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Combination of sowing date with deficit irrigation for improving the profitability of carrot in a tropical environment (Brazil)

D.F. Carvalho[a], A. Domínguez[b,*], D.H. Oliveira Neto[a], J.M. Tarjuelo[b], A. Martínez-Romero[b]

[a] Department of Engineering, University Federal of Rio de Janeiro, BR 465, km 7, 23890-000 Seropédica, RJ, Brazil
[b] Regional Center of Water Research, University of Castilla-La Mancha, Ctra. de Las Peñas, km 3,2, 02071 Albacete, Spain

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ABSTRACT

This study was conducted to determine the most suitable irrigation strategy for improving the water productivity of carrot in Rio de Janeiro (Brazil) by using two sowing dates (June 16th and August 3rd). Experimental data from a two-year field test were used for calibration (2010) and validation (2011) of the simulation of carrot with the MOPECO model under deficit irrigation conditions. In 2010 and 2011 for no-deficit conditions the net irrigation was around 150 and 180 mm in the 1st and 2nd sowing date, respectively. The maximum yield was about 64,000 kg ha^{-1}. The root mean square error (2790 and 2968 kg ha^{-1}) and the relative error (5.3 and 4.9%) values show good fit between the simulated and observed treatments for 2010 and 2011, respectively. Depending on the water stress target, the use of the optimized regulated deficit irrigation in the study area would increase carrot yield by up to 7% and 15% compared with the a constant deficit irrigation strategy for the two proposed sowing dates under the climatic conditions of 2012. In economic terms, the gross margin reached 6849 and 5881 € ha^{-1} for the first and second sowing dates, respectively.

1. Introduction

Water is one of the most limiting factors for crop production in the world. However, due to the increasingly competitive use of water resources for domestic, industrial, environmental and recreational needs (Imtiyaz et al., 2000), and declines in water quality for irrigation, even in humid regions, the area under cultivation has become restricted, requiring farmers to obtain higher productivity per unit area and amount of water (Jensen, 2007).

Carrot (*Daucus carota* L.) is a short duration vegetable (Nagaz et al., 2012) and is one of the best β-carotene sources (Knockaert et al., 2013). Worldwide, the annual production of carrot (and turnips) exceeds 35.6 million of tons (FAO, 2011). In Brazil, it is the main root vegetable in terms of economic value (Luz et al., 2009), with a production area of over 28,000 ha and more than 750,000 tons of roots (Silva et al., 2012). Carrot is an important vegetable in tropical and subtropical areas, and requires suitable temperatures and soil water content, mainly during the crop development stage (Rosenfeld et al., 1998). Although carrot is not very sensitive to slight drought (Suojala, 2000), water deficit may result in root cracking and hardening during root development (Kotecha et al., 1998). Areas with high soil moisture content are unsuitable (Islam et al., 1998).

Because carrot is a crop with high economic value, the irrigation management schedule is designed to obtain maximum yield (Nagaz et al., 2012). Nevertheless, low availability of irrigation water may lead to the use of deficit irrigation, which must be analyzed to determine the most suitable irrigation strategy for reaching the highest water productivity. According to Marouelli et al. (2007), the average carrot yield in Brazil is 29 t ha^{-1}, but values between 50 and 60 t ha^{-1} can be obtained from suitable irrigation management strategies. The management of this crop affects yield and root size. Broadly speaking, higher planting density results in smaller plant size and lower root mass (da Silva et al., 2003; Rajasekaran et al., 2006), while final yield is also affected by harvesting date (da Silva et al., 2008).

Although some authors have studied carrot growth under different water management scenarios (Carvalho et al., 1995; Imtiyaz et al., 2000; Silva et al., 2011b; Lima et al., 2012), models for this crop are still scarce. The optimized regulated deficit irrigation (ORDI) strategy may be of interest for determining the water deficit objective at each phenological stage that reaches the highest yield for a certain overall objective (Domínguez et al., 2012). This methodology may be combined with models like MOPECO

* Corresponding author. Tel.: +34 967 599 200x2587.
E-mail address: alfonso.dominguez@uclm.es (A. Domínguez).

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(economic optimization model for irrigation water management) (de Juan et al., 1996) for simulating the effect of this strategy on final yield and gross margin. To date, MOPECO has not yet been used for simulating crops under tropical conditions.

When success in agriculture is at risk due to price fluctuations and variable climatic conditions (Finger, 2012), irrigation is used to reduce the risk of lower crop yield due to weather variability (Lin et al., 2008), while making it possible for sowing and crop establishment to occur at different times of the year than the typical crop cycles (Oweis and Hachum, 2001). This analysis is relevant because several carrot genotypes are available for different soil and climate conditions in Brazil, which has made carrot cultivation possible in different regions and seasons (Lopes et al., 2008), mainly the Brasília cultivar (cv.) planted throughout the country (Vilela and Borges, 2008; Luz et al., 2009). In Brazil, most vegetables are cultivated in autumn-winter (Lunardi and Lapareta Filho, 1999; Oliveira et al., 2003; Silva et al., 2011b), but sowing carrot in August has been recently adopted in some regions in order to get a second harvest in the spring (Carvalho et al., 1995; Silva et al., 2011a). Therefore, the combination of ORDI with different sowing dates may be of interest for advising the most suitable irrigation strategies for carrot cultivation.

This paper aims to determine the most suitable deficit irrigation strategy for improving the profitability of carrot through higher water productivity in Rio de Janeiro by using two sowing dates. Specific objectives of this work are: (1) to calibrate and validate the parameters required for obtaining the yield (Y_a) versus total net water (TW_N) (net irrigation (I_N) + effective rainfall (P_e)) relationship, and (2) to determine the most suitable irrigation strategy under tropical conditions (for the Rio de Janeiro area) depending on the sowing dates and the availability of water resources.

2. Materials and methods

2.1. Field experiments

Data from the field trials used for the carrot crop simulation were obtained from experiments carried out in 2010 and 2011 at the Integrated System of Agro-Ecological Production (SIPA) located in Seropédica, a State in Rio de Janeiro (southeast Brazil) (43° 41′ West, 22° 46″ South, at an altitude of 33 m above sea level). The soil is classified as Oxisol (*Argissolo Vermelho Amarelo*). At the 0–0.20 m layer it is composed of 8% silt, 70% sand and 22% clay, the bulk density and water content in soil corresponding to field capacity, measured in situ, were 1.59 Mg m^{-3} and 0.181 cm^3 cm^{-3}, respectively.

The experiment was focused on studying the effects of three irrigation regimes (using a drip irrigation system) on the agricultural performance of carrot crop, in addition to one treatment with no irrigation (T1). A common practice in the area during the establishment stage is to supply irrigation water using a sprinkler system. The different irrigation regimes were obtained from drippers with nominal discharge of 3.9 (T2), 6.5 (T3), and 9.0 L h^{-1} (T4), with four replicates in 2010 and 2011. The four irrigation strategies were: T4: full irrigation; T3 and T2: these treatments were irrigated the same number of hours than T4, but receiving 72.2 and 43.3% of irrigation water after establishment, respectively; T1: no irrigation after establishment.

On the seedbeds, with 1.0 m in width, there were four planting rows (4 transversal lines per meter) and two irrigation lines, whose drippers were spaced 0.25 m apart. Thus, there was one irrigation line for every two planting rows and the plot size was 1.15 m^2 (1.0 × 1.15 m). Carrots (Brasília cv.) were planted on June 16th (2010) and August 3rd (2011) by direct sowing and roots were harvested on September 13th and November 3rd, respectively. Due to skipping or delaying the harvest date affect the final yield of carrots (da Silva et al., 2008), a criterion was established for both experimental years. So, plants were harvested when the diameter of the 75% of the T4 roots reached between 2.5 and 3 cm. These reference values are similar to those appearing in the bibliography (Vieira et al., 2005; da Silva et al., 2008). Roots shorter than 10 cm and with defects such as woody texture, cracks, deformations, stains, evident rootlets and soft or dry rottenness were classified as commercially unmarketable (Hortibrasil, 2000; Gomes et al., 2014).

At 30 days after sowing, the plants were thinned to keep 0.10 m distance from one to another. The total commercially marketable yields obtained by the different irrigation treatments (2010 and 2011) are represented in Table 1. As expected, treatments showed significant differences in terms of yield, caused by lower length and/or diameter of roots in more stressed treatments. The average marketable yield of roots harvested at T4 treatment was 88.4% (2010) and 95.8% (2011). For T1, the percentages were 61.4% and 81.6%, respectively.

The irrigation systems were evaluated using uniformity coefficients (Keller and Bliesner, 1990) which were correlated with soil moisture values obtained by both the gravimetric method and the Time Domain Reflectometry (TDR) technique. The net irrigation water (I_N) received by each plot was obtained from soil moisture monitoring using the TDR technique (Sorensen et al., 1997; Carvalho et al., 2011), considering the T4 treatment as the reference for irrigation management. The TDR probes were installed horizontally under the drip irrigation line in two of four replicates at a depth of 0.05, 0.10 and 0.20 m. The TDR100 (Campbell Sci.) was used, with gravimetric method calibration before the sowing date in a field near the experimental area. During the two experimental years and for calibration and validation, gross irrigation (I_G) was considered equal to I_N due to the small plot size and the use of drip irrigation.

The climatic data used were from the weather station Pesagro-Rio (43° 41′ West and 22° 45′ South and, at an altitude of 33 m), which belongs to the Brazilian Meteorological Institute (INMET). P_e was estimated using USDA "curve number 2 methodology" (Soil Conservation Service, 1972; Natural Resources Conservation Service, 2004), and reference evapotranspiration (ET_o) was calculated with the FAO Penman–Monteith method (Allen et al., 1998). Previous lysimeter studies at the same location have reported a reasonably good performance of this equation (Carvalho et al., 2006). P_e for the field tests in 2010 (1st sowing date) and 2011 (2nd sowing date) was 47.0 and 92.6 mm, and ET_o was 240.8 and 276.0 mm, respectively.

2.2. Model description

The aim of MOPECO is to maximize the gross margin (GM) through the efficient use of irrigation water. A set of data is required for the simulation of the optimal "yield vs. total net water ($I_N + P_e$)" (Y-TW_N) function of each crop under the climatic conditions of a certain year. To obtain this function, the model simulates a range of deficit irrigation schedules using the optimized regulated deficit irrigation (ORDI) methodology (Domínguez et al., 2012), considering the effects of irrigation uniformity (López-Mata et al., 2010) and the electrical conductivity of water (Domínguez et al., 2011) on yield. The Y-TW_N function is translated into Y-TW_G (Gross irrigation (I_G) + P_e) to include the application efficiency of the irrigation system. The GM-TW_G function is then calculated using economic data on the crop. Finally, the model calculates the optimal distribution of crops that fulfill the restrictions imposed by the user (Fig. 1).

MOPECO uses the model proposed by Stewart et al. (1977) modified by Rao et al. (1988) for estimating crop yield as a function of the actual versus maximum evapotranspiration ratio (ET_a/ET_m) in the different growth stages. When $ET_a < ET_m$, the plant suffers