review. *Transactions of the ASAE* **43**(4): 937–944.

Shepard, D. 1968. A two-dimensional interpolation function for irregularly-spaced data. In *Proceedings of the 1968 23rd ACM National Conference*. August 27–29, 1968. New York, USA: ACM Press, 517–524. https://doi.org/10.1145/800186.810616.

Spinoni J, Szalai S, Szentimrey T, Lakatos M, Bihari Z, Nagy A, Németh Á, Kovács T, Mihic D, Dacic M, Petrovic P, Kržič A, Hiebl J, Auer I, Milkovic J, Štepánek P, Zahradnícek P, Kilar P, Limanowka D, Pyrc R, Cheval S, Birsan MV, Dumitrescu A, Gy D, Matei M, Antolovic I, Nejedlík P, Štastný P, Kajaba P, Bochnícek O, Galo D, Mikulová K, Nabyvanets Y, Skrynyk O, Krakovska S, Gnatiuk N, Tolasz R, Antofie T, Vogt J. 2015. Climate of the Carpathian region in the period 1961–2010: climatologies and trends of 10 variables. *International Journal of Climatology* **35**(7): 1322–1341. https://doi.org/10.1002/joc.4059.

Steduto P, Hsiao TC, Fereres E, Raes D. 2012. Crop yield response to water. FAO Irrigation and Drainage Paper. Rome, Italy.

Sui R, Fisher DK. 2015. Field test of a center pivot irrigation system. *Applied Engineering in Agriculture* **31**(1): 83–88. https://doi.org/10.13031/aea.31.10539.

Szalai S. 2009. Drought tendencies in Hungary and its impacts on the agricultural production. *Cereal Research Communications* **37**(Supplement 1): 501–504. https://doi.org/10.1556/CRC.37.2009.Suppl.5.

Vellidis G, Liakos V, Porter W, Tucker M, Liang X. 2016. A dynamic variable rate irrigation control system. In *Proceedings of the 13th International Conference on Precision Agriculture*, July 31–August 4, 2016. St Louis, USA; 1–9.

Yari A, Madramootoo CA, Woods SA, Adamchuk VI. 2017. Performance evaluation of constant versus variable rate irrigation. *Irrigation and Drainage* **66**(4): 501–509. https://doi.org/10.1002/ird.2131.

Zhao W, Li J, Yang R, Li Y. 2014. Field evaluation of water distribution characteristics of variable rate center pivot irrigation system. *Transactions of the Chinese Society of Agricultural Engineering* **30**(22): 53–62.