Individual and Combined Use of Sawdust and Weed Mat Mulch in a New Planting of Northern Highbush Blueberry I. Impacts on Plant Growth and Soil and Canopy Temperature

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Abstract. A 2-year trial was established in Oct. 2016 in western Oregon to evaluate the effects of various in-row mulch treatments on the establishment of northern highbush blueberry (*Vaccinium corymbosum* L. ‘Duke’). The treatments included douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco] sawdust, black weed mat (woven polypropylene groundcover), green weed mat, and sawdust covered with black or green weed mat. Soil temperature was unaffected by the color of the weed mat, but it was often higher during the day in beds with weed mat mulch than in those with sawdust alone or sawdust covered with weed mat. Black or green weed mat also resulted in higher canopy temperatures, particularly when sawdust was underneath the weed mat. Plant growth was mainly unaffected by the color of the weed mat, and the maximum depth of the root system was similar among the mulch treatments. However, plants grown with sawdust mulch, with or without weed mat, had a greater canopy width and volume in year 2, a wider root system in both years, and more dry weight (DW) in the crown in year 1 and in the whips in year 2 than those with weed mat alone. Furthermore, plants with weed mat over sawdust were taller in year 1 and had greater canopy cover and more DW in new wood in year 2 than those with sawdust alone, and they had a larger canopy, more root development, and greater DW in the crown, new and old wood, fruit, and pruning wood in one or both years than those with weed mat alone. Over the course of the 2 years of the study, the net gain in total plant DW was lowest when the plants were grown with black weed mat and highest when they were grown with black weed mat over sawdust. Although it was more expensive initially, the use of weed mat over sawdust resulted in more plant growth than weed mat alone due to the insulating properties of the sawdust, and it was more effective for weed control than using sawdust alone.

The Northwest United States is an important production region for northern highbush blueberry (*Vaccinium corymbosum* L.). In 2018, this region, which includes Oregon and Washington, had more than 11,000 ha of blueberry fields (U.S. Department of Agriculture, 2019). Historically, most of the fields in these states were mulched with

douglas fir sawdust. However, sawdust is becoming more expensive (Julian et al., 2011), and many growers are using black, woven, polypropylene landscape groundcover, which is often referred to as “weed mat” (Strik, 2016). Weed mat is more economical for weed control than sawdust, and it can have a positive effect on yield in blueberry (Strik et al., 2017a; Strik and Vance, 2017).

Weed mat captures more longwave radiation and results in warmer soil temperatures than organic mulches, such as sawdust or wood chips (Cox, 2009; Larco, 2010; Strik et al., 2017a). Weed mat has also been shown to increase crop water requirements by up to 50% (Strik et al., 2017a), reduce soil organic matter (Atucha et al., 2011; Choi et al., 2011; Strik et al., 2019), and increase the presence of voles (*Microtus* sp.) relative to sawdust mulch (Granatstein and Mullinix, 2008; Strik

et al., 2017a). However, weed mat mulch had no impact on growth (Choi et al., 2011) or even reduced growth (Neilsen et al., 2003) of apple [*Malus sylvestris* (L.) Mill. var. *domestica* (Borkh.) Mansf.] trees. Likewise, Krewer et al. (2009) reported less yield with weed mat compared with organic mulches in rabbiteye blueberry (*V. virgatum* Ait.), whereas Strik et al. (2017a) found the opposite in a long-term organic study of northern highbush blueberry. Adding a layer of sawdust under black weed mat showed great promise in a long-term study of organic northern highbush blueberry to mitigate the negative effects noted for weed mat alone (Strik et al., 2017b).

Mulches may also affect root growth differently by altering the moisture and temperature in the soil. The optimum temperature for root growth in highbush blueberry is ≈14 to 18 °C (Abbott and Gough, 1987; Spiers, 1995). Therefore, sawdust and other mulches that reduce soil temperature during hot summer months are expected to improve root development. For example, sawdust mulch increased root weight as well as plant height of rabbiteye blueberry compared with bare soil (Patten et al., 1988, 1989). Additionally, northern highbush blueberry plants grown organically allocated more biomass to the roots and crown and had a higher root-to-shoot ratio with sawdust mulch than with black weed mat (Larco et al., 2013). Sawdust mulch insulates the soil from temperature fluctuations and adds organic matter as it decomposes (Strik et al., 2017a, 2019; White, 2006). Other organic mulches, such as pine bark and hardwood woodchips, have similar insulating properties (Cox, 2009; Patten et al., 1988). However, weed management is more time-consuming and expensive when using organic mulches such as sawdust, especially in organic production systems where herbicides have limited efficacy (Julian et al., 2012; Strik and Vance, 2017; Tertuliano et al., 2012). Sawdust mulch also has to be replenished every 2 or 3 years due to decomposition and displacement from wind, animals, and farming activities, thereby adding costs to the production of blueberries (Julian et al., 2011; Strik and Vance, 2017).

Currently, there are several colors of woven polypropylene weed mat available for weed control, including black, white, and green. White weed mat reflects light into the plant canopy, which reduces the soil temperature and influences the fruit quality of apple and blackberry (*Rubus* L. subgenus *Rubus*, Watson) (Funke and Blanke, 2005; Makus, 2007). However, in a recent study of southern highbush blueberry (complex hybrids based largely on *V. corymbosum* and *V. darrowii* Camp.) in Évora, Portugal, the use of white weed mat resulted in excessive weed growth underneath the mulch due to transmittance of photosynthetically active light through the material (R. Machado, unpublished data). In this case, plant survival was ≥90% with green weed mat or aged pine bark mulch, but only 70% with bare soil and black or white weed mat. Bark and green weed mat

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effectively controlled weeds and resulted in lower midday soil temperatures compared to bare soil and black weed mat, which apparently improved canopy development and survival of the plants during establishment. White weed mat, however, reflected more light than any other mulch, resulting in what appeared to be lethal leaf temperatures in the canopy of the plants (Decoteau et al., 1989; Ibarra-Jiménez et al., 2012; Tarara, 2000). Johnson and Fennimore (2005) evaluated seven colored plastic mulches as well as clear and black plastic on strawberry (*Fragaria × ananassa* Duchesne) in California and determined that green and brown mulches provided the best combination of soil warming and weed control benefits.

The objective of this study was to evaluate the impact of different mulches, including sawdust, black or green weed mat, and sawdust covered with black or green weed mat, on crop development in a new planting of northern highbush blueberry. The influences of each mulch on soil and canopy temperature were also studied and related to root and shoot growth in each treatment. White weed mat was not included in the present study due to the aforementioned problems with weed growth under the weed mat.

Materials and Methods

The 0.14-ha trial was established in Oct. 2016 at the Oregon State University North Willamette Research and Extension Center (NWREC) in Aurora, OR (lat. 45°16'47"N, long. 122°45'23"W). Weather data for this site are available from an AgriMet weather station at NWREC (U.S. Department of Interior, 2014). The soil is a Willamette silt loam (a fine-silty, mixed, superactive mesic Pachic Ultic Argixeroll).

Site and preparation. The field was fallow throughout the Spring and Summer of 2016, and weeds were controlled using two applications of glyphosate before soil preparation. A pooled soil sample taken in Oct. 2015 indicated that all nutrients were at appropriate levels for blueberry (Hart et al., 2006). Therefore, no fertilizers were applied to the field before establishing the treatments. In Sept. 2016, the field was ripped to a depth of 0.5 m (parallel and diagonal to the future planting rows) using a single shank. Rows were then power-spaded to a depth of 0.4 m and tilled to a depth of ≈0.2 m. After the soil was prepared, the single shank was used again to rip directly in the center of the future planting rows. A 5- to 8-cm deep layer of sawdust (target application rate of 282 m³·ha⁻¹) was then applied to the in-row area and incorporated by tilling the soil to a depth of ≈20 cm. A bed shaper was used to create raised beds that were ≈1.2-m and 0.6-m wide at the base and top, respectively, and ≈0.3-m high. Standard 18-month-old 'Duke' blueberry plants were removed from 2-L pots and planted on 4 Oct. 2016.

Treatments and field management. Mulch treatments were applied on top of the raised beds and included an 8-cm-deep layer of

douglas fir sawdust, black weed mat (Baycor, Ten Cate Nicolon, Pendergrass, GA), green weed mat (Guerner & Irmãos, Perosinho, Portugal), and black or green weed mat over a 5-cm deep layer of sawdust. In each case, weed mat was installed in a "zippered" system with two 1-m-wide panels overlapping at the middle of the beds. Holes were cut in the weed mat around the crown of the plants. The black and green weed mats had densities of 108 and 130 g·m⁻² and water infiltration rates of 407 and 554 L·m⁻²·min⁻¹, respectively. Plots of each treatment were arranged in a completely randomized block design to account for variability in slope in the field and to facilitate data collection on soil and canopy temperature with five replicates. Each plot included a row of nine plants spaced 0.9 m apart and was separated from adjacent plots in the row by 3 m. Rows were spaced 3 m apart. Guard rows and three-plant border plots were planted on both sides of the main experiment and on the north and south ends of the treatment rows, respectively, and mulched with black weed mat over sawdust.

The plants were irrigated using a line of drip tubing on each side of the row. The tubing had 3.8 L·h⁻¹ in-line emitters every 45 cm and was placed ≈10 cm from the base of the plants. In each treatment, the drip lines were in contact with the soil and covered by the mulch. Liquid urea (20-0-0) was injected through the drip system twice per week from mid-April to late July in 2017, and from mid-April to early July in 2018. A total of 174 kg·ha⁻¹ N was applied the first year, and 108 kg·ha⁻¹ N was applied the second year. Less fertilizer was applied during the second year because the root systems were larger and the plants were able to access more of the N fertilizer than they could in the previous year (Bryla and Strik, 2015).

Alleyways between the rows were planted in Mar. 2017 with a blend of perennial ryegrass (*Lolium perenne* L. 'Shining star'), creeping red fescue (*Festuca rubra* L. 'Boreal'), and hard fescue (*Festuca brevipila* R. 'VNS') and were mowed throughout the trial as needed. Pest and weed management was also performed when necessary using integrated pest management protocols (DeFrancesco et al., 2018).

Soil temperature. Copper-constantan thermocouples (EXPP-T-20; Omega Engineering, Stamford, CT) were installed under a randomly selected drip emitter (15 cm from the center of each plant) in three replicate plots per treatment at depths of 0, 2, 5, 15, and 25 cm from the soil surface. Thermocouples at 0 cm were in direct contact with the sawdust or weed mat that was covering the soil in that particular treatment. Ambient air temperature was measured at a height of 2 m in the middle of the field using a shielded temperature and humidity sensor (HMP/50; Campbell Scientific, Logan, UT). Each measurement was recorded every 15 min from mid-June through the end of September each year using a data logger and multiplexers (CR1000 and AM16/32; Campbell Scientific).

Canopy cover and temperature. Canopy cover and canopy temperature were measured remotely in August using an unmanned aerial system (UAS) (AgBot; Aerial Technology International, Oregon City, OR) equipped with a multispectral camera (RedEdge; Micasense, Seattle, WA) each year and a thermal imaging camera (Vue Pro R; FLIR, Wilsonville, OR) in 2018. Flights were conducted within 1 h of solar noon at an altitude of 15 m. Imagery was processed into an orthomosaic of each spectrum using geospatial software (Pix4D S.A., Prilly, Switzerland) and imported into ArcGIS for analysis (ESRI, Redlands, CA). A modified version of the normalized difference vegetation index (NDVI) was used to distinguish the plants from groundcover using the following formula:

$$NDVI = \frac{(NIR^2 - Red)}{(NIR + Red)} \quad [1]$$

where NIR is a 40-nm-wide, near-infrared spectral band centered at 840 nm, and Red is a 10-nm-wide spectral band centered at 668 nm. Shadows and glare can be a source of error in multispectral imagery (Leblon et al., 1996). To correct for this, the NDVI equation was modified by squaring NIR in the numerator to augment the plant signature relative to shadows and glare, effectively minimizing them. Polygons were drawn around each treatment plot to delineate the plants from the grass alleyways and clipped with the NDVI layer. Each plot was then reclassified into two classes (plant and ground) and manually adjusted to exclude the ground (mulch). To calculate the percent canopy cover, the number of pixels occupying the plant class were multiplied by the ground sampling distance and divided by the plot area. Mean, minimum, and maximum temperatures of the canopy were also analyzed by clipping the thermal layer with the reclassified NDVI layer.

Plant growth and development. The volume of the canopy was estimated before leaf senescence in October each year using the following equation for a circular cone:

$$V = (1/3)\pi r^2 h \quad [2]$$

where r represents plant radius (determined by measuring the width of the canopy at the widest points parallel and perpendicular to the plant row and dividing the average of the measurements by 2) and h represents plant height (maximum height of the plants measured from the top of the raised bed to the highest shoot tip). The measurements were obtained for one plant per plot.

One plant per plot was also netted before leaf senescence to collect the leaves and determine their total dry weight. The leaves were oven-dried at 60 °C and weighed. Then, the plants were pruned in February each year. Once pruned, the northernmost plant in each plot was carefully removed from the soil by digging up as much of the root system as possible using a shovel. The width of the root system was measured parallel and perpendicular to the row, and the depth of roots was measured

as the plant was lifted from the raised bed. The root system volume was calculated using the formula for the volume of a spheroid (using the average of the parallel and perpendicular radii at the soil surface):

$$V = \frac{4\pi}{3} a^2 c \quad [3]$$

where a represents the root system radius (calculated from the average diameter across the root system width parallel and perpendicular to the row) and c represents half the height of the spheroid (root system depth divided by 2). Roots were washed thoroughly to remove as much soil as possible while minimizing the risk of removing finer roots. Each plant was separated into 1-year-old wood ("new"), 2-year-old and older wood ("old"), 1-year-old whips (new shoots arising from the basal portion of the plant), crown, roots, and pruning wood (specific to the plant removed), and weighed fresh either on the same day as removal (aboveground portions of the plant) or within 5 d of digging (roots and crown); when sampling and weighing were delayed, as for roots, plants were stored with soil on to retain moisture and were washed just before sampling. A subsample of pruning wood was dried for 5 d at 60 °C and weighed again to determine the percent moisture to calculate dry weight (DW). Subsamples of all other plant tissues, including senescent leaves, were sent to a commercial laboratory (Brookside Laboratories, New Bremen, OH) for analysis of the percent moisture (for DW calculation) and concentration of macro- and micronutrients (for a companion study). To determine the net DW gain from planting (beginning of year 1) to the end of year 2 (2018), three nursery plants were also submitted to the laboratory for moisture analysis and served as an average baseline to calculate the net gain in total DW from planting to the end of year 2 (Oct. 2018) in each treatment.

Ripe fruit were harvested by hand on 22 and 29 June and 13 July 2018. A subsample of fruit from the first harvest was submitted to the same commercial laboratory for analysis of the percent moisture and to calculate fruit DW using the total fresh yield per plant.

Data analysis. Statistical analyses were performed with SAS version 9.4 (SAS Institute, Cary, NC) using PROC MIXED, and means were separated at the 5% level using Tukey's honestly significant difference test. PROC UNIVARIATE was used to ensure a normal distribution of data before analysis, and log transformations were applied as necessary. Data were analyzed by year except to assess the effect of year on the percent allocation of the DW per plant part using a split-plot design. Preplanned orthogonal contrasts were used to compare the various effects of weed mat color and the addition of sawdust underneath the weed mat. A correlation analysis was used to establish any relationship between calculated root volume and root DW by year.

Results and Discussion

Soil and canopy temperature. Soil temperature was often much lower with sawdust

than with weed mat, particularly on hotter days; these treatments differed by as much as 15 °C at or near the soil surface and up to 5 °C at depths of 5 to 25 cm (Fig. 1). Similar effects of mulch type on soil temperature were observed with southern highbush blueberry in Mississippi (Magee and Spiers, 1995) and peanuts (*Arachis hypogaea* L.) in India (Khan et al., 2000). Soil temperature was also lower with sawdust under the weed mat than with weed mat alone, but it was largely unaffected by the color of the weed mat. In fact, regardless of whether weed mat was used alone or in combination with sawdust, there was no significant difference in soil temperatures in beds with black or green weed mat (Fig. 2). In contrast, green weed mat reduced soil temperatures (at 5 cm) by as much as 7 °C relative to black weed mat in a new planting of southern highbush blueberry in Évora, Portugal (R. Machado et al., unpublished data). In this case, the air temperature averaged a daily high of 30 to 33 °C in June through September. In the present study, the daily high temperatures averaged only 23 to 28 °C during these same months. The soil was also sandier at the site in Portugal. Thermal diffusivity is often higher in sandy soils, which will amplify the positive or negative effects of a given mulch on soil temperature (Villalobos et al., 2016). This might explain why plant survival in Portugal was only 70% with black weed mat but ≥90% with bark or green weed mat.

Weed mat also resulted in higher canopy temperatures than sawdust, particularly when the soil was mulched with weed mat over sawdust (Table 1). Apparently, sawdust buffered conduction from weed mat into the soil, thereby resulting in not only lower soil temperatures but also more radiative and convective heat transfer to the canopy. This is similar to what happens when plastic mulch is laid loosely on the ground, resulting in an air gap between the soil and plastic (Tarara, 2000). However, much like soil temperature, canopy temperature was unaffected by the color of the weed mat in the present study. Tarara (2000) reviewed the literature regarding plastic mulches and, based on the surface energy balance of plastic mulch, demonstrated that the total amount of energy directed at the canopy is quite similar between black and white plastics. Although the optical properties are very different, sensible heat flux (convection) is higher from black than from white plastics, whereas reflectance toward the canopy is higher from white than from black plastics. Therefore, it might be expected that the total energy directed at the canopy via radiation and convection would be similar between black and green weed mats. Based on our thermal images, the surface of green weed mat was indeed several degrees cooler on sunny days than the surface of the black weed mat (data not shown), whereas total radiation reflected was likely higher from green weed mat than from black weed mat.

Canopy and root system size. The mulch treatments had no effect on the width or

volume of the canopy by the end of the first growing season; however, plants grown with black or green weed mat over sawdust were taller than those mulched with sawdust alone (Table 2). This might have been due to higher canopy temperatures with weed mat over sawdust (Table 1). Blueberry plants were taller at the end of the first growing season when they were grown with translucent grow tubes (Tarara et al., 2014), which, much like in the present study, appeared to be due to higher temperatures in the canopy (Tarara et al., 2013, 2014).

In the second growing season, plant width tended to be lower in plants with weed mat alone, whereas those with black or green weed mat produced the narrowest canopies parallel and perpendicular to the row, respectively (Table 2). Consequently, canopy volume was smaller that year with black weed mat alone than with sawdust or black weed mat over sawdust. Canopy cover was greater with black weed mat over sawdust than with either black or green weed mat alone or sawdust. Because canopy cover was measured remotely on each plant in the field, the data were likely more accurate than the single-plant measurements of canopy volume in each plot. However, canopy cover was also measured a few months earlier than canopy volume. By Aug. 2019 (year 3), differences in canopy cover, which are not discussed in detail here, were very similar to the differences in canopy width and volume measured at the end of the previous year and indicated that the percent cover at that point was similar between sawdust and black weed mat over sawdust (33% and 35%, respectively) and significantly lower with black or green weed mat (27%) ($P = 0.0058$). In southern highbush blueberry, pine bark or white-on-black plastic mulches resulted in lower soil temperatures and greater plant growth than black plastic or black weed mat mulches (Magee and Spiers, 1995).

Contrasts likewise showed that the addition of sawdust under weed mat resulted in more canopy volume and cover than weed mat alone in 2018, which again was largely due to greater canopy width across the row. There was no effect of weed mat color on any of the measured canopy variables. Plants grown with sawdust mulch had greater canopy volume after two growing seasons in 2018, but not percent cover, compared with weed mat. In a previous study of 'Duke' blueberry in Oregon, plants grown with black weed mat had less leaf area after two growing seasons than those grown with sawdust, but there was no difference in leaf area index between the treatments (Larco, 2010).

Similar to the trends in canopy development, plants grown with black weed mat over sawdust had greater root volume the first year and a wider root system in either year than those grown with black weed mat alone (Table 3). High soil temperatures under black weed mat may have reduced root growth laterally, particularly at shallower soil depths (≤5 cm), where daytime temperatures often exceeded 30 °C throughout the summer

Fig. 1. Diurnal changes in air and soil temperature at depths of 0, 2, 5, 15, and 25 cm in raised beds of 'Duke' blueberry during the first 2 years after planting (2017–18) in Oregon. The beds were mulched with sawdust, black or green polypropylene weed mat, and black or green polypropylene weed mat over sawdust. The patterns of two of the warmest days in 2017 and 2018 are illustrated.

(Fig. 1). As mentioned previously, the optimal temperature of root growth in highbush blueberry is ≈ 14 to 18°C , and root growth is greatly reduced at soil temperatures $>35^{\circ}\text{C}$ (D. Bryla, personal observations). Spiers (1995) found 1.6-times more root length, on average, when the substrate temperature was

16°C than when it was 38°C in southern highbush and rabbiteye blueberry. He also found increased plant growth with a reduction in substrate temperature. Root development can also be affected by diurnal changes in root temperature. For example, Gonzales-Fuentes et al. (2016) examined the effects of

diurnal changes on root zone temperature in strawberry and found that severe temperature changes of 15°C resulted in 30% less root dry weight than mild changes of 5°C . Clearly, root zone temperatures fluctuated more severely with weed mat than with sawdust or sawdust over weed mat in the present study (Fig. 1).

A. 2017

B. 2018

Fig. 2. Maximum daily soil temperatures at depths of 0, 2, 5, 15, and 25 cm in raised beds of 'Duke' blueberry from June through September of the first 2 years after planting (2017–18) in Oregon. The beds were mulched with sawdust, black or green polypropylene weed mat, and black or green polypropylene weed mat over sawdust. Horizontal bars at a given depth indicate the least significant difference at $P \leq 0.05$. NS, nonsignificant.

The maximum root depth increased by an average of 40% from 2017 to 2018, indicating good root development in each treatment. Root volume also increased between the two years by a total of 32% to 34% with black weed mat or black weed mat over sawdust, 39% to 40% with green weed mat or green weed mat over sawdust, and 56% with sawdust (Table 3). In this case, it appears that color of the weed mat might have had some effect on the expansion of the root system from one year to the next.

Dry weight gain and allocation. The total dry weight of the plants was affected by mulch in 2017 ($P = 0.033$) and 2018 ($P = 0.0055$). In both years, plants grown with black weed mat over sawdust had greater DW than those grown with black weed mat alone, but they had a DW similar to those grown with all other mulches, including sawdust alone, green weed mat alone, or green weed mat over sawdust (Fig. 3). Larco et al. (2013) found no difference between sawdust and black weed mat mulch on the total DW of

Table 1. Effects of sawdust and polypropylene weed mat mulch on canopy temperature of 'Duke' blueberry during the second year after planting (2018) in Oregon.

Mulch	Canopy temp (°C) ^z		
	Minimum	Mean	Maximum
Sawdust	28.2	32.8 c ^y	46.6 d
Black weed mat	27.9	35.3 ab	54.3 bc
Green weed mat	27.7	34.5 b	52.5 c
Black weed mat over sawdust	28.7	35.5 ab	56.7 ab
Green weed mat over sawdust	29.4	36.1 a	57.4 a
Significance	NS	0.0018	<0.0001
Contrasts			
Sawdust vs. weed mat	NS	<0.0001	<0.0001
Sawdust vs. weed mat over sawdust	NS	<0.0001	<0.0001
Black vs. green weed mat	NS	NS	NS
Weed mat vs. weed mat over sawdust	NS	0.0483	0.0165

^zMeasured on 15 Aug. 2018 using a small unmanned aerial system equipped with a thermal imaging camera. The sky was clear during the flight, and ambient air temperature ranged from 26 to 27 °C.

^yMeans followed by the same letter within a column are not significantly different ($P > 0.05$).

^{ns}Nonsignificant.

'Duke' blueberry after one growing season, but after 2 years, the plants with sawdust mulch had a greater DW than those with black weed mat.

The results of the analysis of variance indicated that mulch treatment had no effect on the DW of roots, whips, or senescent leaves in either year (Table 4). However, a

Table 2. Effects of sawdust and polypropylene weed mat mulch on canopy development of ‘Duke’ blueberry during the first 2 years after planting (2017–18) in Oregon.

Mulch	Plant width (cm)				Plant ht (cm)		Canopy volume (m ³) ^z		Canopy cover (%) ^y	
	Parallel to row		Perpendicular to row		2017	2018	2017	2018	2017	2018
	2017	2018	2017	2018						
Sawdust	78	120 a ^x	77	132.2 ab	76 b	108	0.12	0.45 a	9	25 b
Black weed mat	73	98 b	81	117.4 ab	84 ab	106	0.13	0.32 b	10	25 b
Green weed mat	74	102 ab	88	117.0 b	90 ab	111	0.17	0.35 ab	10	26 b
Black weed mat over sawdust	75	109 ab	84	133.0 a	92 a	118	0.16	0.45 a	11	30 a
Green weed mat over sawdust	73	108 ab	83	121.8 ab	95 a	107	0.15	0.37 ab	11	28 ab
Significance ^w	NS	0.0367	NS	0.0119	0.0165	NS	NS	0.0193	NS	0.0416
Contrasts										
Sawdust vs. weed mat	NS	0.0028	NS	0.0041	0.0247	NS	NS	0.0065	NS	NS
Sawdust vs. weed mat over sawdust	NS	NS	NS	NS	0.0014	NS	NS	NS	NS	0.0120
Black vs. green weed mat	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Weed mat vs. weed mat over sawdust	NS	NS	NS	0.0133	NS	NS	NS	0.0207	NS	0.0318

^zCalculated using Eq. [2].

^yMeasured by remote imagery on 31 Aug. 2017 and 15 Aug. 2018. Values include a measurement of every plant in each treatment plot.

^xMeans followed by the same letter within a column are not significantly different ($P > 0.05$).

^wValues are only provided when $P \leq 0.05$.

^{NS}Nonsignificant.

Table 3. Effects of sawdust and polypropylene weed mat mulch on root system development of ‘Duke’ blueberry during the first 2 years after planting (2017–18) in Oregon.

Mulch	Root system width (cm)				Root depth (cm)		Root volume (m ³) ^z	
	Parallel to row		Perpendicular to row		2017	2018	2017	2018
	2017	2018	2017	2018				
Sawdust	56 a ^y	69 ab	57 a	68 a	22	34	0.037 ab	0.083
Black weed mat	45 b	57 b	42 b	51 b	25	33	0.024 b	0.052
Green weed mat	54 ab	65 ab	54 a	57 ab	25	35	0.039 ab	0.071
Black weed mat over sawdust	61 a	74 a	60 a	65 a	25	34	0.049 a	0.086
Green weed mat over sawdust	54 ab	71 ab	56 a	60 ab	23	32	0.038 ab	0.075
Significance ^x	0.0039	0.0296	0.0008	0.0031	NS	NS	0.0029	NS
Contrasts								
Sawdust vs. weed mat	0.0367	NS	0.0068	0.0006	NS	NS	NS	NS
Sawdust vs. weed mat over sawdust	NS	NS	NS	NS	NS	NS	NS	NS
Black vs. green weed mat	NS	NS	NS	NS	NS	NS	NS	NS
Weed mat vs. weed mat over sawdust	0.0035	0.0047	0.0007	0.0041	NS	NS	0.0044	NS

^zCalculated using Eq. [3].

^yMeans followed by the same letter within a column are not significantly different ($P > 0.05$).

^xValues are only provided when $P \leq 0.05$.

^{NS}Nonsignificant.

contrast analysis indicated that whip DW was generally greater with sawdust than weed mat in 2018, confirming the findings of Larco et al. (2013), who compared sawdust to black weed mat for ‘Duke’ and ‘Liberty’ blueberry. A new planting also produced more whips/plant with sawdust mulch than with bare soil for ‘Elliott’ blueberry (White, 2006).

Contrasts also indicate that weed mat over sawdust generally resulted in higher DW in the crown and new and old wood in either year, as well as in the fruit and pruning wood in 2018, than weed mat alone. There was no significant difference in the DW of any plant part when comparing sawdust to black weed mat alone, in contrast to the results reported by Larco et al. (2013) for ‘Duke’ plants that were grown with black weed mat and had lower root and crown DW in years 1 and 2 than those with sawdust mulch. Root DW is difficult to measure on field-grown plants because roots are easily lost during digging and some soil often remains after washing, which could account for the difference between the studies. There was a trend at the end of the first growing season ($P = 0.093$; $r = 0.34$) for root volume to be correlated with root DW, and this correlation was significant

Fig. 3. Effect of mulch (sawdust, polypropylene black weed mat, green weed mat, black weed mat over sawdust, and green weed mat over sawdust) on total plant dry weight of ‘Duke’ blueberry in winter after the first (2017) and second (2018) growing seasons in Oregon. Means $\pm$ SE ($n = 5$). Means followed by the same letter within the year are not significantly different ($P > 0.05$).

Table 4. Effects of sawdust and polypropylene weed mat mulch on the dry weight of 'Duke' blueberry plant parts during the first 2 years after planting (2017–18) in Oregon.^z

Mulch	Dry wt (g/plant) ^y													
	Roots		Crown		Old wood		New wood		Whips		Leaves		Fruit ^x	
	2017 ^a	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
Sawdust	119	297	60 ab ^w	168	57	356 ab	45	113 b	33	113	92	310	105	34
Black weed mat	108	214	49 ab	145	49	272 b	35	110 b	32	25	71	301	98	24
Green weed mat	123	316	41 b	176	56	339 ab	42	143 ab	28	71	92	316	110	27
Black weed mat over sawdust	157	387	68 a	210	65	418 a	57	184 a	55	63	102	334	123	46
Green weed mat over sawdust	163	298	58 ab	184	69	324 ab	57	134 b	34	82	83	297	119	33
Significance ^v	NS	NS	0.0123	NS	NS	0.0427	NS	0.0247	NS	NS	NS	NS	NS	0.042
Contrasts														
Sawdust vs. weed mat	NS	NS	0.022	NS	NS	NS	NS	NS	NS	0.0164	NS	NS	NS	NS
Sawdust vs. weed mat over sawdust	NS	NS	NS	NS	NS	NS	NS	0.0274	NS	NS	NS	NS	NS	NS
Black vs. green weed mat	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Weed mat vs. weed mat over sawdust	NS	NS	0.0020	0.0349	0.0287	0.0424	0.0059	0.0496	NS	NS	NS	NS	0.0179	0.0012

^zThe dry weight of the roots, crown, and new wood averaged 8, 5, and 18 g/plant, respectively, at planting (n = 3).

^yOld wood = 2-year-old or older wood; new wood = 1-year-old wood; whips = new wood that grew from the crown or from the most basal 10 cm of a cane; leaves were collected in the fall (postsenescence); prunings = wood removed during pruning in the winter. All data, except the leaves and fruit, are from plants dug in the winter following the year shown (i.e., plants dug in Feb. 2018 are listed under 2017).

^xThe plants were first cropped in year 2 and harvested in June 2018.

^wMeans followed by the same letter within a column are not significantly different ($P > 0.05$).

^vValues are only provided when $P \leq 0.05$.

^{ns}Nonsignificant.

($P = 0.0001$; $r = 0.70$) after the second year. Although it was easier to dig the younger plants, the root system was less dense, perhaps weakening the correlation between these variables.

The ratio of root (roots and crown) to shoot DW (wood) averaged 0.7 in 2017 and 0.4 in 2018, but it was unaffected by mulch in either year (data not shown). The ratio in year 1 was very similar to those found at the end of the establishment year for conventional plantings of 'Duke' and other cultivars in Oregon (Bañados et al., 2012; Strik et al., 2014). The values were also similar to those reported previously for year 2 of the organic study of 'Duke' but higher than those reported in year 1 of that study (Larco et al., 2013).

Across mulches, aboveground DW increased from 58% of total plant biomass in 2017 to 70% in 2018 ($P = 0.0033$). This can be partially attributed to yield or fruit biomass in 2018, which accounted for an average of 7% of the total DW. In comparison, fruit production accounted for 8% and 13% of the standing plant biomass in a second-year planting of 'Duke' with sawdust and weed mat mulches, respectively (Larco et al., 2013). Allocation of total plant biomass differed between years for roots ($P = 0.0048$), old wood ($P = 0.0008$), whips ($P = 0.031$), and pruning wood ($P = 0.02$). Roots and whips represented a lower proportion of DW in 2018 than in 2017, whereas the opposite was found for old wood and pruning wood (data not shown).

Considering losses in DW, which included senesced leaves and pruning wood in both years and harvested fruit in the second year, net DW gain was greatest for plants grown with black weed mat over sawdust mulch and least for those grown with black weed mat alone (Fig. 4). The difference between these two treatments was obvious in 2018, whereas net DW for green weed mat over sawdust, green weed mat alone, and

Fig. 4. Effect of mulch (sawdust), polypropylene black weed mat (woven polypropylene groundcover), green weed mat, black weed mat over sawdust, and green weed mat over sawdust on dry weight gains and losses from planting through the end of the second growing season in 'Duke' blueberry plants in Oregon. Means $\pm$ SE (n = 5). Mulch had a significant effect on net gain in dry weight in 2017 ($P = 0.023$) and 2018 ($P = 0.0039$).

sawdust mulches were nearly identical after the second growing season.

In summary, we found no difference between black and green weed mat in the present study in terms of their effects on soil or plant canopy temperatures or plant growth responses. However, adding a layer of sawdust under the weed mat increased maximum canopy temperature and decreased soil temperature relative to using weed mat alone, leading to a larger root system in year 1 and a larger canopy in year 2. Total dry weight was also much higher when the plants were mulched with black weed mat over sawdust than with black weed mat alone. Apparently, sawdust served as an insulator between the weed mat and soil, thus reducing thermal conduction and increasing convective heat transfer to the canopy. Weed mat is very

effective for weed control and protects the sawdust layer from erosion, which, over time, may reduce costs relative to using sawdust only (Strik and Vance, 2017). Therefore, together, weed mat and sawdust may be a better option than either mulch alone in new plantings of northern highbush blueberry. As the planting matures, we will continue to examine the effects of the mulch treatments on yield and fruit quality, as well as on the mineral nutrition of the plants.

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