NRC Research Press

ARTICLE

Agricultural water requirements for commercial production of cranberries[1]

Casey D. Kennedy, Peter Jeranyama, and Nickolas Alverson

Abstract: The commercial production of cranberries relies on abundant water resources for frost protection, soil moisture management, and harvest and winter flooding. Given water resource demands and regulations in southeastern Massachusetts, we sought to quantify the annual water requirement for the commercial production of cranberries. Based on 2 yr of monitoring across five sites, the mean water requirement for cranberries was 2.2 (±0.6) m yr^{-1} (one standard deviation in parentheses). On average, the 3 mo maximum area threshold of 3.15 ha was within ~20% of the value currently used to establish water permits for renovated cranberry farms in Massachusetts. Variation in the water requirement was primarily related to differences in the harvest and winter floods, which combined for two-thirds of the annual water requirement. The water requirement for the winter flood exhibited the greatest annual variation (54%), which was relatively low for the harvest flood (20%). Environmental variation was significantly related to water requirements for the winter flood, as well as seasonal irrigation, and should be carefully considered in agricultural water use regulations.

Key words: water management, hydrology, irrigation, agriculture, *Vaccinium*, Massachusetts.

Résumé : La culture commerciale de la canneberge exige d'abondantes ressources hydriques afin d'assurer une protection contre le gel, de gérer la teneur en eau du sol et d'inonder les tourbières à la récolte et en hiver. Face à la demande d'eau et à la réglementation de cette ressource dans le sud-ouest du Massachusetts, les auteurs ont tenté de préciser la quantité d'eau que nécessite la production commerciale de canneberges annuellement. Sur la foi de 2 années d'étude à cinq endroits, cette culture exige en moyenne 2,2 m d'eau par an (écart-type de ± 0,6). Le maximum trimestriel pour la zone minimale de 3,15 ha se situe en moyenne à ~20 % de la valeur qui sert actuellement à établir les permis d'utilisation de l'eau pour les tourbières à canneberges récemment réaménagées, au Massachusetts. La quantité d'eau requise varie principalement avec l'importance des inondations à la récolte et en hiver qui, ensemble, représentent les deux tiers du volume d'eau total. La quantité d'eau nécessaire pour l'inondation hivernale est celle qui varie le plus dans le temps (54 %), l'inondation à la récolte fluctuant relativement peu (20 %). Les variations d'origine environnementale présentent une relation significative avec le volume d'eau nécessaire à l'inondation hivernale ainsi qu'avec l'irrigation durant la période végétative, et on devrait soigneusement en tenir compte dans la réglementation applicable à l'eau utilisée pour l'agriculture. [Traduit par la Rédaction]

Mots-clés : gestion de l'eau, hydrologie, irrigation, agriculture, *Vaccinium*, Massachusetts.

Received 30 September 2015. Accepted 2 May 2016.

C.D. Kennedy.* U.S. Department of Agriculture, Agricultural Research Service, Pasture Systems and Watershed Research Management Unit, East Wareham, MA 02538, USA.

P. Jeranyama. University of Massachusetts Cranberry Station, East Wareham, MA 02538, USA.

N. Alverson. University of Massachusetts, Department of Environmental Conservation, Amherst, MA 01003, USA.

Corresponding author: Casey D. Kennedy (email: Casey.kennedy@ars.usda.gov).

*Casey D. Kennedy currently serves as Guest Editor; peer review and editorial decisions regarding this manuscript were handled by Silvio Gumiere.

[1] This paper is part of a Special issue entitled Precision Agriculture and Soil and Water Management in Cranberry Production.

A correction was made to the e-First version of this paper on 7 February 2017 prior to the final issue publication. The current online and print versions are identical and both contain the correction.

Introduction

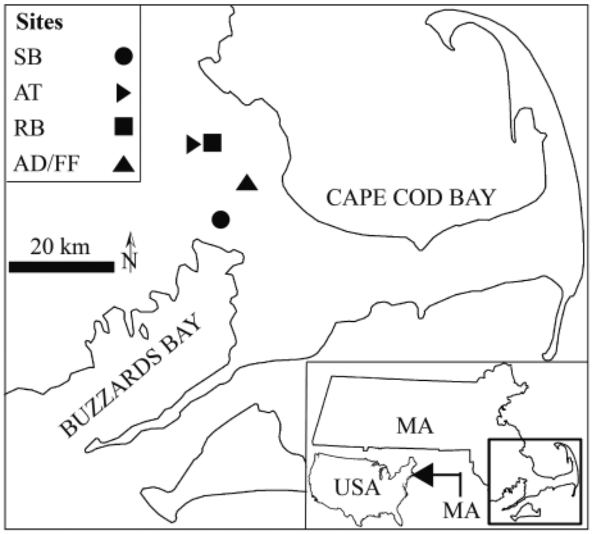
The origin of the US cranberry industry can be traced to the peat bogs of Massachusetts, where commercial production of cranberries has existed for nearly two centuries (Eck 1990). Production of cranberries relies heavily on regional surface water and groundwater supplies for periodic flooding and seasonal irrigation (e.g., Jeranyama et al. 2014). Although access to vast quantities of water is essential for cranberry production, the water demand for crop production may deplete local water resources. Given their shared interest in the protection of water resources, governmental agencies and cranberry growers are eager to develop accurate estimates of agricultural water requirements that support sustainable development of water resources across southeastern Massachusetts.

Accordingly, the Water Management Act authorizes the regulation of surface water and groundwater supplies to ensure adequate water resources for current and future water resource needs (WMA 1986). Given a general paucity of information, a survey of agricultural water management practices in the late 1980s suggested an annual water requirement for cranberry agriculture of ~2.1–3.0 m yr^{-1} (7–10 acre-ft acre^{-1} yr^{-1}), which was about two times the water requirement for winter and harvest flooding (0.9–1.4 m yr^{-1}; Kennedy 2015).

As mandated by the Water Management Act, cranberry farms in excess of an "area threshold" were required to register or apply for a water permit (Gilmore 1987; USDA-NRCS 1988). The area threshold, which notably is based on quarterly (not annual) water use, refers to water withdrawals in excess of 34 523 m^3 over a continuous 91 d period. In the 1980s, the cranberry industry identified the months of October, November, and December as the most water intensive, with the harvest and trash floods, winter flood, and autumn frost irrigation using 18 288 m^3 ha^{-1} (6 acre-ft acre^{-1}) of water. Therefore, the "area threshold" is the minimum bog area that would use in excess of 34 523 m^3 of water on a quarterly basis. Using the 1980s water use rate, the area threshold for "old bogs" was 1.89 ha (i.e., 34 523 m^3 divided by 18 288 m^3 ha^{-1}). Citing innovative water conservation practices, the area threshold increased from 1.89 ha (4.66 acre) to 3.78 ha (9.33 acre) for new constructions or farms implementing the best water management practices.

Despite the cranberry industry's reliance on abundant water resources, direct measurements of the annual water requirement for cranberry production are currently lacking. To fill this gap, we monitored precipitation, flood and irrigation inputs to five cranberry farms over a 2 yr period. Our general objective was to provide values of the agricultural water requirement for cranberries that inform future water resource planning in southeastern Massachusetts. Specifically, we sought to elucidate the management and environmental factors causing variation in the water requirement for cranberry agriculture.

Fig. 1. Map of the study area and location of study sites. The state boundary GIS layer was obtained from the online GIS database at http://www.mass.gov.



Study Area

The study area is southeastern Massachusetts (Fig. 1), where about one-fifth of the US annual cranberry supply is produced from about 5300 ha of active farms (2012–2013 average; USDA-NASS 2014). In Massachusetts, cranberry farms are generally composed of a layer of sand that caps glacial deposits of organic sediment (i.e., peat), ranging in thickness from 1 to 12 m (Deubert and Caruso 1989). Although the North American cranberry (*Vaccinium microcarpum* Ait.) is a wetland plant, it flourishes in relatively dry soils that require irrigation inputs for spring and autumn frost protection and summer soil water management (Bonin 2009; Caron et al. 2016). Water control structures in artificial drainage networks are also used to manipulate flooding, a common management tool practiced by ~90% of cranberry growers to harvest fruit and remove fallen leaves in the autumn and for vine protection in the winter (DeMoranville 2008*a*).

The five study sites include four cranberry farms and one cranberry field (defined here, a farm is an aggregate of fields separated by dikes and water control structures). The sites range in size from 2.1 to 19.2 ha (Table 1) and are located in the towns of East Wareham, Plymouth, and Carver, Massachusetts, where about half of the state's cranberry crop is currently produced (B. Wick, Cape Cod Cranberry Growers' Association, personal communication). The region is also an area of increased competition among agricultural, commercial, ecological, and residential demands for water resources (Masterson et al. 2009). Three of the five sites are planted with the hybrid cultivar Stevens or comparable

Table 1. Characteristics of the five study sites.

Site	City	Scale	Area (ha)	Cranberry cultivar	Frost irrigation	Renovated (year)	Yield[a] (t ha^{-1})
SB	East Wareham	Farm	4.4	M[b]	Co	2007	13.7
AT	Carver	Field	2.1	St	Cy	2009	24.3
RB	Plymouth	Farm	2.8	St	Co	2000	23.0
FF	Plymouth	Farm	19.2	EB, H[c]	Co	No[c]	19.8
AD	Plymouth	Farm	10.4	EB	Co	No	14.4

Note: St, Stevens; M, mixed; EB, Early Black; H, Howes; Co, conventional frost irrigation; Cy, automated cycled frost irrigation.

[a] 2013 and 2014 average.

[b] Two-thirds Stevens or comparable varieties (i.e., large-fruit hybrid cultivars); treated as Stevens in statistical analysis using cultivar as a dependent variable.

[c] Three-hectare field renovated and planted with the Ben Lear cultivar in 2007.

large-fruit hybrids (e.g., Grygleski or Rutger's varieties); two sites are planted with the native varieties Early Black and Howes (Table 1).

During the growing season, irrigation was applied to maintain values of soil water tension between −4 and −7 kPa for sites SB and AT (Bonin 2009; Caron et al. 2016), contrasting with cultural practices of irrigation management (e.g., visual observations and local meteorological conditions) for sites FF and AD. In the case of site RB, growing season irrigation was managed using cultural practices in year 1 and using measurements of soil water tension in year 2. Conventional methods of frost irrigation management (i.e., manually turning pumps on and off) were used for all sites with one exception, site AT, which cycled irrigation pumps based on specified temperature set points (Ndlovu 2015).

Materials and Methods

In autumn of 2014, soil samples were collected from 16 fields across the five study sites (at least one field was sampled from each of the four farm sites). For each field, composite samples of 15–20 soil cores were collected from the soil surface (0–5 cm) and subsurface (5–15 cm) with a 2.5 cm diameter stainless steel soil probe. Samples were mixed and then promptly transported to the laboratory, air-dried, and sieved (2 mm) before analysis. Soil textural analysis was performed with a hydrometer (Gee and Bauder 1986), and percent organic matter was measured by loss of weight on ignition at a temperature of 360 °C held for 2 h (Storer 1984).

A tipping bucket rain gauge (Model RG3, Onset Computer Corp.) was placed on the dike (i.e., embankment) adjacent to each farm with the exception of site FF, where precipitation was assumed to equal that measured at site AD, given the closeness of the two sites (~500 m). A national weather service precipitation gauge (site 192451) that consisted of a 20 cm diameter metal cylinder emptied manually on a daily basis was also located at site SB. Comparison of the aggregated 15 min tipping bucket data and the daily manual gauge data yielded rainfall values for the growing season (1 June to 15 Sept.) that were in excellent agreement, with average differences of about 10% for the two study years. Irrigation volume was measured using a flow meter (McPropeller, McCrometer) that was read manually on a weekly basis.

Sites flooded by gravity flow or using propeller pumps were instrumented with acoustic Doppler area-velocity (AV) meters (Model 2150, Teledyne/Isco). The quality of the acoustic signal was generally exceptional. However, rocks or ice collecting on the sensor resulted in sensor failure for sites SB (year 1 harvest flood) and AT (years 1 and 2 winter flood). In the case of site SB, the flow rate of 824 ± 58 L s^{-1} (mean and standard deviation), which was measured about 2 wk following the cranberry harvest, was combined with the total run time of 9.25 h to estimate the harvest flood volume. For site AT, a relatively small (2 ha) laser-leveled cranberry field, the winter flood volume was estimated based on calculations using continuous (15 min) water level measurements of water stored in the ditches (i.e., ditch area × ditch depth), the soil pore spaces (i.e., field area × ditch depth × drainable porosity), and the area above the surface of the field (field area × surface water depth). Values of ditch depth and area were 0.69 m and 0.21 ha, respectively, and the drainable porosity of coarse sand was assumed (0.27; Johnson 1967). Error in the estimate was about 10%, based on the difference in the measured and estimated values of the harvest flood.

A propeller flow meter installed on an irrigation pump was used to measure additional floodwater inputs for site RB. Trailer pumps were also associated with additional, but relatively minor, floodwater inputs for sites AT, FF, and AD and were instrumented with a clamp-on transient time ultrasonic flow meter (Model TFX, Badger Meter).

Soil water tension was measured at sites AT, SB, and RB to schedule summer irrigation applications. At each site, soil water tension was measured at a depth of 10 cm below the soil surface with a Hortau® tensiometer (models TX3, TX4, and ST2 at sites SB, AT, and RB, respectively). Soil water tension was measured every 15 min, and values were remotely sent to a website that was monitored by the cranberry grower.

Table 2. Start and end dates for the 2 yr of study.

Study year	Date
1	16 Sept. 2013 to 15 Sept. 2014
2	16 Sept. 2014 to 15 Sept. 2015

Analysis

The agricultural water requirement for cranberry was calculated as (1) the volume of water applied to cranberry farms for irrigation and flooding on an annual basis (Table 2), including precipitation during the growing season (Q_{ag}) and (2) the maximum volume of water applied as irrigation or floodwater over a 3 mo continuous period (Q^*_{ag}), per the WMA (1986). For the annual water requirement, water volumes associated with winter and harvest flooding (Q_{fw}), seasonal irrigation (Q_{iw}), and growing season precipitation between 1 June and 15 Sept. (P) were aggregated:

$$Q_{ag} = Q_{fw} + Q_{iw} + P \tag{1}$$

As defined by the Water Management Act, water use in excess of 378.5 m^3 d^{-1} (100 000 gal d^{-1}) over a 3 mo continuous period requires a water withdrawal permit (WMA 1986). For each site and study year, the maximum water use over a 91.2 d interval was used to determine Q^*_{ag}, which generally represented water use for the period between mid-October and mid-January. The value of Q^*_{ag} was then used to determine the area threshold, A_{ag}:

$$A_{ag} = \frac{Q_{WMA}}{Q^*_{ag}(10)} \tag{2}$$

where Q_{WMA} is a constant (34 523 m^3, calculated as 378.5 m^3 d^{-1} × 91.2 d^{-1}), and Q^*_{ag} and A_{ag} have units of mm and ha, respectively.

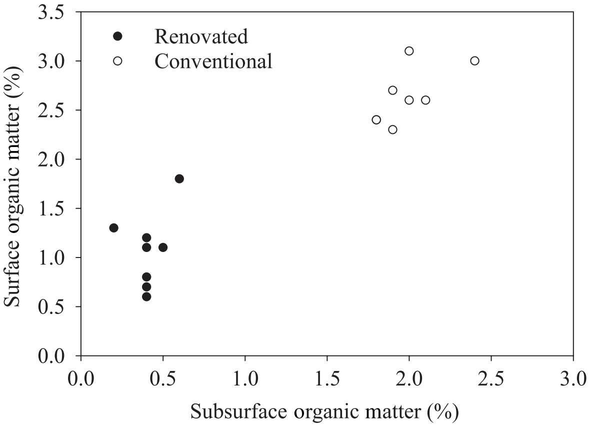
Uncertainty is reported approximately to ±1 standard deviation (i.e., roughly 70% confidence). The level of uncertainty in irrigation volume was taken as 2%, based on the reported instrument accuracy. The expected uncertainty in the floodwater measurement was about 5% (Heiner and Vermeyen 2012). Based on differences between the manual and tipping bucket measurements, uncertainty of 10% was used for growing-season precipitation. Statistical analysis was performed using paired *t*-tests (two-tailed assuming unequal variance) evaluated at 90% confidence ($\alpha = 0.05$) in Microsoft Office Excel 2007.

Results and Discussion

Soil properties

Soil texture analysis showed negligible (<1%) variation in particle grain size between surface and subsurface soils, both of which were composed mostly of coarse sand (95%) with relatively minor amounts of silt (2%) and clay (2%). In contrast, significant vertical stratification was exhibited in soil organic matter, with slightly higher organic matter content in surface vs. subsurface soils (1.9% vs. 1.2%; $P = 0.03$). A general pattern emerged of less organic matter in renovated sites ($P < 0.001$), both in surface and subsurface soils (Fig. 2 and Table 1).

Fig. 2. Percent organic matter in surface (0–5 cm) and subsurface (5–15 cm) soils for renovated and conventional (nonrenovated) sites. Differences in mean values of soil organic matter were significant ($P < 0.001$) for both surface soils (1.1%, renovated; 2.6%, conventional) and subsurface soils (0.4%, renovated; 2.0%, conventional).



Annual water requirement

The annual water requirement for cranberry production ranged from 1459 to 3184 mm yr^{-1}. The mean annual water requirement was 2444 mm yr^{-1} for year 1 and 2023 mm yr^{-1} for year 2 (2 yr mean of 2233 mm yr^{-1}). Mean differences in the water requirement for cranberry farms could not be explained by renovation ($P = 0.99$), despite renovated farms having different soil properties (Fig. 2) and adopting innovated water conservation practices. Generally, flooding represented the most water intensive practice in cranberry farming, combining for about two-thirds of the annual water requirement. As a result, the mean annual water requirement decreased by 17% from years 1 to 2 ($P = 0.22$), largely due to less winter floodwater applied in year 2 (Table 3).

Winter and harvest floods

The water applied for winter and harvest flooding differed between the 2 yr; on average, the winter flood was about one-and-a-half times larger than the harvest flood in year 1, but roughly two-thirds the size of the harvest flood in year 2. Mean values of floodwater decreased between years 1 and 2 for the winter flood ($P = 0.04$) but were not statistically different for the harvest flood ($P = 0.68$).

As a result, annual variation in floodwater was related to the winter flood rather than the harvest flood, which exhibited significantly less annual variation than the winter flood (20% vs. 54%; Table 3). Variability in the

Table 3. Water requirements for cranberry farms.

		Q_{jw} (mm yr^{-1})		Q_{fw} (mm yr^{-1})			
Site	P (mm yr^{-1})	Frost	Crop	Harvest	Winter	Q_{ag} (mm yr^{-1})	A_{ag} (ha)
Year 1							
SB	364±36	317±6	220±4	618±31	1010±51	2529±70	3.42
AT	440±44	129±3	317±6	615±31	682±34	2184±64	2.77
RB	277±28	685±14	236±5	640±13	1347±27	3184±43	2.57
FF	332±33	168±3	178±4	465±23	1037±52	2179±66	3.33
AD	332±33	75±1	146±3	1101±55	489±24	2144±69	2.51
Year 2							
SB	258±26	167±3	228±5	506±25	382±19	1542±41	4.93
AT	354±35	213±4	358±7	668±33	493±25	2085±55	2.98
RB	258±26	405±8	163±3	584±12	505±10	1916±31	3.17
FF	264±26	179±4	236±5	498±25	281±14	1459±39	4.26
AD	264±26	184±4	189±4	1762±88	714±36	3112±99	1.80

Note: P, growing season precipitation, 1 June to 15 Sept.; Q_{jw}, irrigation water; Q_{fw}, floodwater; $Q_{ag} = P + Q_{jw} + Q_{fw}$; A_{ag}, area threshold (see text). Uncertainty at 70% confidence (1 standard deviation) was calculated using measurement error (i.e., P, Q_{jw}, and Q_{gw}) and standard methods of error propagation (Q_{ag}). Due to vandalism of the RB gauge in year 2, the precipitation values for SB were used.

Fig. 3. Variation in air temperature (solid lines) and precipitation (vertical bars) for years 1 and 2 (dark and light gray colors, respectively). Periods of above freezing (>0 °C) temperature are shaded light and dark gray for years 1 and 2, respectively. Closed circles indicate flooding events for years 1 and 2 (black and gray, respectively).

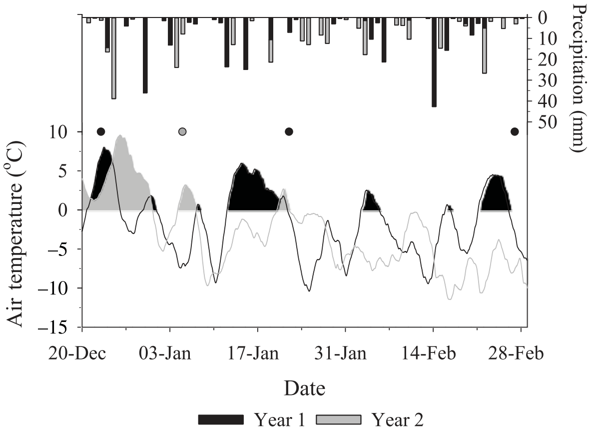
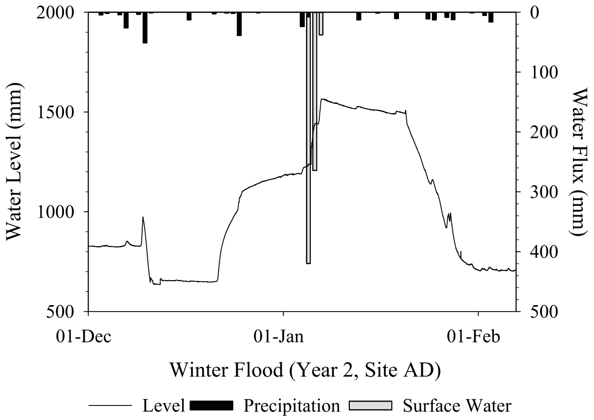


Fig. 4. Winter flood for site AD (year 2), including surface water level (referenced to the ditch bottom) and daily flow inputs of precipitation and surface water.



winter flood was at least partly associated with differences in air temperature between years 1 and 2. In the case of site SB, for example, year 1 included three winter floods that followed extended (5–10 d) periods of above freezing air temperature, whereas one winter flood was applied in year 2 as the result of colder and more constant air temperature (Fig. 3). Snow depth, which may provide vine protection and reduce the need for winter flooding, was 1438 mm in year 1 and 2167 mm in year 2. Generally, warm winters with low snowfall will serve to increase the demand for winter flooding in cranberry farms.

With respect to spatial (site-to-site) variation, the coefficient of variation about mean values of floodwater was, in year 1, 35% and 37% for harvest and winter floods, respectively, and, in year 2, was 67% and 34%, respectively. Precipitation falling onto the farms was relatively constant (Table 3), but variable groundwater inputs were suggested by the near twofold range in hydraulic head gradients across the farms (Masterson et al. 2009). Landscape features that regulate the hydraulic head gradient across bogs, such as peat morphology (Lowry et al. 2009; Hare 2015), may also control the flood holding capacity of bogs. Although not explicit, our results suggest that groundwater-fed cranberry farms with good water holding capacity may decrease the demand for winter flooding (e.g., Fig. 4).

Renovated farms commonly incorporate land from outside the spatial footprint of peat bogs (Kennedy et al. 2015), but differences in mean values of floodwater (harvest, winter, and both) were not related to farm renovation (renovated vs. conventional farms, $P = 0.62$). This finding may be related to external variables, such as water-quality regulations, that confound general relationships between farm renovation and water use (MassDEP 2012).

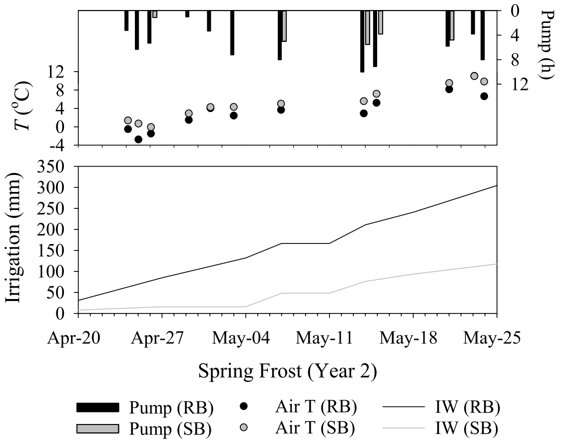
Crop and frost irrigation

Crop irrigation is best viewed as a combination of growing season irrigation and precipitation, as the latter plays a critical role in the evaporative demand of the plant. Crop irrigation (irrigation plus precipitation) ranged from 421 to 757 mm yr^{-1} across all sites and both years, with mean values (±1 standard deviation) of 568 ± 112 and 515 ± 115 mm yr^{-1} for years 1 and 2, respectively. These values were slightly higher than the evaporative demand for cranberry reported by Vanderleest and Bland (2017), which showed average daily evapotranspiration (ET) of 4.2 mm day^{-1} (~440 mm for the growing season). Lower precipitation increased sprinkler irrigation by 4%–33% between years 1 and 2 for all sites with the exception of site RB, which exhibited a one-third decrease in sprinkler irrigation between years 1 and 2. In the case of site RB, a soil tensiometer was installed in year 2 for soil moisture management, whereas conventional approaches (i.e., visual inspection of the soil) were used for irrigation management in year 1. Soil tension values, which were relatively constant compared to site SB, suggested upwelling groundwater that likely lowered the demand for additional sprinkler irrigation. As a result, the use of soil tensiometers lowered the crop irrigation requirement, possibly reducing fuel costs (Ndlovu 2015) and improving crop production (Lampinen and DeMoranville 2003).

Spatial variation in the water requirement for frost irrigation exceeded that for crop irrigation and flooding (90% and 43% for years 1 and 2, respectively). For the study sites, single-factor analysis showed that differences in the mean frost irrigation requirement were related to cultivar type (Stevens vs. Howes and Early Black; $P = 0.10$) but not to irrigation management (cycled vs. conventional; $P = 0.25$; Table 1).

Variation in environmental conditions, particularly air temperature, exerted a strong control on the water requirement for frost protection. For sites RB and SB, which were similar in most respects (i.e., managed by the same grower with the same frost tolerance thresholds), spring frost irrigation was 189–255 mm higher for site RB than site SB. Because of the location of site RB, frost nights were longer and colder requiring greater spring frost irrigation compared with site SB (Fig. 5). As a means of reducing water use at site RB, irrigation pumps could be started and stopped ("cycled") at programmed temperature set points, a practice shown to reduce frost irrigation by 35% (Ndlovu 2015).

Fig. 5. Air temperature (T) for sites RB and SB (closed circles), and pump run times for sites RB and SB (bars). Cumulative irrigation volume for the spring frost season for sites SB and RB (lines).



Water use area threshold

In Massachusetts, "old bog" farms in excess of 1.89 ha are required to apply for a water permit, whereas the water use area threshold of 3.78 ha is about two times higher for "new bog" constructions. Using the formulation under the Water Management Act, we calculated hypothetical water use area thresholds for the five sites (Table 3). Results showed a wide range in values of the area threshold, spanning from 1.80 to 4.93 ha. Mean values of the area threshold increased from 2.92 ha in year 1 to 3.43 ha in year 2, but differences between mean annual values were not statistically significant at 90% confidence ($P = 0.42$; Table 3). Although renovations that include leveling peat bogs can significantly reduce water use for flooding, variation in the water use area threshold was not related to farm renovation ($P = 0.62$).

Conclusion

Across the five sites, the annual water requirement for the production of cranberries ranged from 1459 to 3184 mm yr^{-1} (Table 3). Based on state-mandated permitting requirements, the area threshold for cranberry ranged from 1.80 to 4.93 ha with a mean value of 3.15 ha. Although highly variable, the calculated mean area threshold was within ~20% of the "new bog" area threshold value of 3.78 ha (9.33 acre) (USDA-NRCS 1988), which is currently used to guide agricultural water regulations in Massachusetts.

Generally, differences in the area threshold were related to spatial and temporal variations in the water applied for flooding, with the harvest and winter flood combining for 779–2475 mm yr^{-1} (mean = 1440 mm yr^{-1}). The water requirement for the winter flood, which decreased up to 73% between years 1 and 2, was related to the number of flooding events and controlled by extreme temperature fluctuations (Fig. 5). In contrast, annual variation in the water requirement for the harvest flood was relatively low (range = 7%–60%; mean = 20%). The annual variation in the harvest flood was less than 18% for all sites except for site AD. In the case of site AD, half of the bog was harvested in September and half in October, which significantly increased the size and variation of its agricultural water requirement (Table 3). Although included in all water use calculations, site AD, specifically its harvest flooding practices, is not represenative of most bogs in Massachusetts.

Sprinkler irrigation for frost protection and crop production accounted for, on average, one-fourth of the annual water requirement (sprinkler irrigation plus growing season precipitation accounted for one-third of the water requirement). Water requirements for spring frost protection were significantly related to cultivar type, as would be expected based on the critical temperature (i.e., frost tolerance) for different cranberry varieties (DeMoranville 2008*b*). Crop irrigation generally increased with decreasing growing season precipitation with the exception of site RB, which displayed the opposite trend (i.e., decreases in crop irrigation with decreasing precipitation). In the case of site RB, adoption of an automated soil moisture management system was associated with a lower crop irrigation requirement.

Acknowledgements

Material presented here is based on work supported in part by NESARE grant LNE12-316. Cooperation of Massachusetts cranberry growers is gratefully acknowledged. A very special thanks to Jim McLaughlin (Massachusetts Department of Environmental Protection) who provided an earlier review of the manuscript. The helpful comments of two anonymous reviewers are also gratefully acknowledged.

Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture (USDA). USDA is an equal opportunity provider and employer. It prohibits discrimination in all its programs and activities on the basis of race, color, national origin, age, disability, and where applicable, sex, marital status, familial status, parental status, religion, sexual orientation, genetic information, political beliefs, reprisal, or because all or part of an individual's income is derived from any public assistance program. (Not all prohibited bases apply to all programs.) Persons with disabilities who require alternative means for communication of program information (Braille, large print, audiotape, etc.) should contact USDA's TARGET Center at (202) 720-2600 (voice and TDD). To file a complaint of discrimination, write to USDA, Director, Office of Civil Rights, 1400 Independence Avenue, S.W., Washington, D.C. 20250-9410, or call (800) 795-3272 (voice) or (202) 720-6382 (TDD).

References

Bonin, S. 2009. Régie agroenvironnementale de l'irrigation en production de canneberges (*Vaccinium macrocarpon* Ait.). M.S. thesis, Université Laval, Department of Soil and Food Engineering, Québec City, QC.

Caron, J., Bonin, S., Pepin, S., Kummer, L., Vanderleest, C., and Bland, W.L. 2016. Determination of irrigation set points for cranberries from soil- and plant-based measurements. Can. J. Soil Sci. **96**(1): 37–50. doi:10.1139/cjss-2015-0037.

DeMoranville, C.J. 2008*a*. Flood management. Pages 66–71 *in* C.J. DeMoranville and H.A. Sandler, eds. Cranberry production: a guide for Massachusetts. University of Massachusetts Publication, East Wareham, MA.

DeMoranville, C.J. 2008*b*. Frost management. University of Massachusetts Publication, East Wareham, MA.

Deubert, K.H., and Caruso, F.L. 1989. Bogs and cranberry bogs in southeastern Massachusetts. University of Massachusetts Cranberry Experiment Station, East Wareham, MA. 31 pp.

Eck, P. 1990. The American cranberry. Rutgers University Press, New Brunswick, NJ. 420 pp.

Gee, G.W., and Bauder, J.W. 1986. Particle-size analysis. Pages 383–411 *in* A. Klute, ed. Methods of soil analysis, part 1 physical and mineralogical methods. 2nd ed. Agronomy Monograph 9 SSSA and ASA, Madison, WI.

Gilmore, B.A. 1987. Cranberry water threshold calculation, G.A.F Engineering, Inc., prepared for the Cape Cod Cranberry Growers (obtained from James McLaughlin, Mass. Department of Environmental Protection, August 2015).

Hare, D.K. 2015. Hydrogeological control on spatial patterns of groundwater seepage in peatlands. M.S. thesis, University of Massachusetts Amherst, Amherst, MA. [Online]. Available: http://scholarworks.umass.edu/cgi/viewcontent.cgi?article=1161&context=masters_theses_2.

Heiner, B.J., and Vermeyen, T.B. 2012. Laboratory evaluation of open channel area-velocity meters. U.S. Bureau of Reclamation, Denver, CO. 15 pp.

Johnson, A.I. 1967. Specific yield: compilation of specific yields for various materials, Report Rep. 1662D, Washington, D.C., USA.

Jeranyama, P., DeMoranville, C., and Waddell, J. 2014. Using canopy temperature, soil tension and moisture measurements as tools in cranberry irrigation. Proc. 10th Int. Symp. on Vaccinium and Other Superfruits Acta Horticulturae (ISHS) **1017**: 487–492.

Kennedy, C.D. 2015. Hydrologic and nutrient response of groundwater to flooding of cranberry farms in southeastern Massachusetts, USA. J. Hydrol. **525**: 441–449. doi:10.1016/j.jhydrol.2015.02.038.

Kennedy, C.D., Buda, A.R., Kleinman, P.J.A., and DeMoranville, C. J. 2015. Chemical and isotopic tracers illustrate pathways of nitrogen loss in a cranberry bed. J. Environ. Qual. **44**: 1–7. doi:10.2134/jeq2014.12.0549. PMID:26437115.

Lampinen, B.D., and Demoranville, C.J. 2003. Effect of irrigation and sand application on cranberry growth and yield. Hortscience, **38**(3): 483. [Abstr.].

Lowry, C.S., Fratta, D., and Anderson, M.P. 2009. Ground penetrating radar and spring formation in a groundwater dominated peat wetland. J. Hydrol. **373**(1–2): 68–79. doi:10.1016/j.jhydrol.2009.04.023.

MassDEP. 2012. Final total maximum daily load of total phosphorus for White Island Pond Plymouth/Wareham, MA. TMDL Report MA95166-201009-1 CN 3302. [Online]. Available: http://www.mass.gov/eea/agencies/massdep/water/watersheds/total-maximum-daily-loads-tmdls.html#2.

Masterson, J.P., Carlson, C.S., and Walter, D.A. 2009. Hydrogeology and simulation of groundwater flow in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts, Scientific Investigations Report 2009-5063. 110 pp.

Ndlovu, F. 2015. Evaluation of spring frost damage control methods and an assessment of cold hardiness in cranberry (*Vaccinium macrocarpon* Ait.). Ph.D. dissertation, University of Massachusetts, Amherst, Amherst, MA.

Storer, D.A. 1984. A simple high sample volume ashing procedure for determining soil organic matter. Commun. Soil Sci. Plant Anal. **15**: 759–772. doi:10.1080/00103628409367515.

USDA-NASS. 2014. Cranberry area harvested and yield, 2014. National Agricultural Statistics Database. USDA National Agricultural Statistics Service, Washington, DC. [Online]. Available: http://usda.mannlib.cornell.edu/usda/current/NoncFruiNu/NoncFruiNu-01-23-2015.pdf.

USDA-NRCS. 1988. Water conservation and utilization study, southeastern Massachusetts. U.S. Department of Agriculture, Natural Resources Conservation Services (formerly Soil Conservation Service), in cooperation with the Commonwealth of Massachusetts Division of Water Resources. 34 pp.

Vanderleest, C.P.L., and Bland, W.L. 2017. Evapotranspiration from cranberry compared with the equilibrium rate. Can. J. Soil Sci. **97**. This issue. doi:10.1139/cjss-2015-0093.

WMA. 1986. Water Management Act. [Online]. Available: https://malegislature.gov/Laws/GeneralLaws/PartI/TitleII/Chapter21G.