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Irrigation controller mechanically actuated by soil-water tension: II - Field evaluations

Alexsandro C. S. Almeida¹, Tarlei A. Botrel², Steven R. Raine³, Antonio P. de Camargo², Marinaldo F. Pinto⁴ & Conan A. Salvador⁴

¹ Universidade Federal da Grande Dourados/Faculdade de Ciências Agrárias. Dourados, MS. E-mail: almeidaacs@yahoo.com.br (Corresponding author)

² Universidade de São Paulo/Escola Superior de Agricultura Luiz de Queiroz. Piracicaba, SP. E-mail: tabotrel@usp.br; acpires@usp.br

³ University of Southern Queensland/Institute for Agriculture and the Environment. Toowoomba, Queensland, Austrália. E-mail: steven.raine@usq.edu.au

⁴ Universidade Federal Rural do Rio de Janeiro/Departamento de Engenharia. Seropédica, RJ. E-mail: mfpufrrj@yahoo.com.br; conanayade@yahoo.com.br

Key words:

irrigation scheduling
technological innovation
tensiometer
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ABSTRACT

In this study, a field evaluation of the performance of an irrigation controller mechanically actuated by soil-water tension (SWT) was performed. The controller employs a tensiometer used as a sensor of SWT to directly control a mechanically actuated hydraulic valve. Six controllers were installed in an orchard to control the irrigation for six rows of plants over 64 days. Each controller controlled the irrigation of one lateral drip line. The drip irrigation system was gravity-fed from a water source placed 7 m above the soil surface. The SWT and the pressure in each lateral line were measured to evaluate the performance of the controllers. All the controllers tested in the field autonomously initiated and terminated the irrigation during the evaluation. Irrigation events were initiated when values close to the set soil-tension values were reached and were terminated at lower soil-tension values. As the SWT in the root zone was maintained close to the setup threshold plus 20% tolerance for at least 90% of the evaluation period, the performance of the controllers was considered satisfactory. The proposed controller was shown to be functional and was operated effectively for an SWT range of up to 30 kPa, which is commonly encountered under high-frequency irrigation conditions.

Palavras-chave:

manejo da irrigação
inovação tecnológica
tensiômetros
automação

Controlador de irrigação mecânico acionado pela tensão da água no solo: II - Avaliações em campo

RESUMO

O objetivo deste trabalho foi avaliar, em campo, o desempenho de um controlador de irrigação acionado mecanicamente pela tensão de água no solo. O controlador utiliza um tensiômetro como sensor da tensão de água do solo para controlar diretamente uma válvula hidráulica acionada mecanicamente. Seis controladores foram instalados em um pomar para controlar a irrigação de seis linhas de plantas durante 64 dias. Cada equipamento controlou a irrigação de uma linha lateral. O sistema de gotejamento foi pressurizado por gravidade devido a uma fonte de água localizada sete metros acima da superfície do solo. Todos os controladores testados no campo acionaram e desligaram a irrigação autonomamente durante o período de avaliação. Os eventos de irrigação foram iniciados quando as tensões de água no solo atingiram valores estabelecidos e terminaram em baixos valores de tensão. O desempenho foi considerado satisfatório, pois as tensões de água no solo foram mantidas dentro das faixas estabelecidas considerando-se uma tolerância de 20% para pelo menos 90% do tempo. O controlador proposto mostrou-se funcional e operou adequadamente para uma faixa de tensões de água no solo até 30 kPa, comumente utilizadas em condições de irrigação com alta frequência.



INTRODUCTION

The availability of soil water for planting is one of the key factors that affect crop yield. In areas where the precipitation is insufficient to satisfy the crop water requirements, farmers must schedule irrigation adequately to achieve their crop-yield goals. An effective irrigation schedule considers when to irrigate and how much water to apply for maximizing the profit and water-use efficiency (Ayars & Phene, 2007; Pardossi et al., 2009).

Irrigation based on the availability of soil water has been a practical solution for simplifying irrigation scheduling on farms (Stirzaker & Hutchison, 2005; Létourneau et al., 2015; Nolz et al., 2013; Dabach et al., 2016). Soil-water tension (SWT), which determines the availability of soil water to plants, is a critical factor in the regulation of plant growth. A device that can sense the SWT in situ and produce an electrical output signal can be used to control irrigation automatically (Ayars & Phene, 2007). Automatic irrigation scheduling using soil sensors has been applied, yielding increases in the efficiency of water use (Hoppula & Salo, 2007; Dabach et al., 2013; Miller et al., 2014) and reductions in pollution by reducing the runoff or leaching of nutrients (Zotarelli et al., 2011).

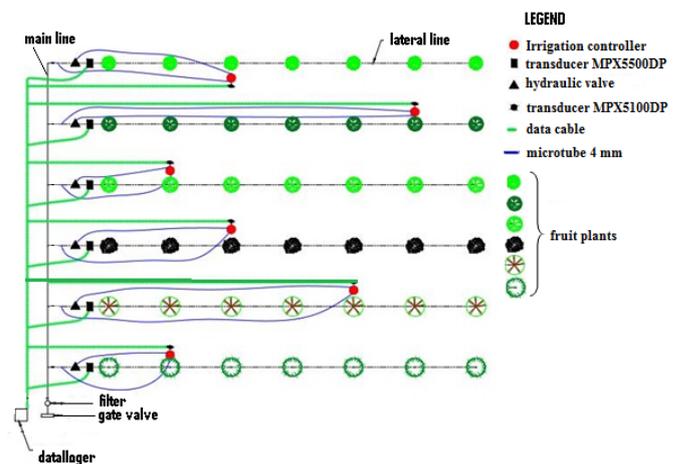
However, all the aforementioned controllers and most commercially available controllers are powered by electricity and thus restricted to areas where electricity is available (Pinmanee et al., 2011). It is necessary to develop irrigation controllers without external power requirements for farms that do not have electrical power in developing countries.

Studies have been conducted to address this demand. Peterson et al. (1993) developed an irrigation control valve that mechanically links the SWT of a tensiometer to a piston, which opens and closes the valve. Another controller employs a flexible diaphragm assembled at the top of a tensiometer as a pressure sensor to mechanically activate an irrigation valve (Klein, 2001). Both mechanical controllers performed well under laboratory conditions but neither was evaluated under field conditions. A controller using valves assembled in a tensiometer to activate counterweight and control cylinders was able to mechanically start irrigation when the SWT reached 45 kPa and stop irrigation when the SWT decreased below 30 kPa (Pinmanee et al., 2011) for lychee trees. However, the design does not permit adjustment for operation under different SWT thresholds.

Therefore, the objective of this study was to evaluate the performance of a novel mechanically actuated irrigation controller in field conditions.

MATERIAL AND METHODS

The field experiment was performed in Piracicaba-SP, Brazil (22° 42' 38.7" S; 47° 37' 45.5" W). Six controllers were installed to control a drip irrigation system in an orchard containing various species of fruits during 64 days of evaluation. The drip irrigation system was gravity-fed from a water source placed 7 m above the soil surface. The irrigation system consisted of a head control manifold, one main line, and six lateral lines (Figure 1). The irrigation head control manifold included



Each row has a different species of plant

Figure 1. Field experimental setup with six rows of fruit plants

a 25-mm disc filter with a 120 mesh, a manometer, and a bypass valve. Each lateral line was fitted with a ball valve, a flow-control valve (irrigation supply valve), a tensiometer controller, and seven microtube emitters discharging 4 L h⁻¹ (inner diameter of 0.7 mm and length of 25 cm) at the base of a fruit tree.

Each controller was installed close to a tree and was used for controlling the irrigation of the lateral line in which the monitored tree was located (Figure 1). The controllers were located 15 cm away from the tree trunk and placed at a depth of 15 cm. Microtubes with inner diameters of 4 mm were connected to the hydraulic valve of each lateral line using the mechanical irrigation controllers. Whenever the SWT reached the activation SWT pre-set by the controller, the pressure inside the microtube (4 mm) was reduced, and the hydraulic valve was opened.

To evaluate the performance of the controllers, the SWT and the pressure in each lateral line were monitored constantly. All the irrigation controllers were equipped with pressure transducers (MPX5100DP) in the tensiometers to measure the SWT. The pressure heads on the hose in the lateral line (after the hydraulic valve) were monitored by pressure transducers (MPX5500DP) to indicate the time and duration of irrigation events. All the pressure-transducer sensors were connected to a data-acquisition system developed exclusively for this experiment.

The developed data-acquisition system consisted of a PIC18F4550 microcontroller, a real-time clock (RTC) circuit, a memory card, a liquid crystal display with 16 characters and two lines, and other electronic components (Figure 1). The responses of the sensors were measured every 15 s. Every 5 min, the microcontroller calculated the average of the measured values and recorded it on the memory card. Each record contained the date, time, and pressure-transducer reading. The RTC circuit was used to provide the date and time accurately and maintain this data even during power outages. The data-acquisition system had other electronic components, including a voltage regulator, resistors, capacitors, and buttons. The automatic performance of the SWT-based strategy was evaluated in an irrigation season of 64 days by

setting the configuration of the system at the start of the season and limiting further operator interaction to only downloading data and cleaning filters.

Each controller sample was calibrated by applying a vacuum to the tensiometer with a syringe. The required activation SWTs were achieved by twisting the adjustment spring nut until the hydraulic valve opened. Thus, according to linear equations (1) and (2) obtained previously for each controller, the controllers for each row of plants were set to initiate irrigation events at the following SWT values: C1, 12 kPa, C2, 16 kPa, C3, 20 kPa, C4, 18 kPa, C5, 22 kPa, and C6, 28 kPa.

$$SWT_{initiate} = 1.332x + 6.9 \tag{1}$$

$$SWT_{terminate} = 1.1708x + 4.4 \tag{2}$$

where:

$SWT_{initiate}$ and $SWT_{terminate}$ are the SWT values for starting and stopping irrigation, respectively (in kPa), and x is the

displacement vector (i.e., the distance by which and direction in which the spring is deformed, in mm).

RESULTS AND DISCUSSION

Each of the controllers tested in the field autonomously initiated and terminated irrigation during the evaluated period. Irrigation events were initiated when values close to the set SWT values were reached and were terminated at lower SWT values.

Figure 2 shows the SWT values and irrigation events during the evaluation days at the locations of the six controllers. The controllers exhibited adequate responses to changes in the SWT. The irrigation events occurred when SWT values close to the pre-set ones were reached. Likewise, irrigation events were terminated at similar values throughout the experiment.

Controllers C2 (Figure 2B) and C5 (Figure 2E) presented a single discrepant SWT value around the 16th and 44th days because of a maintenance routine in which the air chamber of

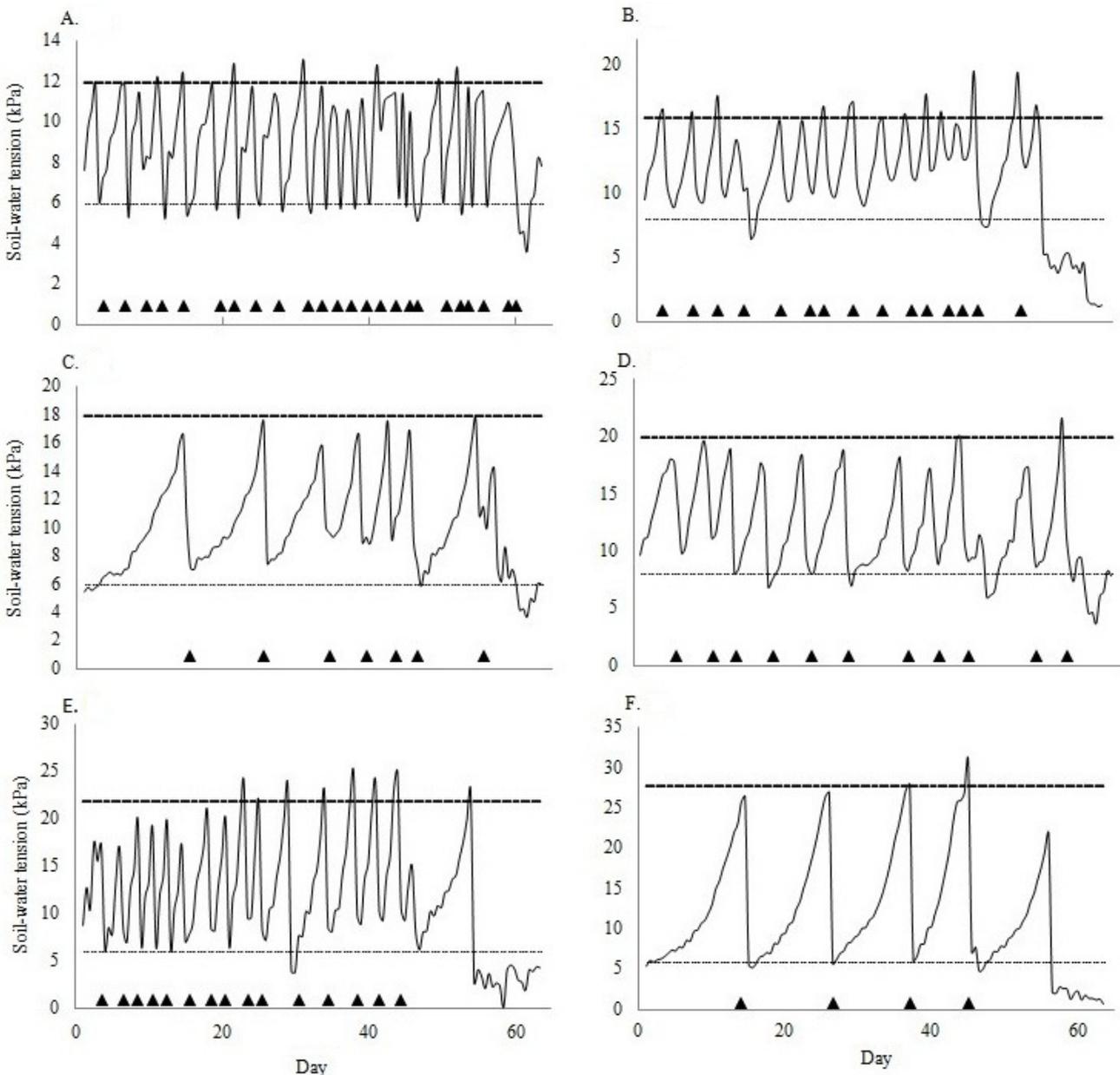


Figure 2. SWT with respect to time, when irrigation controllers were used to activate irrigation

the tensiometer was filled with water. Controllers C5 (Figure 2E) and C6 (Figure 2F) started irrigation at a slightly larger SWT than desired (approximately 3 or 4 kPa). However, this can be improved by replacing the spring with one having a higher spring coefficient.

In general, the controllers initiated irrigation at SWT values near the setup threshold, with a deviation smaller than 4-5 kPa (Table 1). This indicates that the controllers triggered irrigation at a relatively constant SWT. Furthermore, for most of the experiment, they were effective for maintaining the SWT in the root zone close to the pre-set value.

Because the SWT in the root zone was maintained close to the setup threshold plus 20% tolerance, the performance of the controllers was considered satisfactory. In evaluating an electronic irrigation controller, Miranda et al. (2005) considered the performance of a controller satisfactory if the SWT in the root zone was kept less negative than the SWT threshold plus 20% tolerance at least 90% of the time. In the present experiment, the six controllers showed a variation coefficient lower than 20% for most of the evaluation period.

The lowest SWT values ranged from 5.1 to 7 kPa for the first 50 days of evaluation, when there were no rain events (Figure 2). However, these SWT values were not the SWT values at which the irrigation was terminated. The controllers terminated irrigation at a greater SWT (varying from 7.3 ± 0.4 to 9.4 ± 0.4 kPa among the six controllers). This suggests that after the irrigation stopped, the wetting front continued moving downward, increasing the water content and decreasing the SWT.

The controllers exhibited a lower coefficient of variation for terminating irrigation than for starting irrigation (Table 1). However, slight deviations from the target values for starting irrigation were expected, as the tested controllers were handmade prototypes with manufacturing differences. The deviations might be reduced with an automated manufacturing process.

At the end of the evaluation period, rainfall was recorded over five days (days 46, 57, 61, 62, and 63), which caused reductions in the SWT values. The controllers responded well to the SWT during this rainy period and did not initiate any irrigation events.

Differences in the irrigation frequency were observed because the controllers were installed for various species of plants and different sets of SWTs activation. In general, a higher SWT for initiating irrigation yielded less frequent irrigation. These results support the theory that a larger irrigation threshold (drier) yields a longer time required for

the matric head to reach the threshold and initiate irrigation, resulting in fewer irrigation events (Hoppulla & Salo, 2007; Muñoz-Carpena et al., 2008; Daback et al., 2013).

An explanation for rows 1, 2, and 5 having the highest frequencies of irrigation (27, 16, and 15 irrigations events, respectively) is that the plants were in the fruiting and flowering stages. During these stages, the transpiration rate increased, and the soil dried faster due to increased water uptake by the roots (Daback et al., 2013; Daback et al., 2016). Therefore, there was a significantly larger loss of water through transpiration compared with the other rows, where the plants were in vegetative stages.

The variation coefficient of the irrigation duration ranged from 11 to 37% among the controllers. This variation is largely attributed to the low uniformity of the handmade controllers. With industrial fabrication, the repeatability should be improved. Another study reported a similar variation in irrigation systems controlled by tensiometers (51 to 90%) and a commercial water-sensor probe (49 to 2%) (Muñoz-Carpena et al., 2008). The authors attributed these variations in part to the intrinsic variability of the soil-water properties and the variability of the soil-water probe calibration, which affects the response of irrigation systems. This variation in this study was magnified because drip irrigation was used, in which there were no uniformly wetted soil volumes.

The proposed controller is functional, simple to use, and irrigators can adjust it according to their needs. Such characteristics may be expected to motivate small-plot farmers to adopt this technology in places where other technologies are somehow unavailable. According to Stirzaker & Hutchinson (2005), the barriers to ideal irrigation practices are as much socio-economic and cultural as they are technical. In general, simpler technology affords larger opportunity for adoption by small-plot farmers.

The major criticism of the use of tensiometers to control irrigation is the high-frequency maintenance required in some types of soil with a high sand content (Muñoz-Carpena et al., 2005; Nolz et al., 2013). However, in this study, low maintenance was performed over the evaluation period (64 days), and the irrigation controllers operated continuously without instrumentation problems. This may be because the relatively moist conditions of the heavy clay soil were maintained in the field experiment.

A variation was observed in the irrigation duration of 11 to 37% among controllers. Another study reported a similar variation in irrigations systems controlled by tensiometers (51 to 90%) and a commercial water-sensor probe (49 to

Table 1. Average values and standard deviation of the SWT for initiating and terminating irrigation, number of irrigation events and irrigation duration observed in the field evaluation for the six irrigation controllers

Controller	Average SWT for starting irrigation	Standard deviation	Average SWT for stopping irrigation	Standard deviation	Number of irrigations	Irrigation duration (h)
	kPa					
1	12.6 (3%)	1.10	7.3 (6%)	1.20	26	2.26 (35%)
2	18.5 (5%)	0.95	14.5 (7%)	2.10	16	4.05 (26%)
3	19.1 (7%)	1.20	10.3 (21%)	2.20	11	11.00 (31%)
4	17.9 (4%)	3.50	9.4 (4%)	1.20	7	6.07 (37%)
5	21.9 (17%)	3.20	8.4 (5%)	1.60	15	2.92 (12%)
6	32.2 (13%)	4.50	7.9 (18%)	2.30	4	0.95 (11%)

In parentheses is the variation coefficient

52%) (Muñoz-Carpena et al., 2008). The authors attributed these variations in part to the intrinsic variability of the soil-water properties and the variability of the soil-water probe calibration, which affects the response of irrigation systems. This variation in this study was magnified because drip irrigation was used, where there were no uniformly wetted soil volumes.

The tensiometer controller appeared to be well suited to the clay-soil environment when used at relatively low SWTs. Activation SWTs up to the limit of tensiometer use (~80 kPa) can be controlled using the same controller design by installing an adjustment spring with an appropriate higher spring coefficient. However, the required maintenance may be higher if the target activation tension is increased or the controller is used in sand, where the ceramic tip-to-soil contact is expected to be poor (Muñoz-Carpena et al., 2008).

The performance of the controller relies on the proper maintenance of the tensiometer and the proper installation of the tensiometer to obtain good contact between the porous capsule and the soil. Therefore, irrigators must be well trained to use these controllers.

The proposed controller offers a potentially useful approach for controlling irrigation systems. However, further research is necessary to improve issues regarding the repeatability, longevity, and reliability of this method. Additionally, the controller performance must be evaluated in different farming situations (soil types, placement depth, threshold values, and irrigation systems) to obtain more conclusive results (Soulis et al., 2015).

CONCLUSIONS

1. The proposed irrigation controller was operated effectively for a range of SWTs up to 30 kPa. Higher SWTs can be achieved by using springs with an appropriate higher spring coefficient.

2. The equipment is simple to use and can be easily adjusted by irrigators according to their needs. Such characteristics are expected to motivate small-plot farmers to adopt this technology in places where other technologies are somehow unavailable because of a lack of electricity.

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