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Effect of intra-irrigation meteorological variability on seasonal center-pivot irrigation performance and corn yield

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A B S T R A C T

Water application depth of a center-pivot (CP) irrigation system is not uniformly distributed across a field due to emitter package design, tower dynamics, and meteorological variability. The objective of this research was to measure and model the effect of the intra-irrigation meteorological variabilities on CP seasonal water distribution pattern and corn yield. The 2013 irrigation season of a commercial CP cropped with corn was analyzed. From 60 irrigation events applied to the corn, 10 were evaluated using radial catch cans. The mechanical movement of CP towers for the sixty irrigation events was characterized using Global Navigation Satellite System-Real Time Kinematic (GNSS-RTK) monitoring. Meteorological variables at 1 s frequency were measured with an automatic weather station installed in the farm. The ballistic model calibrated and validated for rotating spray plate sprinklers under different nozzle sizes and wind conditions was mounted on the CP lateral, following the correspondent sprinkler package. The CP lateral was moved following the measured or simulated tower dynamic, and the current or averaged meteorological conditions of each irrigation event were applied to the corn. Crop yield was simulated by coupling the water distribution pattern simulated under the different cases with the Ador-crop model. Differences were observed for simulated seasonal water distribution pattern of the CP under homogeneous wind conditions (averaged for each irrigation event) or under variable of time wind conditions (measures). Simulated yield considering discontinuous tower dynamics and intra-irrigation meteorological variability has the largest correlation coefficient with the measured corn yield. Other factors were not considered in the yield simulation as variability in nutrient availability, emergence problems, and diseases and soil variability could explain the differences between the simulated and measured corn yield. The intra-irrigation meteorological variability has an important effect on the water distribution pattern of windy irrigation events of CP systems. Depending on the wind speed along the crop season, the intra-irrigation variability will have a major or minor effect on seasonal water distribution pattern and crop yield variability.

1. Introduction

The center pivot (CP) is one of the most popular pressurized irrigation systems used worldwide. In an attempt to reduce the energy costs associated with their use, the actual trend is to use low-pressure systems with spray sprinklers. This new generation sprinklers include rotating spray plate sprinklers (RSPS) and fixed spray plate sprinklers (FSPS). CP irrigation is, however, energy intensive. The increasing unit cost of energy and possible shortages of energy in the future are intensifying efforts to develop acceptable design concepts and management strategies for reducing energy use that do not excessively lower the uniformity and/or efficiency of application (Moreno et al., 2012). A system with reduced operating pressure but with excessive runoff and poor uniformity would be an unacceptable way of decreasing energy use. The development of simulation tools to analyze the effect of nozzle package, working pressure, tower dynamics, and other variables affecting center-pivot irrigation can help to establish the adequate design and management strategies.

Water application uniformity is an important performance criterion for the design and evaluation of CP sprinkler irrigation systems. Water application depths of a CP system is not uniformly distributed–nor in space (across the field) and nor in time (the whole irrigation season)–and depends on the sprinkler package, field topography, tower dynamics, and meteorological conditions.

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Catch-can tests have been the method used to characterize the water distribution uniformity for CP. Field evaluation of each design concept and management strategy on which a CP system might operate is a tedious and expensive process. Catch-can tests are very time-consuming, and data can be collected only along a limited number of radial or circular lines. In fact, most tests involve only one set of catch cans. If a CP system rotates at a constant speed, and the meteorological and technical (percentage timer setting, PTS (%)) conditions are constant, a spatial water application depth map may be constructed based upon data from only one radial line. However, most CP systems operate on variable field conditions. Variations in meteorological and technical conditions can change the water application depth and irrigation uniformity at different lateral positions even with flow control nozzles or pressure regulators at each head. In such cases, using catch-can tests to determine the spatial distribution of water application depth and application uniformity is not practical. An alternative method is to use computer simulation models to generate water application depth data. A model that represents the performance of CP systems operating at different technical and meteorological conditions would greatly facilitate the evaluation process.

Crop water needs can vary due to within-field differences in soil texture, topography, and biotic stresses (O'shaughnessy et al., 2013). Knowledge of water spatial distribution in a field is essential for site-specific crop management, as such distribution maps can be used to adjust the input rates and target the critical areas in a field (known as precision farming). Once areas of either over-application or under-application are identified from the distribution maps, appropriate management practices can be taken to correct them. Current research on CP irrigation focus on precision farming by controlling site-specific variable rate irrigation (VRI) technologies (Kranz et al., 2012; O'shaughnessy et al., 2013; Evans et al., 2013; McCarthy Alison et al., 2014). To apply VRI, knowledge of irrigation water distribution patterns and crop water availability distribution for the whole CP irrigated area is needed. Factors affecting the irrigation water distribution patterns, such as the sprinkler package, working pressure, tower dynamics, and meteorological conditions, should be considered in the analysis. In addition to irrigation distribution depths, factors affecting soil water availability for crop are those related to soil water holding capacity.

The simulation of CP water distribution patterns resulting from different sprinkler types has traditionally been conducted by mathematically overlapping experimentally measured isolated sprinkler patterns (Clark et al., 2003). Molle and Le Gat (2000) proposed a model using a mixture of beta probability. Recently, Sayyadi et al. (2012) proposed a new approach based on Artificial Neuronal Networks (ANN) to simulate the effects of wind on the distribution pattern of single sprinklers. A new approach based on droplet trajectory modeling was proposed by Ouazaa et al. (2015) to simulate water distribution patterns for FSPS. In addition, the water distribution model was coupled with a simulation model of the pivot tower dynamics, incorporating most of the factors affecting irrigation water distribution pattern variability. Intra-irrigation variability of meteorological condition during a CP irrigation event could also be important and affects the spatial variability of applied irrigation depth. O'shaughnessy et al. (2013) conducted catch-can trials and reported that wind speed and direction did not appreciably modify uniformity of application, but affect the absolute application depth within the VRI management zone. Wind speed and direction should be considered when applying site-specific or precision irrigation management. In the literature, the effect of wind speed has been analyzed from a partial point of view using radial or partial circle catch-can configurations (Dukes, 2006; O'shaughnessy et al., 2013). There are no previous studies analyzing the effect of intra-irrigation variability of wind speed and direction on the water distribution of the total CP irrigated area. Also, the cumulative effect for the whole crop irrigation season was not reported in the literature.

The principal objective of this study was to advance the development of a CP model. Ouazaa et al. (2015) proposes a model that includes the simulation of water distribution patterns for FSPS package and CP tower dynamic. In this research, the simulation of water distribution patterns was extended for RSPS package, and the intra-irrigation meteorological variability during a CP irrigation event was included in the model. Furthermore, the new CP model was coupled with a crop model to simulate water distribution of the whole irrigation season and corn yield. Experimental determination of irrigation uniformity (for selected irrigation events) and spatial variability of corn yield was conducted to validate the model. The new model provides a valuable tool to analyze and quantify the effects of factors such as intra-irrigation meteorological variability and/or tower dynamics on CP water distribution patterns and crop yield variability. The effects were analyzed for individual irrigation events and for a whole corn irrigation season.

2. Material and methods

2.1. The case study

The studied CP cropped with corn was located in Marracos (Spain), at the north west of Zaragoza (Latitude: 42° 5′ 27″ N—Longitude: 0° 46′ 35″ W). The CP, a valley machine (manufactured by Valmont Industries, Nebraska, USA), had four towers with 50 m spans and an overhang of 25 m. In the 2013 irrigation season, the original sprinkler package of the machine (FSPS, Nelson D3000) was replaced with RSPS with 6-streams red plates (R3000Nelson Irrigation Corp., Walla Walla, Washington, USA), maintaining the pressure regulators of 138 kPa. The new sprinkler package had 40 nozzles of 21 different diameters ranging from 2.2 mm to 8.7 mm. The distance between the nozzles was constant and equal to 5.56 m. The first nozzle was installed at 10.27 m from the pivot point and the last one at 224.54 m from the pivot point. The nozzles were located 2.0 m above the soil surface by using a semi-rigid plastic drop pipe. More details of the CP irrigation machine can be found in Ouazaa et al. (2015).

2.2. Simulating water distribution patterns for RSPS using the ballistic model

2.2.1. Drop velocity and trajectory characterization at the exit of the deflecting plate

Nine nozzle diameters of RSPS working at 138 kPa were selected for experimental characterization. Drop velocities and angles at the exit of the deflecting plate were measured using the photographical method proposed by Salvador et al. (2009). The aim of these experiments is to estimate drop energy losses due to jet impact with the sprinkler deflecting plate. A minimum of 40 drops per nozzle size were selected for measurements. The selection of the drops was performed based on image quality since the drop should be adequately focused (located near the vertical plane containing the reference ruler). The main difference between drop velocity at the nozzle and after the impact was attributed to the energy losses at the plate (Ouazaa et al., 2014).

2.2.2. Experimental characterization of RSPS water distribution pattern under different technical and meteorological conditions

Six nozzle diameters of RSPS were selected (2.4, 3.8, 5.1, 6.7, 7.9, and 8.7 mm) for experimental water distribution pattern characterization. Experiments were carried out at 138 kPa working pressure (most common operating pressure of RSPS), maintained by pressure regulator installed just upstream the sprinklers. For each nozzle diameter, field tests were carried out at 3