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Automated cycled sprinkler irrigation for spring frost protection of cranberries

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ABSTRACT

Overhead (sprinkler) irrigation is commonly used for spring frost protection of cranberries in southeastern Massachusetts, United States. Historically, conventional forms of irrigation management have been used, generally consisting of running irrigation pumps continuously throughout the night and into the early morning until ambient air temperature reached 1–2 °C above the critical temperature of the plant. However, a general paucity of information exists on the horticultural and hydrological effects of on-off "cycling" of irrigation pumps based on pre-programmed temperature setpoints. To fill this gap, three years of monitoring were conducted to quantify the relative effects of cycled and conventional spring frost irrigation on cranberry bud damage, crop yield, and water use. Results showed that cycled irrigation reduced seasonal water use from 33 to 80% compared to conventional frost irrigation, with water savings under cycled frost irrigation ranging from 113 to 198 mm (mean ± SD: 176 ± 47 mm). Despite some variation in type and amount of observed bud damage, values of cranberry yield were similar between the two methods or higher for cycled irrigation. The conventional frost irrigation method always applied more irrigation water, possibly increasing soil saturation and anaerobic conditions that are known to lower crop yield in cranberry. Together, these results point to cycled irrigation as a water management strategy that can enhance cranberry production and reduce agricultural water use in southeastern Massachusetts.

1. Introduction

Commercial cranberry production has existed for nearly two centuries in southeastern Massachusetts (Eck, 1990), where one-fifth of North America's cranberry supply is produced (Alston et al., 2014). Water resources are protected in Massachusetts under the Water Management Act, which authorizes the regulation of agricultural, industrial, and residential water withdrawals over 100,000 gallons per day (WMA, 1986). Agricultural water management for commercial production of cranberries consists of (1) periodic flooding for harvest, winter protection, leaf removal, and sanding, and (2) sprinkler irrigation for soil water management and frost protection (DeMoranville, 2008a,b). Water conservation efforts have focused primarily on irrigation, particularly for soil water management (Pelletier et al., 2013; Jabet et al., 2017), despite irrigation using half as much water as flooding (Kennedy et al., 2017). Although its water footprint is smaller than flooding, irrigation is just as important to cranberry production. It provides vital protection of the cranberry plant from frost injury, which can cause major to complete crop loss in a matter of hours (DeMoranville, 2008b, p. 63).

The need to protect from frost events is not unique to cranberry. Many fruit crops, including apples, peaches, grapes, and strawberries, are susceptible to such damage and may be protected using sprinkler irrigation (Heineman et al., 1992). However, because bogs commonly form in isolated depressions, the trapping of cold air on windless nights enhances the likelihood of spring frost damage of cranberries (DeMoranville, 2008b; p. 60). On nights with no cloud cover, heat energy radiated from the cranberry plant is lost to the upper atmosphere, causing soil, air, and crop temperatures to cool significantly (Curtis, 1936; Perry, 1998). As a result, air temperatures can reach 11° C lower in cranberry bogs than in surrounding upland areas (DeMoranville, 2008b; p. 60).

Frost damage occurs as water within the plant cell freezes. The temperature at which this occurs will vary depending on the plant part and biochemical characteristics that change during plant development. The frost tolerance of a plant, or the minimum tem-

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Table 1
Critical temperature (°C) of terminal cranberry buds of two cultivars at different developmental stages (DeMoranville, 1998).

	Spring Dormant	White Bud	Bud Loosening	Bud Swell	Bud Elongation	Roughneck
Early Black	−7.8	−6.7	−5.6	−3.9	−2.8	−1.4
Stevens	−6.7	−5.6	−3.9	−2.8	−1.4	−1.4

perature at which a plant can withstand serious injury, is referred to as the critical temperature. For nascent cranberry buds, the critical temperature is below the freezing point of water and varies with growth stage (DeMoranville, 1998; Table 1). Methods for frost protection include wind machines, heaters, and sprinkler (overhead) irrigation (Perry, 1998). Developed in the 1960s, sprinkler irrigation is the most widely used frost protection method on cranberry farms (Norton, 1968). During frost irrigation, latent heat released during phase change (e.g., water to ice) is transferred to the plant, protecting sensitive tissues.

Frost irrigation can be classified into the groups of "conventional" or "cycled" irrigation. Conventional frost irrigation consists of monitoring air temperature, starting irrigation pumps at 1–2 °C above the critical temperature, and running pumps continuously into the early morning when the air temperature rises above the critical temperature. Historically, Massachusetts cranberry growers have used conventional frost irrigation. Contrasting with conventional irrigation, automation is a key component of cycled irrigation. Air temperature is also monitored, but an automated system is used to turn ("cycle") irrigation pumps on and off based on specified temperature setpoints, which include starting and stopping irrigation pumps at about 1 and 3 °C, respectively, above the critical temperature. The automated cycled irrigation system described here differs from that developed in previous work on other crops, which used meteorologic data (bud temperature, wind speed, and relative humidity) and crop information to determine when to start irrigation, and an energy balance model to determine the irrigation application rate and pulse cycles (Perry et al., 1980; Perry, 1986). The automated cycled irrigation system of Perry et al. (1980) was later adapted to strawberries (Stombaugh et al., 1992; Heinemann et al., 1992; Goulart et al., 1993) and to apples (Heisey et al., 1994; Koc et al., 2000), with results pointing to water use reductions between 25 and 89% compared to conventional irrigation.

In the current study, we evaluate the performance of automated cycled irrigation for spring frost protection of cranberries. The research was conducted on a site in Massachusetts where cycled and conventional methods of frost irrigation were applied to different fields within the same farm. The single-farm approach allowed for a relatively controlled experiment for the comparison of the frost protection methods. From 2013 to 2015, hydrologic and horticultural data were collected over three spring frost seasons. These data were used to quantify the effects of cycled and conventional spring frost irrigation on cranberry bud damage, crop yield, and water use for both native and hybrid cranberry cultivars.

2. Materials and methods

2.1. Study site and design

The study was conducted in Middleboro, Massachusetts, United States, on a 14.0-ha cranberry bog called Benson's Pond Bog (Fig. 1). The cranberry bog was a natural peat wetland before it was ditched and cultivated for commercial cranberry production in the 1920s. Two irrigation pumps were used for applying spring frost irrigation (Table 2). The cycled irrigation pump was used for frost protection of 9.7 ha of the bog, and the conventional irrigation pump for frost protection of 3.4 ha in years 1 and 2 and 4.4 ha in year 3 (a 0.9-ha field was under construction in years 1 and 2; Table 2). The study was arranged as repeated measures in a split plot model, which included frost protection method (cycled and conventional) in the main plots and cultivar type (Early Black and Stevens) in the subplots (SAS Institute, 2011).

Table 2
Dates and areas irrigated for study years 2013–2015.

Study Year	Dates	Irrigated Area (ha)	
		Cycled	Conventional[a]
1	16 Apr.–7 Jun., 2013	9.70	3.38
2	16 Apr.–12 Jun., 2014	9.70	3.38
3	23 Apr.–15 Jun., 2015	9.70	4.26

[a] Small (0.87 ha) portion of the field was under construction in years 1 and 2.

Horticultural data were collected from four cranberry fields within Benson's Pond Bog, which were divided between fields of cycled and conventional frost irrigation management and sampled for bud damage and crop yield (Fig. 1). Frost protection methods were applied to whole plots across all cultivars, including the native variety 'Early Black' and the hybrid cultivar 'Stevens', which together represented 57% of the 2012 cranberry production in Massachusetts (Joe DeVerna, Ocean Spray, Inc., personal communication, 2012).

2.2. Temperature

Air temperature was measured using an Onset® temperature sensor (model S-TMB-M00) placed in the center of the bog (T_{bog}) (Fig. 1). The sensor was located below the plant canopy 0.1 m above ground, and was housed within a radiation-shielded enclosure. It measured ambient air temperature with an accuracy of ± 0.2 °C. Air temperature was logged on 5-min intervals and sent wirelessly to a website where it was stored. For both conventional and cycled irrigation, irrigation was initiated when the temperature at the vine tips reached 1.1° C above the critical temperature of the 'Stevens' cultivar (Table 1). For conventional irrigation, once it was initiated, irrigation was applied throughout the night and stopped in the early morning when the ambient temperature reached above freezing (usually around 0700 h). For cycled irrigation, once initiated, the pumps turned off when air temperature reached 3.3° C above the critical temperature, then cycled on and off through the night, restarting at the initiation temperature (1.1° C above $T_{critical}$). Several such cycles would be possible during the night, depending on the severity of the frost event.

The critical temperature ($T_{critical}$), which is the minimum temperature at which a plant can withstand serious damage, varies with the developmental stage of the plant (DeMoranville, 1998). For each spring season, the research team collected weekly samples of cranberry buds from a nearby bog (~6 km southeast of Benson's Pond Bog). The buds were returned to the laboratory, where they were carefully inspected for developmental growth stage to determine $T_{critical}$ (Table 1).

Since the 1920s, cranberry researchers have used an analytical model to predict spring frost events (Franklin et al., 1943). The frost model is based on regional field observations and local weather station data. Model input parameters include, but are not limited to, local weather station measurements of dry bulb temperature, wet bulb temperature, and dew point. Using this model, the Cape Cod Cranberry Growers' Association now provides a frost warning service to its paying members, which include the Benson's Pond Bog grower. The frost model predicts the minimum on-bog air temperature for the Massachusetts cranberry-growing region, assuming environmental conditions that are consistent with a severe frost event (i.e., negligible cloud cover and wind). The model was used