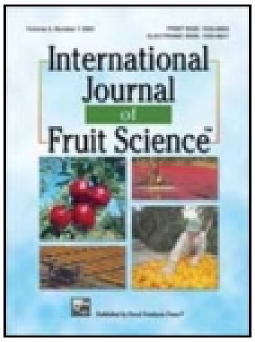

International Journal of Fruit Science

ISSN: 1553-8362 (Print) 1553-8621 (Online) Journal homepage: www.tandfonline.com/journals/wsfr20

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To cite this article: J. F. Hunt, C. W. Honeycutt & D. Yarborough (2010) Effect of Pine Bark Mulch on Lowbush Blueberry (*Vaccinium angustifolium*) Water Demand, International Journal of Fruit Science, 10:4, 390-415, DOI: 10.1080/15538362.2010.530117

To link to this article: https://doi.org/10.1080/15538362.2010.530117

International Journal of Fruit Science, 10:390–415, 2010

ISSN: 1553-8362 print/1553-8621 online
DOI: 10.1080/15538362.2010.530117

Effect of Pine Bark Mulch on Lowbush Blueberry (*Vaccinium angustifolium*) Water Demand

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*Mulching has been reported to moderate soil temperatures, lessen the erosive effects of rain, suppress weeds, and reduce evapotranspiration losses from crops worldwide. Lowbush blueberry (*Vaccinium angustifolium*) growers seeking an alternative and/or a complement to supplemental irrigation require accurate crop-specific information on the water conserving benefits of mulch. Twenty-eight weighing lysimeters equipped with soil moisture monitors were used at five sites throughout the Downeast Region of Maine to compare water budgets of lowbush blueberry grown on un-mulched and mulched soils. Despite occurrence of the second wettest growing season in 60 years, April through September mean hourly soil water potential values at all sites indicated significantly ($p < 0.001$) drier conditions in un-mulched compared with mulched soils. Differences in soil water potential values between un-mulched and mulched soils were much more pronounced during three dry periods, totaling approximately 53 days, than during the 2009 growing season as a whole. Over the course of one 27 day dry-period, soil water potential values of un-mulched soils at two lysimeter stations indicated a need for irrigation more than 60% of the time, compared with 7–10% of the time for mulched soils. Mulching was found to reduce diurnal*

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fluctuations of both soil water potential and volumetric water content. Early morning water deposition was significantly reduced by mulching at nearly all lysimeter stations; however, mulch-associated reductions in peak-hour evapotranspiration losses more than compensated for lower water inputs from dew and fog. During the three major periods of dry conditions, mulch reduced the evapotranspiration rate by an average of 0.045 ± 0.003 cm/day at three crop-rotation fields and 0.039 ± 0.027 cm/day at four prune-rotation fields. The greater variability in evapotranspiration rate reduction found among prune-rotation fields was considered due to differences in pruned shoot emergence from the mulch. These results indicate that mulching represents a viable method for alleviating drought-induced water stress for lowbush blueberry in Maine.

KEYWORDS *water, drought, mulch, irrigation, blueberry,* Vaccinium angustifolium

INTRODUCTION

Lowbush blueberry production is an integral part of Maine's agricultural heritage and an important contributor to the state's economy, generating more than $80 million (U.S.) in direct revenue in 2007 alone (University of Maine, 2009). Lowbush blueberry production in Maine occurs on approximately 24,300 ha (60,000 ac) of naturally acidic soils ranging from the southwestern foothills to the mid-coastal regions of the state. Maine's climate is humid, with mean annual precipitation typically exceeding 110 cm (Boone, 1997). However, variability in the timing of rainfall often does not allow for optimal growth of lowbush blueberry. Supplemental irrigation and water conserving practices, such as mulching, represent important opportunities for improving the profitability of Maine's lowbush blueberry industry.

Mulching has been shown to reduce evaporative soil water loss by both moderating soil temperatures, and by providing a physical barrier between the soil surface and the atmosphere (Swanson and Calkins, 1995; Monks et al., 1997; Pickering et al., 1998; Chen et al., 2007). Although there are few restrictions on the kinds of materials that may be used for mulch, it is nevertheless advisable to evaluate the effects of novel mulch before widespread use. Kroggman et al. (2008) found that mulch consisting of waste cranberry leaves and fruit actually reduced the yield and leaf nitrogen content of the New Jersey highbush blueberry. In Maine, the ready availability of wood products, such as bark, sawdust, and wood chips, has made these materials the traditional mulch of choice for lowbush blueberry. Wood product mulches have been shown to suppress weeds and reduce the incidence of frost heaving in lowbush blueberry fields (Smagula and Goltz, 1988). Research has also shown that wood product mulches facilitate the spread of lowbush blueberry rhizomes and aid in the recovery of areas made bare by erosion (Kender and Eggert, 1966; Grant et al., 1982). This can be particularly important where efforts to control weeds with herbicides have increased erosion susceptibility (University of Maine, Wild blueberry fact sheet #221).

In this study, we investigated the effect of pine-bark mulch on the water budget of lowbush blueberry at five sites in Downeast Maine. Weighing lysimeters were used to determine differences in evapotranspiration (ET) rates between mulched and un-mulched lowbush blueberry plots. In addition, soil water was monitored using hourly automated tensiometer and time domain reflectometer (TDR) measurements. We hypothesized that pine-bark mulching over lowbush blueberry would increase soil water availability by: (a) reducing evaporative losses from the soil and (b) increasing the amount of water added to the soil through dew deposition.

MATERIALS AND METHODS

Research Sites

Research on the effects of mulch upon lowbush blueberry water demand was conducted at seven lysimeter stations located at five different sites, varying in distance to the Maine coast from 0.8 km (∼0.5 mi.) to 25.7 km (∼16 mi.). One of the sites, Blueberry Hill Farm located in Jonesboro, ME, is an experimental farm operated by the University of Maine. Management practices at this farm, such as irrigation, pruning, and pesticide application, were controlled throughout the study period. The four sites located in Jonesport, Deblois, Northfield, and Addison were all privately owned, and thus subject to the management practices of their owners. The Deblois and Jonesboro sites each contained two weighing lysimeter stations (Airport and Smooth Plains) and (BBH1 and BBH2), while the Jonesport, Northfield, and Addison sites had one weighing lysimeter station each. Each weighing lysimeter station consisted of four weighing lysimeters installed several meters apart in a rectangular orientation around a central data logger (Starr and Yarborough, 2006; Hunt et al., 2009a). Sites at Jonesport, Jonesboro, and Deblois also contained weather stations to measure meteorological data parameters, such as air temperature, relative humidity, solar radiation flux, wind speed, precipitation, and visibility. In order to study the two-year lowbush blueberry production cycle, lysimeters were placed in fields containing both crop year and prune year plants.

The lysimeter stations at Jonesboro and Deblois were irrigated using raised sprinkler heads atop movable piping. Irrigation at the experimental farm in Jonesboro was applied when the average soil matric potential of the outside tensiometers decreased below −20 kPa, while irrigation at Deblois was based upon proprietary scheduling. Irrigation was applied three times at the Jonesboro stations and 8 times at the Deblois stations throughout the 2009 growing season.

Soils varied at the five sites, with root zone soil textures ranging from silty clay to loamy sand. The coarsest soil was found in Jonesport, the site closest to the coast (~0.8 km). Soils there are mapped as an Adams-Croghan complex (sandy, isotic, frigid Typic Haplorthods and sandy, isotic, frigid Aquic Haplorthods), with a lowbush blueberry root zone consisting of loamy sand for the upper 10 cm, that is underlain by sand. Soils at the two Jonesboro stations (~6.4 km from coast) are mapped as Colton gravelly sandy loams (sandy skeletal, isotic, frigid Typic Haplorthods) with 0% to 3% slopes. These soils are excessively drained and have a depth to water table of greater than 203 cm (80 in.). Soils at the Addison site (~8 km from coast) are a complex of Buxton silty clay loam (fine, illitic, frigid Aquic Dystric Eutrudept) and Lamoine silty clay (fine, illitic, nonacid, frigid Aeric Epiaquept) formed from glaciolacustrine and fine glaciomarine deposits. The Addison root zones are less well drained and have lower hydraulic conductivity than those at the other six sites. Soil at the two Deblois sites (~14 and 15 km from the coast) is classified as Marsardis sandy loam (sandy-skeletal, isotic, frigid Typic Haplorthods), and is considered to be somewhat excessively drained with moderately high permeability. Soils at the Northfield site, approximately 25.7 km from the coast, are classified as a complex of Hermon sandy loams (sandy-skeletal, isotic, frigid Typic Haplorthods) and Monadnock fine sandy loams (coarse-loamy over sandy or sandy-skeletal, isotic, frigid Typic Haplorthods). These soils were subject to occasional flooding due to their proximity to a nearby lake. The finer textured soils at Addison and Northfield were chosen to offer a contrast from the coarser soils at Jonesboro, Deblois, and Jonesport.

Weighing Lysimeters

The 28 weighing lysimeters used in this study were constructed as detailed by Storlie and Eck (1996) and Starr et al. (2004). Briefly, the lysimeter design featured a rectangular inner chamber constructed from 1.91 cm (0.75 in.) thick treated plywood inside an outer chamber frame constructed from 3.18 cm (1.25 in.) thick treated plywood. The inner chamber, containing soil and blueberry plants, rested upon a single ball-bearing that was centered atop a temperature-compensated weighing load cell. Outside surfaces of the inner chamber were treated with fiberglass cloth and resin. The inner chamber of each lysimeter had dimensions of 46 cm × 46 cm (18 in. × 18 in.) with a surface area of 0.21 m^2 (2.25 ft^2) and a depth of 44.5 cm (17.5 in.), giving a total internal volume of 0.94 m^3 (3.28 ft^3). Four small, rigid springs were positioned between the inner and outer chambers to prevent contact between the two chambers. A drainage collection system, consisting of perforated piping, was run from the bottom of the inner chamber to a carboy positioned in an access port adjacent to the outer chamber. Drainage was periodically measured to assess and monitor the water-holding capacity of each lysimeter. Lysimeter accuracy was tested periodically during each growing season using calibration weights, and errors in mass measurements were generally less than 2%.

Mulching

Approximately 7.6 cm (~3 in.) of one-year composted pine-bark mulch was spread evenly over the surfaces of two weighing lysimeters at each of the seven stations. Mulch applications were made over a two-day period (April 23–24) before appreciable new seasonal plant growth began. Mulch was spread between plants by hand, and care was taken to insure for the full emergence of stems from the mulch. At prune-year fields, mulch was applied immediately following the hand cutting of old stems close to the lysimeter surface.

Lysimeter Data Analysis

The 10 min changes in weight for each lysimeter were summed into hourly changes. Hourly changes in lysimeter weight at a particular site were then eliminated if site rain gauges indicated any precipitation for that hour, or alternatively, records indicated the application of irrigation for that hour. Elimination of these "rain hours," rather than entire "rain days" allowed the use of a much larger data set. In addition, inclusion of all days eliminated the bias of using only "dry" days of generally greater solar flux. As in all lysimeter studies, data associated with excessive drainage, site flooding, animal activity, or similar perturbations to the experimental conditions were eliminated from consideration. Hourly data not eliminated due to the above considerations were summed and averaged for the 24 hr of each day. If the difference between the sum and the average for any given day exceeded 15%, then the ET rate for that day was eliminated from consideration. This quality control criterion was followed to avoid using data with too many missing hours, which would result in calculation of an inaccurate daily ET rate.

Soil Water Measurements

Differences in soil water between the mulched and the un-mulched lysimeters were monitored at all sites by manually read tensiometers inserted to a depth of 7.6 cm (3 in.), the typical upper limit of the root zone of lowbush blueberry. At Smooth Plains, Kelly Point, Addison, and BBH, automated

Watermark soil moisture sensors were also used to take hourly soil water potential readings. As in the case of the tensiometers, these probes were also placed to a depth of approximately 7.6 cm (3 in.). Hourly data readings of soil water content, air temperature, and relative humidity were then recorded and stored on WatchDog data loggers. At BBH2, TDR was used to measure the volumetric water content of that station's lysimeter soils. Each lysimeter at BBH2 was equipped with one TDR probe that recorded data on a 20-min interval using a Campbell Scientific (Logan, Utah, USA) multiplexor/data logger combination.

RESULTS AND DISCUSSION

Weather and Evapotranspiration

Figure 1 compares the April through September 2009 growing season monthly precipitation totals at Blueberry Hill Experimental Farm (BBH) in Jonesboro, Maine, with 60-year mean monthly precipitation totals for the location. Precipitation totals for the months of June, July, and August were 130%, 97%, and 68% greater, respectively, in 2009 than the 60-year mean values for these months. Overall precipitation for the 2009 growing season totaled 91.4 cm, which was nearly 60% greater than the 60-year growing season mean of 57.2 cm. Solar flux rates during the months of May, June, and July were 10.3%, 15.7%, and 29.1% lower in 2009 than the mean values for

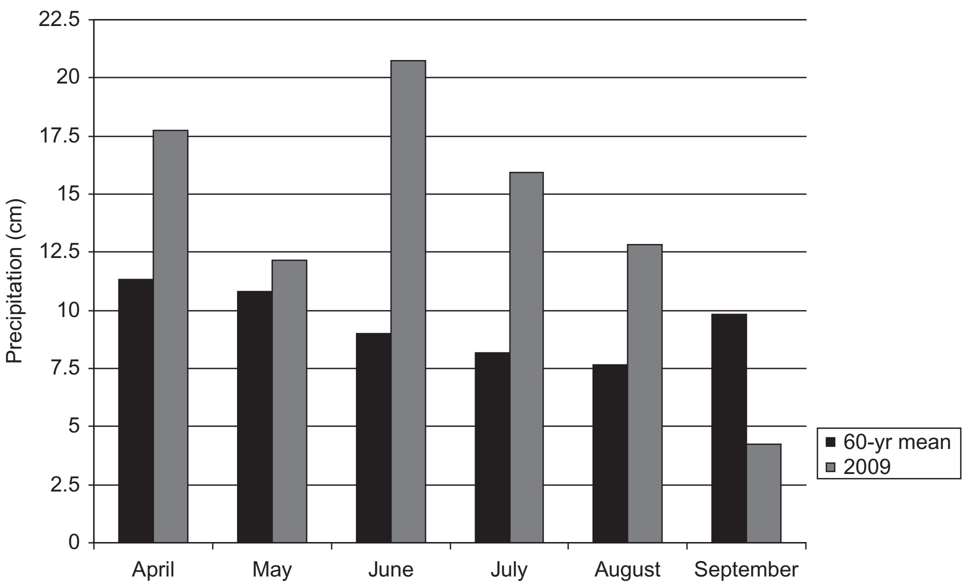

FIGURE 1 Comparison of 2009 monthly precipitation totals with 60-year mean monthly totals for Blueberry Hill Experimental Farm, Jonesboro, Maine.

TABLE 1 Comparison between 2009 and 2005–2008 Mean Monthly Reference Evapotranspiration (ET_o) Rates (cm/wk) at Blueberry Hill Experimental Farm, Jonesboro, Maine

Month	2005–2008[z]	2009[z]
April	1.94 (0.76)	1.60 (0.63)[y]
May	2.31 (1.00)	2.01 (0.83)
June	2.71 (1.25)	2.23 (0.87)[y]
July	3.21 (1.10)	2.35 (0.88)[y]
August	2.68 (1.02)	2.31 (0.99)
September	1.94 (0.76)	1.70 (0.51)[y]

[z]Standard deviations from mean values are given in parentheses.
[y]Designates significant monthly differences between 2009 values and those of 2005–2008 using Student's *t*-test.

these months during the previous four-year period (2005–2008) for which this data was collected. Table 1 illustrates how the lower solar flux rates impacted the Penman-Montief reference evapotranspiraton rates (Ref. ET) at BBH for 2009. Reference ET rates in 2009 were significantly lower ($p < 0.05$) for the months of April, June, July, and September than for the same months during 2005–2008. In particular, the combination of lower solar flux rates and higher than normal precipitation amounts in 2009 decreased June and July reference ET rates at BBH by nearly 40% compared to the mean values for those months from the 2005–2008 time period. The cooler and wetter weather conditions led to lower soil water evaporative potential for Maine lowbush blueberry throughout much of the 2009 growing season. Because the reduction of soil surface water evaporation is believed to be the most important effect of mulching on water demand, mulch engendered water savings in 2009 might be expected to be lower than normal (Steiner, 1989).

The weighing lysimeters employed in this study were designed to function best in normal to dry conditions. One reason for this limitation was the inherent difficulty of determining water losses from our weighing lysimeters when water inputs to them were occurring simultaneously. In addition, the relatively low water-holding capacity of the weighing lysimeters employed also caused difficulties in quantifying drainage losses when additional water was added to already saturated lysimeters. Calculations of the actual ET rate, therefore, excluded hours during which rainfall, irrigation, and/or drainage took place. Due to the absorbent nature of the pine bark, mulched lysimeters during wet conditions tended to retain more water above the soil surface while losing less water through drainage. This mulched-trapped water was then more available for surface evaporation than soil infiltrated water. Evaporation of this retained water was then likely to be quantified as ET, rather than drainage, resulting in higher apparent ET rates from mulched lysimeters relative to un-mulched lysimeters under very wet conditions.

Conversely, under very dry conditions, mulched soils had sufficient available water to meet plant and atmospheric demands, while un-mulched soils did not. This again led to higher ET rates from mulched lysimeters than from un-mulched lysimeters. As in the previous case, however, such results can be misleading. Rather than indicating that mulched soils lose more water under dry conditions than un-mulched soils, such results are, in fact, a verification of the effectiveness of mulch in retaining moisture. Hence, the mulched soils had more water available during very dry-periods than the un-mulched soils, and were subsequently better able to meet ET demands during these times. These results are consistent with the work of Unger and Wiese (1979) who reported that evaporation (E) from bare soils exceeded that from wheat mulched-soils for 15 days before the trend reversed for the final 20 days of the study due to insufficient soil moisture in the bare soils. Evaporation from a wetted soil has long been thought to be initially dependent upon evaporative potential and later, as available soil moisture decreases, upon soil diffusivity (Ritchie, 1972; Idso et al., 1974; Van Bavel and Hillel, 1976). It is during this latter stage of E that the water savings imparted by mulch are particularly important.

Figure 2 illustrates the effect of these varying soil moisture conditions on actual ET rates at the Smooth Plains lysimeter station from July 24 to August 20, 2009. The cool and rainy conditions at the beginning of that 28-day period are reflected in higher ET rates from mulched compared to un-mulched soils. Drying soil conditions over days 6 and 7 eventually produced a shift in ET, with water losses from un-mulched soils overtaking those from mulched soils. This period of mulch-engendered water savings lasted approximately 15 days, during which time mean daily high air temperature

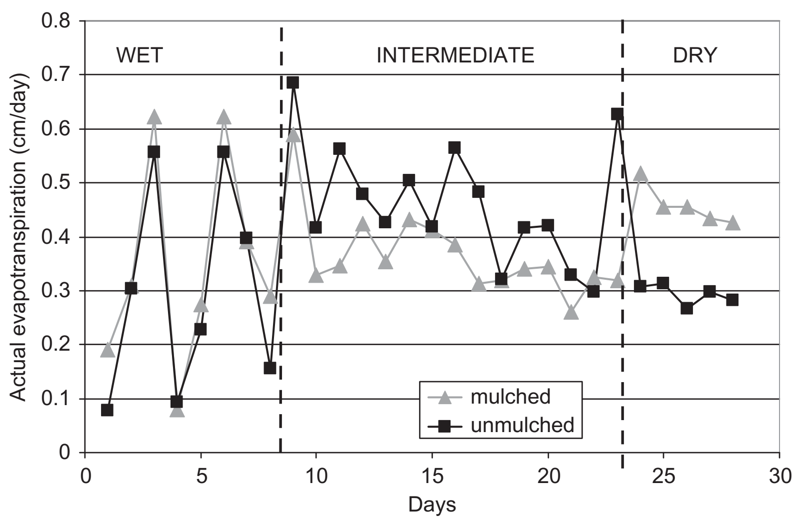

FIGURE 2 Illustration of the effect of soil and atmospheric conditions on the mean actual ET rates of mulched and un-mulched lysimeters from July 24 to August 20, 2009, at Smooth Plains, Deblois, Maine.

(max AT) and weekly Ref. ET rate were 26.4°C (80°F) and 3.61 cm/week (1.42 in./wk), respectively. Available water in the un-mulched soils eventually became limiting by day 24, and another ET trend reversal occurred. Continued hot and dry weather conditions (30.9°C max AT, 3.96 cm/wk Ref ET) over the last 5 days of the period shown resulted in much higher ET rates from mulched soils than un-mulched soils. Again, these higher mulched ET rates reflect moisture conserved during the previous 15 days; moisture that was subsequently available to meet atmospheric and lowbush blueberry water demand.

In addition to illustrating the factors influencing lysimeter-determined ET rates, Figure 2 also shows that while cooler and wetter weather conditions dominated the 2009 growing season in Maine, opportunities existed for studying the effect of mulch on soil water evaporation. These opportunities took the form of three periods of generally moderate conditions, totaling approximately 53 days that occurred at each of the five study sites during the 2009 growing season. Table 2 shows the dates of the periods for each site, along with their associated total precipitation amounts and mean daily Ref. ET rates. In some cases, the timing of the periods differed slightly according to geographic location, but all periods ended immediately before the onset of a large precipitation event. Reference ET rates at each site generally varied according to coastal proximity, with more inland sites having slightly higher values for this weather-related parameter due to greater mean temperatures and solar flux inputs (Hunt et al., 2009b).

Soil Water

Table 3 shows a full season (May through September) summary of hourly mean soil water potential differences from the five lysimeter stations. For all stations, the mulched lysimeter soils had significantly ($p < 0.001$) higher mean soil water potential values than did the un-mulched soils. Overall, mean soil water potential values were nearly 65% more negative in the un-mulched lysimeters than in the mulched lysimeters. The high standard deviations associated with each mean value in Table 3 reflect the wide range of soil moisture conditions present throughout the growing season at each station.

TDR was also used at the BBH2 lysimeter station as a means of monitoring the relationship between actual water content and soil water potential. From May 1 through September 30, 2009 (3,637 hr) mean hourly soil water content at BBH2 was significantly ($p < 0.001$) greater in the mulched lysimeters (24.2%) than in the un-mulched lysimeters (23.6%). Despite the significant differences between mulched and un-mulched systems in the whole season results for both soil water potential and soil water content, such data sets include large periods of nearly homogeneous, near-saturated conditions. To better illustrate the degree to which pine-bark mulch reduced

TABLE 2 Weather Conditions for 2009 Dry Periods at Five Sites in Downeast Maine

Period Characteristics	Jonesport Kelly Pt. (Prune)	Jonesboro BBH1 (Prune), BBH2 (Crop)	Addison (Crop)	Deblois Smooth Plains (Crop), Airport (Prune)	Northfield[y] (Prune)
Period 1:	June 3–9	June 3–9	June 3–9	June 3–9	NA
Mean daily Ref. ET (cm)	0.46	0.38	0.37[z]	0.46	NA
Precipitation (cm)	0	0	0	0	NA
Period 2:	August 4–22	August 4–22	August 5–22	August 2–21	August 4–22
Mean daily Ref. ET (cm)	0.42	0.43	0.41[z]	0.49	0.54[z]
Precipitation (cm)	0	0.05	0.08	0.18	0
Period 3:	Sept. 1–24	Sept. 1–26	Aug. 30–Sept. 26	Sept. 1–26	Aug. 30–Sept. 26
Mean daily Ref. ET (cm)	0.24	0.27	0.30[z]	0.32	0.41[z]
Precipitation (cm)	1.04	1.07	1.35	1.07	1.40

[z]Due to a lack of solar flux data, reference ET is estimated based upon available weather data.
[y]The Northfield site was flooded during period 1 and therefore no data was collected there at that time.

TABLE 3 Summary of Mean Soil Water Potential Differences between Mulched and Un-Mulched Weighing Lysimeters from April 1 to September 30, 2009, for Five Sites in Downeast Maine

Site	Mulched soil water potential (cb)[z]	Un-mulched soil water potential (cb)[z]	Number of total data hours
Addison (Crop)	7.7 (7.7)	11.0 (8.9)[y]	3,144
BBH 1 (Prune)	8.1 (10.8)	14.4 (18.3)[y]	3,625
BBH 2 (Crop)	5.8 (5.9)	9.9 (8.4)[y]	3,646
Kelly Point (Prune)	6.6 (9.5)	12.0 (13.5)[y]	3,341
Smooth Plains (Crop)	5.1 (12.3)	7.4 (17.5)[y]	3,472

[z]The values in parentheses represent standard deviation from the mean values.
[y]Represent significant differences ($p < 0.001$) between the mulched and un-mulched means for each site using Student's *t*-test.

soil water loss rates during the 2009 growing season, a closer examination of the three soil drying periods is necessary.

DRY-PERIOD 1

Figure 3 shows the soil water potential curves for the crop-year lysimeter stations during dry-period 1. Water potential values correspond to the amount of energy required to remove water from the surrounding soil matrix, with more negative values reflecting drier conditions. Finer textured soils, such as the silty clay loams of Addison hold a greater volume of water than do the coarser sandy loams of BBH2 and Smooth Plains. However, finer soils also hold water more tightly than do coarse soils, resulting in a compromise between water storage and water availability. In practice this means that plant-available water in the Addison soils is sufficiently reduced to require irrigation at potential values below −35 kPa, while the soils of BBH2 and Smooth Plains warrant irrigation when water potential values fall below −20 kPa. Therefore, during dry-period 1, the water potential values of the un-mulched lysimeter soils at Addison and Smooth Plains are indicative of non-critical drying conditions, while those at BBH2 indicate a need for irrigation.

The lower water potential values at Smooth Plains relative to BBH2 were the result of three irrigation applications at Smooth Plains between hours 10 and 70, and therefore, do not reflect inherent differences in water holding capacities between the sites. The stabilizing effect of mulch during soil drying cycles is evident from the magnitude of differences in diurnal fluctuations between mulched and un-mulched lysimeters at Addison. Although less obvious at BBH2 and Smooth Plains during dry-period 1, differences in diurnal fluctuations between un-mulched and mulched water potential curves are strongly evident during subsequent dry-periods.

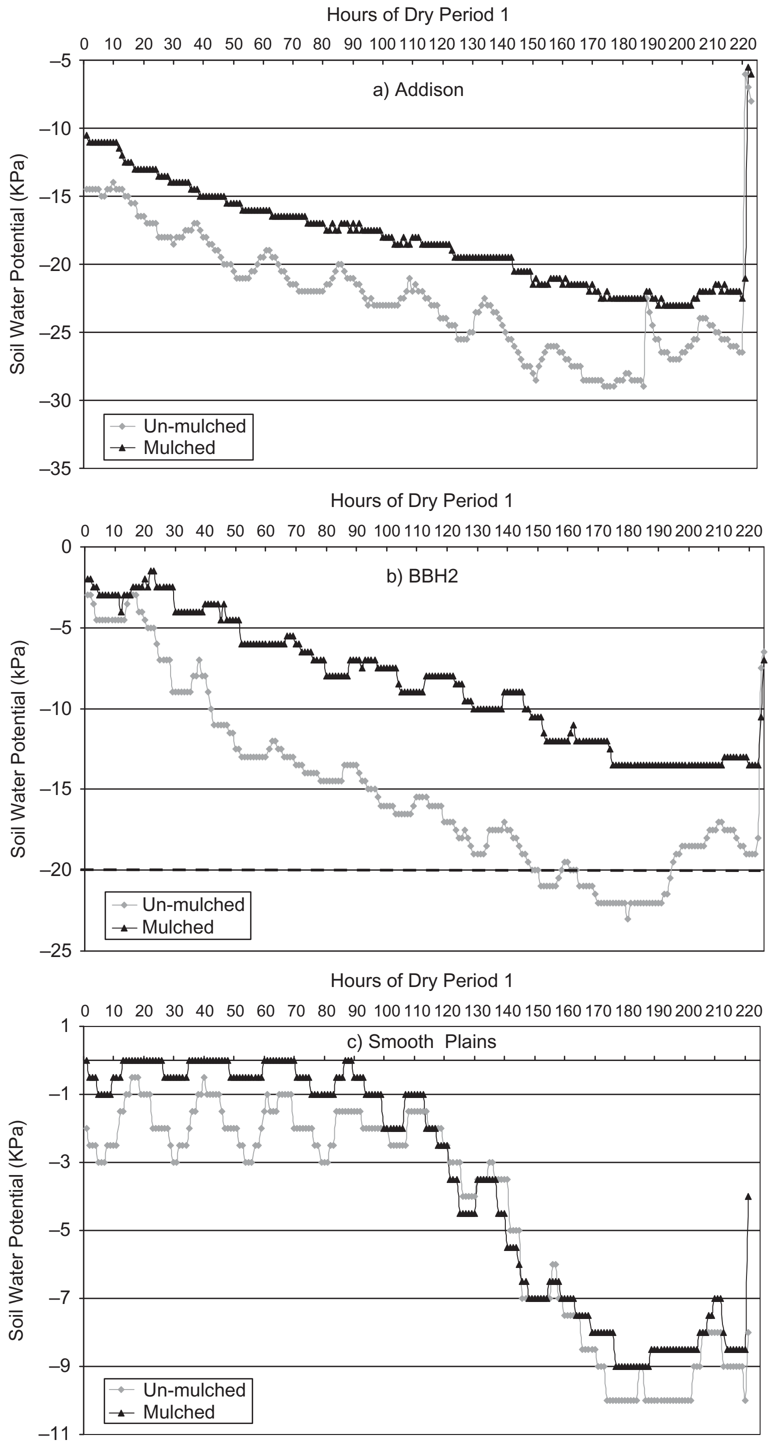

FIGURE 3 Soil water potential curves at crop-year lysimeter stations in (a) Addison, (b) Blueberry Hill, and (c) Smooth Plains during dry period 1 (June 3–12, 2009).

The effect of mulching on water savings during dry-period 1 was best illustrated at BBH2 where a lack of irrigation allowed soil drying to progress unabated. The first dry-period at BBH2 lasted approximately 225 hr from June 4–12. As can be seen from Figure 3, at no point during dry-period 1 did the mean soil water potential in the mulched lysimeters decrease below −15 kPa. In contrast, mean soil water potential in the un-mulched lysimeters declined to less than −20 kPa for 45 hr. Two precipitation events eventually ended this dry-period. The first event, much lighter than the second, began at approximately hour 191 and deposited 0.25 cm (0.10 in.) of rain on the site. As Figure 3b illustrates, tensiometers in the un-mulched lysimeters responded immediately by increasing from approximately −22 kPa to −17 kPa. Soil water potential in the mulched lysimeters remained relatively stable, increasing by only 1–2 kPa during this first precipitation event. Such attenuated responses to both heat and small amounts of precipitation are characteristic of mulched soils (Nath and Sarma, 1992). The physical barrier provided by mulch delays both water loss through evaporation as well as infiltration of small amounts of precipitation. Relatively small amounts of water intercepted and held by mulch, such as occurred at hour 191, may be more subject to evaporative loss before it infiltrates into soil. While mulched soils may not always benefit from small water inputs to the same extent as un-mulched soils, this is usually more than compensated for by the overall decrease in evaporative losses from mulched soils.

In contrast to the first precipitation event at BBH2, a uniform and rapid increase in soil water potential in both mulched and un-mulched lysimeters was observed following the second precipitation event, which began at hour 220 of the first dry-period and amounted to approximately 6.4 cm (2.52 in.) of rain. In this case, the precipitation was substantial enough to readily saturate the mulch and penetrate to the soil below. It is important to note that weather conditions at BBH during this short dry-period were typical for the location during early June. Maximum and mean hourly air temperatures recorded for the period were 22.8°C (73.0°F) and 13.1°C (55.6°F), respectively, while mean relative humidity was 70.4%, with near saturated air occurring each evening from the hours of about 11 PM through 7 AM. Despite the low evaporative potential of those conditions, the sandy loam soils typical of the blueberry growing region of Maine can dry rather quickly in the absence of precipitation or irrigation, as shown by the steep descent of the un-mulched mean soil water potential curve in Figure 3. By providing a physical barrier to the atmosphere and by moderating soil temperatures, mulch acts to significantly slow the drying process.

Figure 4 illustrates the stabilizing effect of mulch on the mean soil water content for the BBH2 lysimeter station during dry-period 1. Before the second precipitation event, mean volumetric water content of the un-mulched lysimeters varied 4.3% (between 22.8% and 18.5%), while that of the mulched lysimeters varied only 2.0% (between 25.0% and 23.0%). Thus,

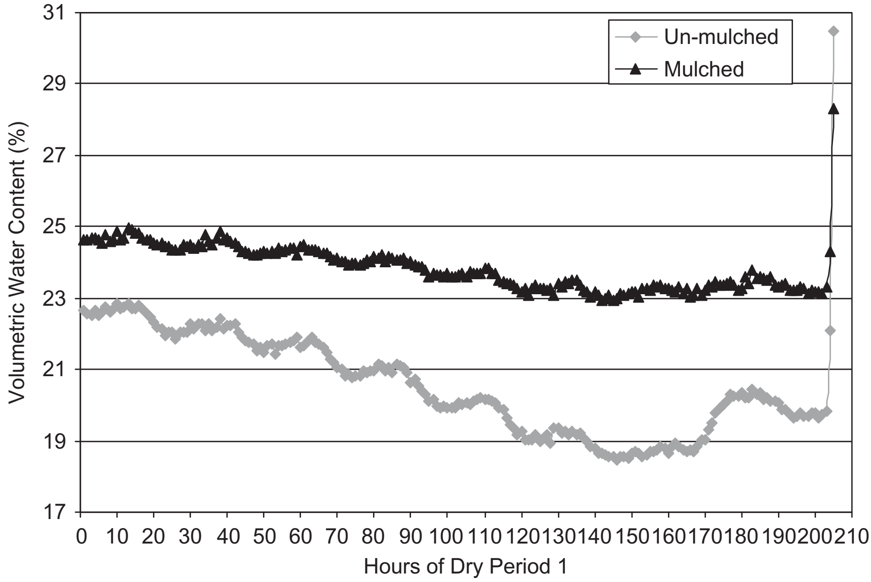

FIGURE 4 Volumetric water content of mulched and un-mulched weighing lysimeter soils at Blueberry Hill crop-year lysimeter station during dry period 1 (June 4–12, 2009).

during dry-period 1, mulched lysimeter soils at their driest had greater mean volumetric water content than un-mulched lysimeter soils at their wettest.

Dry-Period 2

Dry-period 2 lasted longer than dry-period 1 and produced higher mean daily Ref. ET rates at all sites than dry-period 1 or dry-period 3 (Table 2). It can, therefore, be expected that soil water stress was greater during dry-period 2 than at any other time during the 2009 growing season. Figure 5 illustrates the hourly mean soil water potentials of the crop-year stations during dry-period 2. As in dry-period 1, un-mulched soil water potential values at Addison were less than those of the mulched soils but remained slightly above the threshold value (-35 kPa) recommended for irrigation initiation at that site. In contrast, soil water potentials in the un-mulched soils of both BBH2 and Smooth Plains fell below −20 kPa by hour 200 of this period. Diurnal fluctuations in water potential were again more pronounced in the un-mulched than the mulched lysimeter soils at all sites. Due to both the coarseness of the soil and to a lack of irrigation at the site (BBH2 was irrigated three times during period 2), soil water potential differences between mulched and un-mulched soils were most extreme at Smooth Plains during this period. Although having soils similar in texture to those at BBH, Smooth Plains is located approximately 16 km further inland, and therefore,

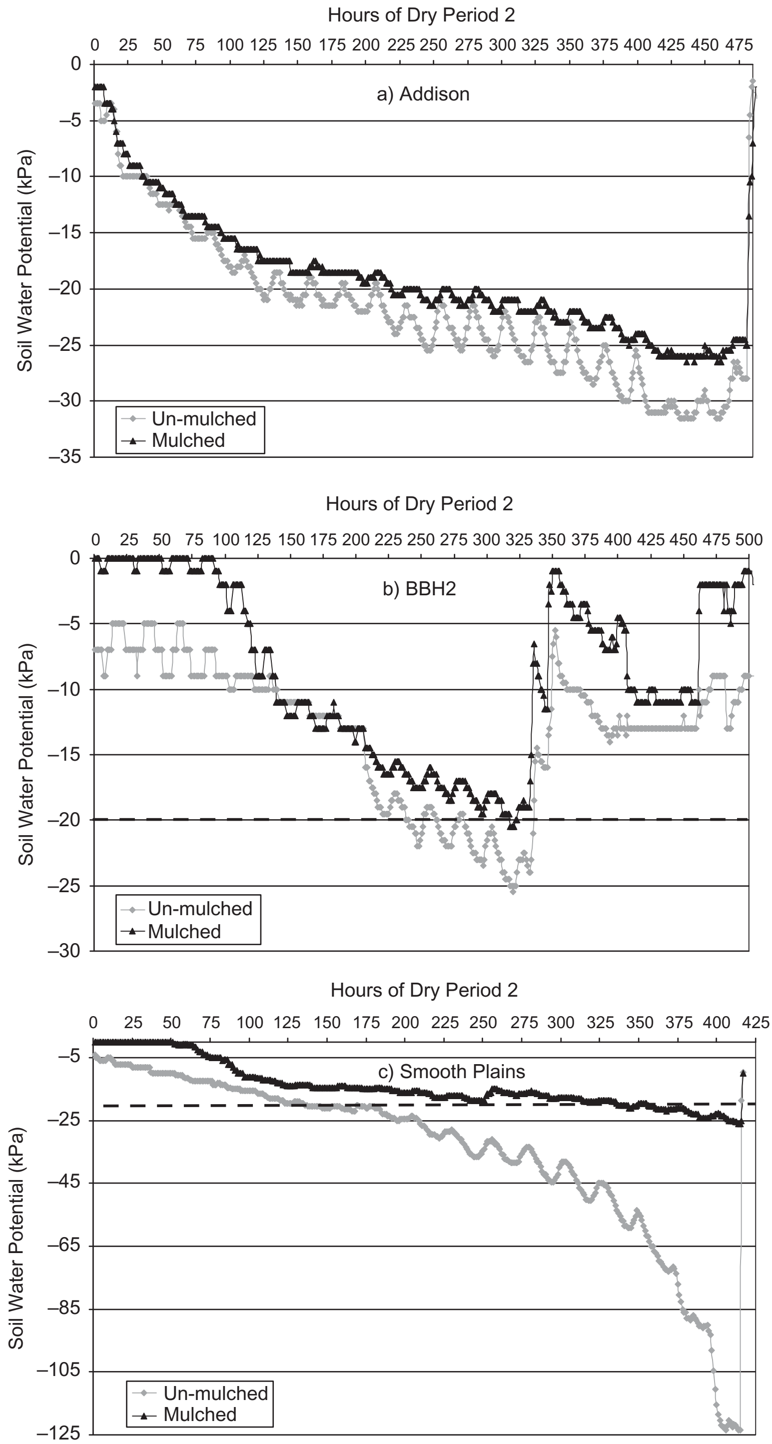

FIGURE 5 Soil water potential curves at crop-year lysimeter stations in (a) Addison, (b) Blueberry Hill, and (c) Smooth Plains lysimeter stations during dry period 2 (August 4–20 (22), 2009).

is subject to greater evaporative demand due to higher mean daily temperatures and solar flux rates (Hunt et al., 2009b). Soil water potential values at this site were less than −20 kPa for 277 hr in the un-mulched soils compared with only 79 hr in the mulched soils. In addition, minimum mean soil water potential reached −124 kPa in the un-mulched soils, compared with a minimum mean of −26 kPa in the mulched soils. In a sandy loam soil, −124 kPa is generally considered to be excessively dry, while −24 kPa is very near the −20 kPa benchmark water potential typically used for irrigation initiation (University of Maine, Fact sheet 631).

Figure 6 shows the volumetric water content at BBH2 for the first 420 hours of dry-period 2. Unlike at the Smooth Plains' lysimeter station where drying conditions were allowed to continue unabated, three irrigations of approximately 1.50 cm (0.60 in.) were performed at BBH 2 lysimeter station during the hours of 327–332, 344–349, and 457–463. The general patterns of soil drying as well as the effects of two of the three irrigations are apparent in Figure 6. By the conclusion of the period, the three irrigations had temporarily stabilized the mean volumetric water contents for both the mulched and the un-mulched lysimeter soils at approximately 22%. Prior to the irrigations, mean volumetric water contents had fallen to growing-season low values of 17.4% and 18.9% for the BBH 2 un-mulched and mulched lysimeter soils, respectively. In addition, the rates of decrease in mean volumetric water content were greater in the un-mulched lysimeter soils than in the mulched lysimeter soils. This suggests that in the absence of irrigation, the un-mulched soils at BBH2 would likely have continued to dry out at a greater rate than the mulched soils.

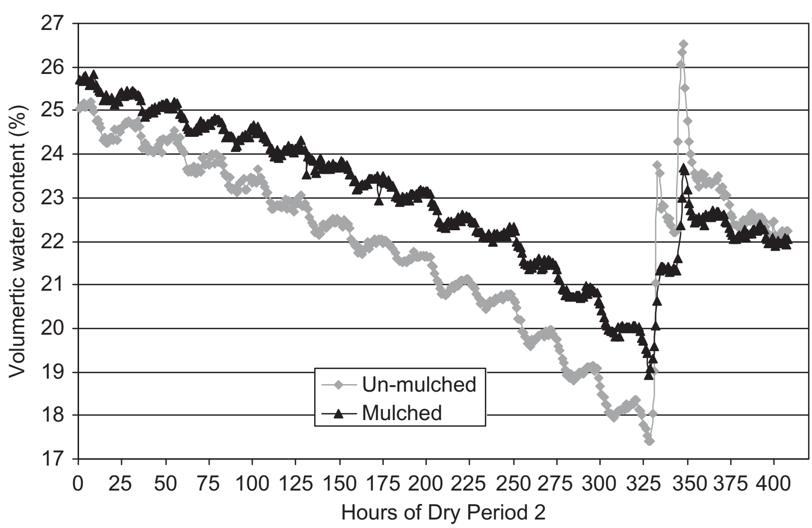

FIGURE 6 Volumetric water content of mulched and un-mulched weighing lysimeter soils at Blueberry Hill crop-year lysimeter station during dry period 2 (August 4–23, 2009).

Dry-Period 3

Similar differences in soil moisture characteristics between mulched and un-mulched lysimeter soils were once again observed at all sites during dry-period 3 (Figure 7). The lack of irrigation at Smooth Plains and BBH2 during this period resulted in comparable patterns in soil water potential at both sites. For the 662 hr of dry-period 3, soil water potential at Smooth Plains was less than −20 kPa for 433 hr (65.4%) in the un-mulched soils and 50 hr (7.6%) in the mulched soils. For BBH2, soil water potential was less than −20 kPa for 405 hr out of 669 hr (60.5%) in the un-mulched lysimeters and 67 hr (10.0%) in the mulched lysimeters. Mulch-related differences in diurnal fluctuations in water potential were again evident during this third dry-period. As in previous dry-periods, independent verification of water potential curves was provided by volumetric water content results at BBH2 station (Fig. 8).

Significant differences in soil water potential were found between mulched and un-mulched lysimeter soils at all five lysimeter stations equipped with hourly soil monitors during periods 2 and 3. Such soil moisture differences between mulched and un-mulched soils are consistent with results observed in other recent mulching studies (Zhang et al., 2009, Egrinya et al., 2008). Ramakrishna et al. (2006) reported soil water levels in un-mulched plots of groundnut following 10 consecutive rainless days to have been reduced from field capacity to below wilting point, while nearby plots mulched with wheat straw maintained soil water levels well above the wilting range.

Evapotranspiration Differences of Mulched and Un-mulched Lysimeters

Table 4 shows the water loss differences between mulched and un-mulched lysimeters at each of the seven stations during the three dry-periods of the 2009 growing season. Overall water savings for the crop-year fields of Addison, BBH2, and Smooth Plains averaged 0.043 cm (0.017 in.)/day, 0.048 cm (0.019 in.)/day, and 0.043 cm (0.17 in.)/day, respectively. These rates correspond to approximately 1.25 cm (~0.5 in.) of water savings per month for the crop-year fields during relatively dry conditions. Such water savings are comparable to the amount of water used for a typical single irrigation of lowbush blueberry. Recent studies have also shown significant water savings attributable to the use of mulch. In a micro-lysimeter study on the effect of mulch on evaporation from winter wheat on the North China Plain, Chen et al. (2007) found that 2–3 cm of chopped corn stalk material spread on the soil surface reduced whole season (6 month) evaporation by 5.6 cm (2.2 in.). Similarly, Zhang et al. (2009) reported mean soil water savings of 2.8 cm (1.1 in.) and 2.0 cm (~0.8 in.) using approximately 2 cm

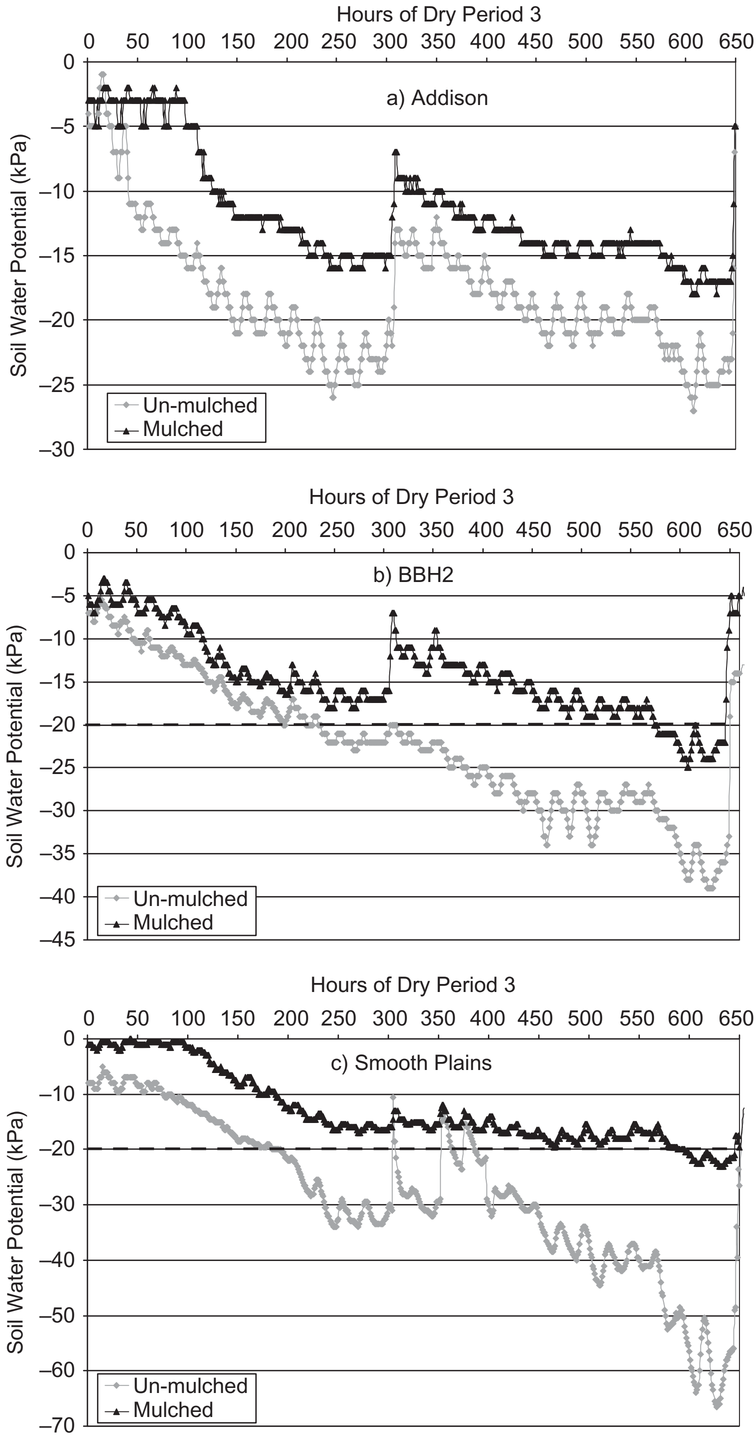

FIGURE 7 Soil water potential curves at crop-year lysimeter stations in (a) Addison, (b) Blueberry Hill, and (c) Smooth Plains during dry period 3 (September 1–26, 2009).

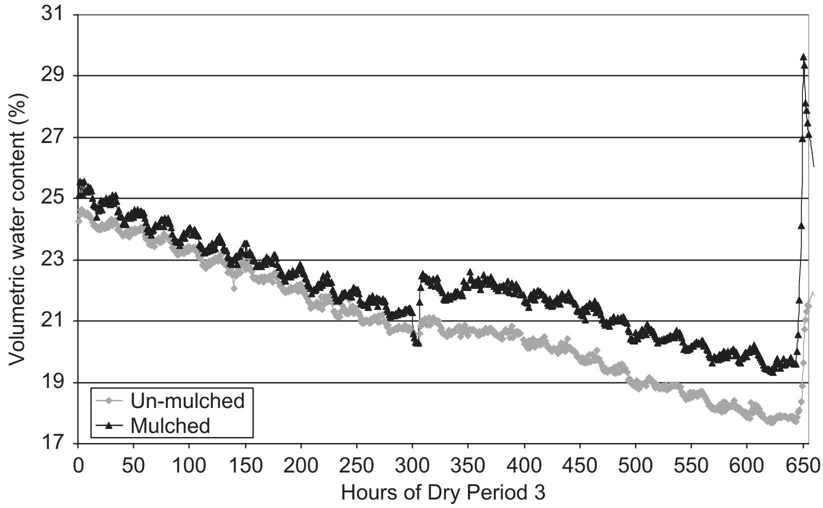

FIGURE 8 Volumetric water content of mulched and un-mulched weighing lysimeter soils at Blueberry Hill crop-year lysimeter station during dry period 3 (September 1–26, 2009).

of wheat straw mulch in upland and lowland wheat fields, respectively, in the Loess Plateau of China.

The overall water savings for the Smooth Plains station given in Table 4 do not include results for dry-period 1, where multiple irrigations for that period resulted in a shortage of useable data. Likewise, soil moisture levels in the un-mulched Smooth Plains lysimeters became so low during the final 5 days of dry-period 2 (Fig. 5) that mulched lysimeter ET rates exceeded un-mulched lysimeter ET rates. The low total water savings of 0.28 cm at Smooth Plains during dry-period 2 was therefore in large part due to the inability of soils at that station to meet plant and atmospheric water demand due to very low soil moisture content. The relative ET rates between mulched and un-mulched systems associated with transitions from high to moderate to inadequate soil moisture levels at Smooth Plains are shown in Figure 2. If the final five days of data from dry-period 2 are eliminated from the Smooth Plains data set, water savings there for the period would amount to 1.14 cm (0.45 in.), and total water savings for periods 2 and 3 would amount to 2.26 cm (1.17 in.).

The absence of dry-period 1 data for all of the prune-year stations was due to inadequate plant coverage of the associated mulched lysimeters. Plant coverage needs to be complete over the surface of weighing lysimeters in order to properly calculate water loss rates. It is our belief that mulching was performed too soon after pruning in April 2009, and resulted in delayed rhizome regeneration and shoot development at all prune-year lysimeter stations. Thus, full plant coverage of the lysimeter surfaces was delayed until at least mid-July at those stations. In retrospect, this proved to be less

TABLE 4 Water Savings by Mulching at Seven Weighing Lysimeter Stations in Downeast Maine During Selected Periods of the 2009 Growing Season

Lysimeter Station	Dry period 1 hours	Water savings (cm)	Dry period 2 hours	Water savings (cm)	Dry period 3 hours	Water savings (cm)	Overall dry period hours	Water savings (cm)	Entire season hours	Water savings (cm)
Addison (Crop)	163	0.53	439	0.89	649	0.79	1,230	2.21	2,947	0.76
Airport (Prune)	—	—	317	(−0.05)	530	0.53	847	0.48	3,004	0.99
BBH 1 (Prune)	—	—	430	0.86	618	1.22	1,048	2.08	3,378	0.15
BBH 2 (Crop)	168	0.48	446	1.52	635	0.51	1,249	2.51	2,798	1.06
Kelly Point (Prune)	—	—	454	1.42	572	1.68	1,026	3.10	3,244	1.57
Northfield (Prune)	—	—	282	0.76	617	0.00	899	0.76	1,266	0.05
Smooth Plains (Crop)	—	—	467	0.28	311	1.12	778	1.40	3,089	2.03

of an experimental setback than might have otherwise been the case due to the much higher than normal early-season precipitation that rendered much of the pre-August water loss data un-useable. Nevertheless we suggest that lowbush blueberry growers apply mulch at least 1 month after pruning to better avoid a possible reduction in prune-cycle fruit bud formation.

For dry-periods 2 and 3, mulch associated water savings were more variable in the prune-year stations than in the crop-year stations. Overall dry-period savings for the pruned stations ranged from 0.48 to 3.10 cm. The negative water savings during dry-period 2 at Airport station were likely due to delayed growth of plants in the mulched lysimeters relative to that in the un-mulched lysimeters. Similarly, the low water savings at Northfield during dry-period 3 were likely due to a lack of water in that station's un-mulched lysimeter soils in the final 6 days of that period. The largest overall dry-period water savings (3.10 cm) occurred at the pruned Kelly Point station, which is located in a coastal site that typically has lower air temperatures and greater water inputs through fog deposition (Hunt et al., 2009b) than the other stations. It is therefore likely that the observed mulch effects at Kelly Point were due in large part to sustained low but adequate soil moisture in both the mulched and un-mulched lysimeters throughout periods 2 and 3. As discussed in the section "Weather and Evapotranspiration," low but adequate soil moisture represents optimum conditions for comparing the water-conserving benefits of the mulch.

Soil water savings for the entire season, including the dry-periods, are also included in Table 4. In five out of seven stations the whole-season water savings are lower than the overall dry-period savings for those stations. Ostensibly, this implies that ET rates from un-mulched lysimeters at those five stations were lower than those from mulched lysimeters for much of the season. However, mulched and un-mulched soil water potential measurements at all stations for the non-dry-periods were statistically similar and usually indicative of saturated or near-saturated conditions. Thus, unlike the Kelly Point dry-period data that indicated low but adequate soil moisture levels, whole-season lysimeter data from all stations recorded long periods of sustained near-saturated soil conditions. The amount of available water contained in saturated or near-saturated soils greatly surpasses the amount needed to meet plant and atmospheric demand. Whole season data for each station was, therefore, largely invalid due to the interplay of the unusually wet growing season with the low water holding capacities of the lysimeters, as discussed earlier. The lower total data hours recorded for the entire season at BBH2 relative to BBH1 were due to weather-related delays in the repair of a faulty load cell at that crop-year station. Similarly, the low number of entire-season hours for Northfield was due to excessive flooding of the lysimeters at that station.

Table 5 shows three distinct time intervals of lysimeter water loss rates observed for the 53 dry-period days. In Downeast Maine, the early morning hours between 300 and 800 (3 AM to 8 AM) correspond to a time of maximum dew and fog formation (Hunt et al., 2009b). Net additions of water were made during this time period to six of the seven un-mulched lysimeter stations, and to one of the seven mulched lysimeter stations. Water additions were significantly ($p < 0.05$) greater in the un-mulched than in the mulched lysimeters in four stations. These results are counter to our initial expectations of greater water inputs from dew formation and fog deposition to the mulched lysimeters, and are at least partly due to higher evaporative losses of small water inputs from the mulched relative to the un-mulched surfaces. However differences in water inputs between stations during these hours suggest the involvement of site specific effects as well. In a 2008 study, Graf et al. found dew deposition onto bare loam soil surfaces to be greater than that to lapilli-mulched surfaces. In that study, mulch was found to have a faster nocturnal cooling rate than bare loam soil, a pre-requisite for dew formation, however, the greater hygroscopicity of the soil ultimately made for higher condensation gains in the un-mulched systems. Similarly, Li (2002) reported greater dew deposition to bare loam soils relative to gravel-mulched surfaces of greater pore size and lower hygroscopicity. In the current study, the greatest additions of water during the early morning hours were made to the un-mulched lysimeters at Kelly Pt. and Addison, the stations of closest coastal proximity. The Addison soils were the finest textured soils in the study, consisting of a complex of silty clay loams and silty clays. As Table 5 shows, the differences in water balance during the three time intervals were most extreme at the Addison station. This was most likely a function of the high hygroscopicity of the soils at that site, which were able to adsorb large amounts of water during the night-time hours but subsequently lost a large percentage of that water via daytime evaporation. In contrast, the loamy sand soils at Kelly Pt. were the coarsest soils in the study and therefore unlikely to have high hygroscopicity relative to soils from other sites. Instead, the un-mulched soils at this most coastal site (<0.6 km from ocean) likely benefited from higher rates of early morning fog-drip, which typically occur there compared to other sites (Hunt et al., 2009b). For coastal sites, like Addison and Kelly Pt., fog formation is also prevalent in the evening hours between 1800 and 200 (6 PM to 2 AM). Consequently, these stations were the only ones to show positive gains in water to the un-mulched lysimeters during these hours.

The previously mentioned studies by Graf et al. (2008) and Li (2002) concluded that the most critical water benefit conferred by mulch was that of evaporation suppression. This was clearly the case in the current study as the mulched lysimeters at all stations lost significantly ($p < 0.05$) less water during the 900–1700 (9 AM to 5 PM) time interval than did the un-mulched lysimeters (Table 5). The greatest water savings during this time interval occurred at Addison where mulching reduced ET losses by nearly 9 cm. In general, peak-hour ET losses were reduced enough by mulching to easily

TABLE 5 Dry Period Changes in Mean Water Balance (cm) of Mulched and Un-Mulched Weighing Lysimeters During Three Daily Time Periods

	Hours 300–800 (Peak dew deposition)		Hours 900–1,700 (Peak evapotranspiration)		Hours 1,800–200 (Night-time)	
Lysimeter Station	Un-mulched	Mulched	Un-mulched	Mulched	Un-mulched	Mulched
Addison	0.72	−0.55***	−20.22	−11.24***	5.97	0.44***
Airport	0.14	−0.09^{NS}	−8.85	−8.39*	−0.44	−0.21^{NS}
BBH 1	0.32	−0.82***	−7.48	−4.11***	−2.91	−3.05^{NS}
BBH 2	−0.67	−0.70^{NS}	−12.39	−9.60***	−1.83	−2.10^{NS}
Kelly Point	1.05	−0.17***	−12.43	−7.94***	0.12	−0.05*
Northfield	0.03	0.14^{NS}	−10.34	−9.79***	−0.79	−0.73^{NS}
Smooth Plains	0.18	−0.14*	−10.60	−9.44**	−1.62	−1.05^{NS}

*, **, ***Represent significant differences at the $p < 0.05$, 0.01, and 0.001 level, respectively, in mean net hourly period differences among mulched and un-mulched lysimeters.
^{NS}Represents no significant differences in mean net hourly period differences among mulched and un-mulched lysimeters.

compensate for the observed greater rates of dew and fog water inputs to the un-mulched blueberry soils.

SUMMARY AND CONCLUSIONS

Pine-bark mulch significantly improved soil water retention at seven lowbush blueberry lysimeter stations in Downeast Maine. The effects of mulch were greater during three periods of moderately dry conditions in 2009 than during the growing season as a whole. Water potential and volumetric water content data from the three dry periods indicated significantly drier conditions in un-mulched relative to mulched soils of both crop and prune-year fields. Lower diurnal fluctuations in soil water potential and volumetric water content in mulched lysimeters indicated more stabilized temperature and relative humidity regimes within these soils. Mulched soils had significantly fewer hours where soil water potential values indicated a need for irrigation. During 53 days of dry conditions, lysimeter water savings associated with mulch averaged 0.045 ± 0.003 cm/day at three crop-year fields and 0.039 ± 0.027 cm/day at four prune-year fields. Water savings at prune-year fields were much more variable between stations than at crop-year fields due to differences in the emergence times of pruned shoots from the mulch. Contrary to expectations, dew and fog water deposition was found to add greater amounts of water to un-mulched lysimeters than to mulched lysimeters. The effect of mulch on the suppression of peak-hour ET water loss, however, more than compensated for the lower water inputs from dew and fog. The results of this study indicate that pine-bark mulch can significantly reduce water loss from Maine lowbush blueberry soils even in years of excessive rainfall.

ACKNOWLEDGMENTS

The authors wish to thank Gordon Starr and Ben LaGasse for installing the lysimeters used in this study.

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