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Real-time irrigation: Cost-effectiveness and benefits for water use and productivity of strawberries

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ABSTRACT

Although California is experiencing permanent water deficits compensated by irrigation, the state accounts for more than 90% of total strawberry production in the United States. There is a critical need to optimize yield and crop water productivity (CWP), as influenced by irrigation management. Although studies have reported that irrigation management based on soil matric potential (ψ) has the potential to increase yield and CWP compared to conventional practices, the cost of this technology may be a limiting factor for some growers. In this study, we assessed the cost-effectiveness of wireless tensiometer technology (WTT) for field-grown strawberries in California in comparison with the conventional irrigation management. As a second step, we evaluated the cost-effectiveness of deficit irrigation. Using data from eight sites, we calculated multiple linear regressions (MLR) to describe the relationship between: (1) fresh market yield and average soil matric potential reached before irrigation initiation (ψ_{irr}) and (2) water use and ψ_{irr}. Based on MLR results, we evaluated the technical performance of each irrigation management method and conducted an economic analysis. Our results showed that adopting a precise irrigation scheduling tool such as WTT is cost-effective and leads to water savings relative to conventional irrigation. Our results also revealed that any water savings associated with a deficit irrigation strategy are costly for strawberry growers.

1. Introduction

With more than 1.3 million metric tonnes of strawberries (*Fragaria x ananassa* Duch.) produced each year, the United States is the world's second largest supplier for both fresh and frozen markets (FAOSTAT, 2016). Remarkably, California leads all states in strawberry production, accounting for more than 90% of U.S. production (U.S. Department of Agriculture, 2013). Because of sustained and severe drought conditions, the major strawberry growing regions of California experienced substantial water supply problems between 2011–16 (USDA, 2016). The state relies heavily on irrigation, with much of the surface irrigation water supplied by state and federal water projects (USDA, 2016). In drought years, however, many farmers compensate for reduced surface water delivery by increasing water withdrawals from groundwater wells (USDA, 2016). In addition, certain areas of coastal California do not have access to the delivered irrigation water and therefore rely solely on well water. The western United States is currently facing a number of difficulties, including long-term aquifer depletion, potential land subsidence, and salt water intrusion and nitrate contamination in local aquifers (California Departement of Water Resources, 2014; Fulcher et al., 2016; Gallardo et al., 1996; Gray et al., 2015; Scanlon et al., 2012). This situation can be particularly critical when aquifers are non-renewable sources of freshwater with naturally low recharge rates, which is found in many areas (USDA, 2016). Consequently, there

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Abbreviations: ψ_{irr}, soil matric potential at irrigation initiation; IT, irrigation threshold; WTT, wireless tensiometer technology; CWP, crop water productivity; RCBD, randomized complete block design; MLR, multiple linear regression; FMY, fresh market yields; WU, water use; BEP, break-even point; EV, expected value; DI, deficit irrigation

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is a critical need to increase crop water productivity to ensure rational freshwater use in areas of intensive agricultural activity (Lea-Cox et al., 2013).

Strawberry plants are sensitive to water stress (Hanson, 1931) due to their shallow root system (Manitoba Minister of Agriculture, Food and Rural Development, 2015). When the crop is drip irrigated, adequate irrigation management is required to meet plant water requirements because only limited volumes of soil are wetted (Coelho and Or, 1998). The effectiveness of such irrigation is highly dependent on its scheduling, and it is thus important to determine the best timing and duration of irrigation events to limit over-watering, which often results in wasted water and soluble nutrients and lower crop yields (Saleem et al., 2013; Létourneau et al., 2015). Irrigation management practices have been studied extensively in field-grown strawberries (El-Farhan and Pritts, 1997). The methods most commonly used in California are based either on crop evapotranspiration (ET) or on soil moisture measurements.

Evapotranspiration estimates the quantity of water used by the crop during a given time period based on weather data and a field estimate of crop coefficients (Kc) (Grattan et al., 1998). Several studies have reported that ET-based irrigation has the potential to optimize water applications in strawberries (Cahn et al., 2016; Hanson and Bendixen, 2004; Yuan et al., 2004). Despite being an inexpensive decision-making tool (costs are negligible as many websites offer free access to potential evapotranspiration calculations and tabulated crop coefficient values; Allen et al., 1998; California Irrigation Management Information System, 2017), this approach estimates water usage indirectly and therefore is not as accurate as direct-measurement methods (Lea-Cox, 2012). To compensate for crop evapotranspiration losses (Allen et al., 1998), ET estimates past water requirements to predict future water applications, thus eliminating the possibility of managing irrigation in real-time. While common grower practices aim for water applications equivalent to approximately 100% of crop ET, recent studies suggest that improved irrigation scheduling methods, such as irrigation based on soil matric potential (ψ), can generate water savings without compromising strawberry yields or fruit quality, once an optimal irrigation threshold (IT) has been defined (Muñoz-Carpena et al., 2003; Létourneau et al., 2015; Migliaccio et al., 2008; Shae et al., 1999). By optimizing irrigation efficiency, the ψ-based method is likely to enable strawberry farmers to better meet sustainability and economic objectives.

Wireless soil sensor technology combines traditional soil matric potential monitoring with wireless communication, thus allowing real-time data reporting and irrigation management (Chappell et al., 2013; Lea-Cox et al., 2013). In California, it has been shown that yields decreased sharply at soil matric potentials of less than -8 to -12 kPa in sandy loam to clay loam soils, suggesting that ψ-based irrigation may provide optimal yield and CWP at soil matric potentials ranging from -10 to -15 kPa in field-grown strawberries (Létourneau et al., 2015). In similar conditions, Anderson (2015) showed that ψ-based irrigation at an IT of -17 kPa could increase yield and CWP compared to conventional irrigation which was usually drier (ψ_{irrs} of -27, -31 and -42 kPa). These results are consistent with other research studies, where significantly higher strawberry yields were obtained using an IT of -10 kPa compared to ITs ranging from -30 to -70 kPa (Guimerà et al., 1995; Peñuelas et al., 1992; Serrano et al., 1992). Although most growers are receptive to the idea of wireless sensor networks, they have so far been reluctant to adopt WTT because it is more costly – involving an investment in equipment of more than $1500 per hectare – than the conventional irrigation management method (Majsztrik et al., 2013; Lea-Cox, 2012). However, no analysis assessing the cost-effectiveness of this technology has been conducted for strawberry production in North America.

WTT also opens up a range of possibilities for fine-tuned irrigation strategies, such as deficit irrigation (DI), which has been shown to reduce water use and improve CWP in many crops (Geerts and Raes, 2009; Fereres and Soriano, 2007; Zwart and Bastiaanssen, 2004). In strawberries, Létourneau et al. (2015) obtained higher CWP in drier treatments (lower ITs) than in wetter treatments (-26 kPa vs -10 kPa; -15 kPa vs -8 kPa). Likewise, in Finland, in a strawberry crop grown in a sandy soil, Hoppula and Salo (2007) obtained higher CWP with irrigation initiated at -60 kPa instead of -15 kPa. Considering that most Californian strawberry growers must pay for water, it could be beneficial to develop a controlled dry-irrigation management strategy that uses tension sensors to save water.

In this study, we first assessed the cost-effectiveness of ψ-based management using WTT with an optimal IT of -10 kPa in field-grown strawberries in California, in comparison with the conventional irrigation management method. In a second time, we evaluated the cost-effectiveness of deficit irrigation using WTT by simulating a set of reduced-irrigation scenarios.

2. Materials and methods

2.1. Site description and experimental designs

We collected the data analyzed in this study over five growing seasons and on eight experimental sites covering a range of soil properties, cultivation periods, strawberry cultivars and farming practices used in field strawberry production in California, USA (Table 1). We arranged treatments in all sites except site 1 in a randomized complete block design (RCBD) with three to five replicates (Table 1). We divided sites, all located in a typical temperate, Mediterranean climate, into two groups according to their location: northern strawberry growing region (Group N: sites 1–4) and southern strawberry growing region (Group S: sites 5–8). We grew strawberry plants on raised beds covered with a plastic mulch according to standard farming practices (Strand, 2008), with two (Group N) or four (Group S) plant rows per bed. In Group N, day-neutral strawberries (*Fragaria* × *ananassa* Duch.) were planted by the farm team in November in silty clay and clay loam soils. Trials ran from April to October on sites 1, 3 and 4, and from mid-April to late June on site 2. In Group S, short-day strawberries were planted by the farm team in sandy loam soils in October with fresh market harvest period falling between January/February and May/June, depending on the growing season.

2.2. Irrigation system specifications and ψ_{irr} measurements

At all sites, sprinkler irrigation was used by the farm team up to proper establishment (for 4–6 weeks after planting). Subsequently, we used drip-irrigation until the end of the season. We irrigated growing beds by two (Group N) or three (Group S) drip lines (0.34–0.70 $\mathrm{L \cdot h^{-1}}$ per emitter, depending on the site, with 20-cm emitter spacing). We installed field monitoring stations reporting real-time ψ measurements through wireless networks and web servers in all treatments in one or two blocks (Group N) or in one to three blocks (Group S) (Table 1). A TX3 wireless monitoring station (Hortau, Quebec, Qc, Canada) consisted of two model HXM80 tensiometers, buried at two different depths (15 and 30 cm), that measured ψ at 15-min intervals. In ψ-based treatments, the shallow probe, located in the root zone, indicated when a set IT was reached and when irrigation should be initiated. The deep probe, located below the root zone, indicated when to stop irrigation to prevent water percolation and nutrient leaching under the root zone. In conventional treatments, the probe at a 15-cm depth reported the average soil matric potential reached before irrigation and the deep probe monitored the soil water status at a 30-cm depth.

2.3. Irrigation treatments

Irrigation treatments in our study concern post-establishment irrigation. A total of twenty-five ψ-based treatments consisted of different irrigation initiation thresholds ranging from -8 kPa to -35 kPa