Plastic Biodegradable Mulches Reduce Weeds and Promote Crop Growth in Day-neutral Strawberry in Western Washington

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Abstract. Day-neutral strawberry (Fragaria ×ananassa) is typically grown in plasticulture production systems that use black polyethylene (PE) mulch for weed management and promotion of crop growth and yield. The objectives of this research were to evaluate several commercial plastic and paper biodegradable mulch (BDM) products [Bio360, Experimental Prototype (Exp. Prototype), and WeedGuardPlus] in comparison with standard black PE mulch and bare ground cultivation in day-neutral strawberry grown in an annual system in northwestern Washington. Mulch performance [as percent visual cover (PVC)], weed suppression, marketable yield, plant biomass, and fruit quality were evaluated in ‘Albion’ and ‘Seascape’ strawberry grown in 2014 and 2015. PVC measured at the end of the production season was lowest for the Exp. Prototype (8%) in 2014 and was greatest for Bio360 (90%), WeedGuardPlus (90%), and PE (98%). In 2015, PVC at the end of the production season was again lowest for Exp. Prototype (62%), followed by WeedGuardPlus (64%), Bio360 (93%), and PE mulch (97%). Overall, weed pressure was higher in 2015 relative to 2014 and was greatest in the bare ground treatment in both years of the study. By the end of the 2015 season, weed cover in the bare ground treatment was 95%, followed by WeedGuardPlus (50%), Exp. Prototype (34%), PE (25%), and Bio360 (15%). Yield showed year and cultivar effects and was higher in mulched treatments. Plant biomass showed varying effects; root biomass was lowest in ‘Seascape’ in 2015 under the bare ground treatment and greatest under Bio360, which was similar to PE mulch and WeedGuardPlus. Leaf biomass was lowest in the bare ground treatment and highest in mulched treatments (except in 2015, when leaf biomass was intermediate for plants grown with WeedGuardPlus). Crown biomass showed a similar trend and was overall greater for plants grown in mulched treatments except for Bio360 in 2014, which was the same as the bare ground treatment. Overall, fruit quality was maintained among strawberry grown with BDMs, with soluble solids concentration (SSC, %) and titratable acidity (TA) being the only variables to show treatment effects. SCC tended to be lower in fruit from bare ground plots. TA was different for ‘Seascape’ in 2015 with fruit from bare ground and Exp. Prototype treatments having higher TA than the PE treatment. This study demonstrates that BDMs can be comparable to PE mulch in terms of performance and impacts on crop productivity in day-neutral strawberry, suggesting that BDMs could be a viable alternative to PE mulch for strawberry growers in the Pacific Northwest.

Total U.S. strawberry (Fragaria ×ananassa) production was estimated to be 1.59 million t from 21,245 ha in 2016 [National Agricultural Statistics Service (NASS), 2017]. About 79% of the U.S. strawberry industry is concentrated in California, which predominately uses remontant/perpetual-flowering (i.e., day neutral) cultivars grown in annual plasticulture systems (California Strawberry Commission, 2017). Strawberry production in the Pacific Northwest (PNW), specifically Oregon and Washington, ranks fourth and fifth in national strawberry production, generating 5233 and 3810 t in 2016, respectively (NASS, 2017). The PNW strawberry industry traditionally produced fruit for processing and grew June-bearing cultivars in matted-row production systems without plastic mulch. This regional industry is currently undergoing a transition as acreage and production of processing strawberry declines because processors are increasingly buying cheaper strawberries from California. Consumption and value of fresh-market day-neutral strawberry is increasing, however, with the value of fresh market strawberry production in Washington and Oregon increasing 43% between the years 2000 and 2016 (NASS, 2001, 2017). Consequently, many PNW growers are exploring plasticulture production using day-neutral cultivars targeting the fresh market.

Black PE mulch is extensively used in plasticulture because of its low cost and ability to manage weeds, conserve soil moisture, modify soil temperatures, increase crop yields and quality, and promote on-farm profitability (Fernandez et al., 2001; Freeman and Gnaeyen, 2005; Garwood, 1998; Lament, 1993; Miles et al., 2012). These benefits extend to both conventional and organic production systems, as PE mulches may be used for weed management in organic agriculture as long as the mulch is completely removed from the field once the growing or harvest season is complete (§205.206 (United States Department of Agriculture; USDA, 2014a) and §205.601 (b)(2)(i–ii) (USDA, 2014b)]. Presently, plastic BDMs are not allowed in certified organic production, but may be a tool to enhance sustainability in nonorganic production systems (Miles et al., 2017).

Despite the horticultural and economic benefits of PE mulch, removal, and disposal imposes both financial and environmental problems. Removal and disposal of PE mulch can be costly (Galinato and Walters, 2012; Galinato et al., 2012; Ghimire and Miles, 2016; Lucas et al., 2008) and was estimated to be $1100 per hectare in strawberry systems in western Washington. These costs are expected to increase as the cost of labor increases (R. Sakuma, personal communication). To avoid these costs, some growers resort to stockpiling, landfilling, burying, or burning removed mulches, which causes hazards to the environment and human-health (Garthe and Kowal, 1993; Hakkarainen and Albertsson, 2004; Levitan, 2005). While mulch recycling is available in some regions, it is limited in the PNW and this adds to growers’ disposal costs for transport and cleaning of plastic mulch (G. Jones, personal communication). The significant transportation and labor costs needed to recycle PE mulch impede the adoption of plastic mulch recycling and the overall sustainability of plasticulture specialty crop production.

BDMs may minimize some of the economic, environmental, and human health impacts associated with PE mulches and their associated disposal (Kasirajan and Nguonqio, 2012; Miles et al., 2017). These materials are manufactured from feedstocks derived from fossil fuels plus natural materials (e.g., starch polysaccharides and cellulose, up to 20% of the BDM) (Jamshidian et al., 2010; Miles et al., 2017). BDMs are engineered to completely
biodegrade within 2 years, with 90% of their mass released as CO$_2$ and water and the remaining 10% residing in the soil as microbial biomass (according to International Organization for Standardization 17556 and ASTM D5988). BDMs are applied using the same field equipment as PE mulch and are designed to be functionally similar to PE mulch. BDMs have undergone extensive testing in vegetable production systems. Depending on the specific product, BDMs have been found to completely deteriorate within soils after 13 months of incorporation and produce yields comparable to crops grown with PE mulch (Cowan et al., 2013; Haapala et al., 2014; Li et al., 2014; Miles et al., 2012).

BDMs have not been tested widely in strawberry and could be a suitable alternative to PE mulch in expanding plasticiculture production systems. Bilck et al. (2010) found white and black BDMs made from blends of cassava (Manihot esculenta) starch and polybutylene adipate-co-terephthalate (PBAT) maintained yield and berry quality relative to PE mulch in short-day ‘Ventana’ strawberry grown in Brazil. Mechanical properties measured 8 weeks after application showed BDMs had reduced tensile strength and elongation at break, whereas film rigidity was higher relative to PE mulch. However, the BDM films were found to provide adequate mulch functionality in terms of groundcover and maintenance of yield in this production system. Yield and fruit quality were similar to PE mulch in short-day ‘Honor’ and ‘Camarosa’ strawberry grown with five BDMs made from Mater-Bi (Novamont S.p.A, Novara, Italy) in Portugal (Costa et al., 2014). BDMs have also been studied as a tool to suppress weeds and enhance establishment of short-day ‘Jewel’ and ‘Honeoye’ strawberry grown in a perennial matted-row system (Weber, 2003). Black polymer (IP40 Black) and paper mulch (Planters paper; Ken-Bar, Inc., Reading, MA) were effective at reducing weeds, but limited runner production necessary for matted-row establishment. Modification of soil temperature by mulches is an important aspect of strawberry production systems. White-on-black BDMs M2 and M3 (Mater-Bi) and M1 (Biomind; Polivouga, Albergaria-a-Velha, Portugal) in autumn–winter strawberry production showed 70%, 86%, and 20% soil coverage, respectively, at the end of the crop cycle, whereas PE mulch had 100% soil coverage (Andrade et al., 2014). Soil covered with these BDMs had 0.02 to 2.78 °C higher soil temperatures in the summer period at 15 cm depth than soils covered with PE mulch, which the authors of the study inferred was a key contributing factor to the reduced yields observed across all BDM-treated plots relative to PE. In other studies, soil treated with black BDMs (Ecoflex, BASF, Florham Park, NJ) overall showed a slightly lower soil temperature than low-density PE (LDPE, Pliant Corp., Schaumburg, IL) mulch at a depth of 1 cm in the soil (Ngoaquio et al., 2008). These studies show that different BDMs have different effects on soil temperature; the impact of BDMs on soil temperature will be an important factor in how well BDMs fit in strawberry production.

The objectives of this research were to evaluate several commercial plastic and paper BDM products and to compare them with standard black PE mulch and bare ground cultivation in day-neutral strawberry grown in an annual system in western Washington. Mulch performance, including deterioration and weed suppression ability, as well as impacts on plant growth, yield, and fruit quality were measured to assess mulch performance and suitability for commercial production systems.

**Materials and Methods**

**Plot establishment and maintenance.** The study was conducted at the Washington State University (WSU) Northwestern Washington Research and Extension Center in Mount Vernon, WA (lat. 48°26′28.9″N, long. 122°23′44.1″W). Soil is a field silt loam, characterized as a mixed, nonacid, and mesic Aquic Xerofluent (USDA, 2017). The experimental design was a randomized complete block split-plot with five mulch treatments and two strawberry cultivars replicated four times. The main plot treatment consisted of three BDMs, PE mulch, and bare ground (Table 1). The subplot treatments consisted of day-neutral strawberry cultivars, Albion and Seascape. The experiment was carried out in 2014 and repeated in 2015 in an adjacent field (soil type was still a field silt loam). Main plot treatments were hand-applied to 6.1-m-long raised bed plots in May 2014 and June 2015. Raised beds were formed using a mechanical bed shaper (Rain-Flo 2600; Rain-Flo Irrigation LLC., East Earl, PN). Resultant beds were 0.61 m wide, 0.25 m tall, spaced 4.3 m apart on the center; plots within a row were separated by 0.9 m. Before mulch application, pressure-compensating drip tape (20 cm emitter spacing, 1.3 LPH, Aqua-Traxx; Toro, Bloomington, MN) was centered on the raised beds. Tensiometers (Irrometer, Riverside, CA) were installed in the third replicate (row) of the bare ground and PE treatments at depths of 30.5 and 45.7 cm and were used to schedule irrigation. All plots were irrigated when tensiometers averaged ~30 kpa (Hoashi-Erhardt and Walters, 2014).

After mulch application in May 2014 and June 2015, bare-root ‘Albion’ and ‘Seascape’ strawberries were planted in all treatments in holes that were punctured with a 41-cm long dibble bulb and seed planter (DeWit Tools, TDI Brands, Jasper, IN). Resultant holes were 7.6 cm in diameter and 15.2 cm deep. The dibble was found to tear the paper mulch, so a knife with a 10-cm long blade was first used to cut an “X” shape in the mulch, which created four flaps that were folded and the dibble was subsequently used to create the planting holes. Planting holes were arranged in staggered double rows, with 25.4 cm between each twin row and 30 cm between plants within a row. Each plot contained 38 plants total, with 19 plants each of the cultivars Albion and Seascape. Any plants that failed to grow within 2 weeks after planting were replaced. All runners were removed from plants throughout the duration of the experiment and blooms were removed for 6 weeks before being allowed to form fruit.

The site was managed according to the recommended guidelines for day-neutral strawberry grown in western Washington (Hoashi-Erhardt and Walters, 2014). A custom blend preplant fertilizer (6N–8.7P–16.6K; Wilbur-Ellis Co., Burlington, WA) was broadcast at a rate of 20 kg·ha$^{-1}$ N 2 weeks before bed formation and planting in both years of the study. Supplemental fertilizer (20N–8.7P–16.6K; Plant Marvel Laboratories, Inc., Chicago Heights, IL) dissolved in water and injected through the irrigation system was provided beginning in July of both years at a rate of 5.6 kg·ha$^{-1}$ N per week. On 24 July 2015, 56 kg·ha$^{-1}$ of MgSO$_4$ (Magriculture; Premier Magnesia, LLC., Waynesville, NC) was applied through fertigation, and on 3 and 10 Aug. 2015, foliar applications of 8% CaCl$_2$ (Phyta-Cal QC; CA Organic Fertilizers, Inc., Hanford, CA) were applied at 4.7 L·ha$^{-1}$. Applications of MgSO$_4$ and CaCl$_2$ were made based on visual observations of symptoms indicating these nutrients were lacking and production guidelines (Hoashi-Erhardt and Walters, 2014).

**Data collection.** Soil temperature was recorded (HOBO U12 logger; Onset Computer, Bourne, MA) every 15 min throughout the growing season in 2014 and 2015.

Table 1. Mulch treatments evaluated in ‘Albion’ and ‘Seascape’ strawberry grown in Mount Vernon, WA, 2014–15.

| Mulch product | Company | Composition$^*$ |
|---------------|---------|-----------------|
| Bio360 | Dubois Agrinovation, Saint-Remi, Quebec, Canada | Mater-Bi = PBAT; biodegradable and compostable; black; 20 μm cellulose; biodegradable and compostable; maroon; 230 μm TPS and PHA; biodegradable and compostable; black; 20 μm |
| WeedGuardPlus | Sunshine Paper Co. LLC, Aurora, CO | TPS = polybutene adipate terephthalate; TPS = thermoplastic starch; PHA = polyhydroxyalkanoate; PE = polyethylene |
| Experimental prototype | Custom Bioplastics, Burlington, WA | Standard agricultural PE mulch; nondegradable; black; 20 μm |
| Polyethylene | Poly Expert, Laval, Quebec, Canada | PE = polyethylene |

$^*$PBAT = polybutylene adipate terephthalate; TPS = thermoplastic starch; PHA = polyhydroxyalkanoate; PE = polyethylene
were installed in one replicate block to a depth
of 10 cm and were 10 cm away from a plant
crown. Mean air temperature, relative hu-
midity, precipitation, and soil temperature
(recorded at 5 cm depth) were collected every
15 min from a weather station located 0.7 km
away and evaluated monthly from June
through September of each year (WSU
AgWeatherNet, 2017).

To assess mulch deterioration, visual obser-
vations of rips, tears, and holes were observed
and recorded as PVC of the soil on the
15th and 30th of each month during the
experiment. The percentage of weed cover
was also recorded to assess weed suppression
by the mulch treatment. PVC and weed cover
were determined in a permanently designated
0.6 m x 0.9 m area in the center of each split
plot were recorded within 48 h after harvest-
ing, with fruit being stored at 1.7
°C. Total marketable and unmarketable fruit weight
were picked by hand and transported to
harvested by subplot three times per week;
2014 and from 17 Aug. to 5 Oct. 2015 (6 and
50% PVC was reached in both years by the end of the growing season with
Bio360 (21.5 °C) and slightly lower under
WeedGuardPlus (20.4 °C) and the new
formulation of the Exp. Prototype (20.2
°C). Average soil temperatures between
June and Aug. 2014 and 2015 at 5 cm depth
from an adjacent area with mixed species
grass groundcover were 19.2 and 19.3 °C,
respectively.

Results

Environmental data. Weather conditions
from June through September were slightly
warmer and drier in 2015 relative to 2014
(Table 2). Compared with 2014, average air
temperature was 2 and 1 °C higher in June
and July 2015, respectively, similar in Au-
gust for both years, and 1.8 °C higher in Sept.
2015. Relative humidity was generally lower
throughout the growing season in 2015
(76.5%) than in 2014 (83.1%). Precipitation
from June through September was 10.5 mm
lower in 2015 (37.8 mm) than in 2014 (27.3
mm), with precipitation deficits occurring in
June and July of 2015.

Soil temperature was higher in 2015 than
2014; however, the data logger in the bare
ground treatment consistently malfunctioned
and data for Sept. 2014 and all of 2015 are not
reported for that treatment. Similarly, the
data loggers malfunctioned in Sept. 2015
across all treatments so those data are like-
wise not reported. A few notable differences
occurred with regard to soil temperature.
Between June and Aug. 2014, soil tempera-
tures averaged 19.8 and 19.7 °C in the
WeedGuardPlus and PE treatments, respec-
tively. Average soil temperatures for the
same time period were 20.0, 20.3, and
20.3 °C for the Bio360, Exp. Prototype, and
bare ground treatments, respectively. This
trend of soil temperatures among the mulch
 treatments was not observed in 2015. Soil
temperature from June through August in
2015 was highest under PE (21.7 °C) and
Bio360 (21.5 °C) and slightly lower under
WeedGuardPlus (20.4 °C) and the new
formulation of the Exp. Prototype (20.2
°C). Average soil temperatures between
June and Aug. 2014 and 2015 at 5 cm depth
from an adjacent area with mixed species
grass groundcover were 19.2 and 19.3 °C,
respectively.

PVC and weed pressure. PVC differed
due to treatment (P < 0.0001), but did not
differ due to year or cultivar (P = 0.62 and
P = 0.77, respectively). There was an interaction
between treatment and year (P = 0.003). By
the end of the growing season in 2014, PVC
reached 8% for the Exp. Prototype, whereas
PVC was 90% for both Bio360 and WeedG-
uardPlus and 98% for PE (Fig. 1). By the end
of the season in 2015, PVC reached 62% for
the Exp. Prototype, 64% for WeedGuardPlus,
93% for Bio360, and 97% for PE.

In 2014, there were minimal weeds across
all of the mulched treatments throughout the
growing season except bare ground plots,
which averaged 47% weed cover by the last
sampling time point on 30 Sept. (data not
presented). Percent weed cover in 2015

Table 2. Environmental and soil temperature data for day-neutral strawberry grown with different mulch
treatments in Mount Vernon, WA, 2014 and 2015.

| Variables | 2014 | 2015 |
|-----------|------|------|
| Air temperature (°C) | | |
| June | 15.1 | 17.8 |
| July | 18 | 15.8 |
| Aug. | 17.1 | 18.8 |
| Sept. | 17.9 | 14 |
| Relative humidity (%) | | |
| June | 82.3 | 80.7 |
| July | 84.0 | 85.3 |
| Aug. | 76.2 | 75.0 |
| Sept. | 72.7 | 81.9 |
| Precipitation (mm) | | |
| June | 29.0 | 32.8 |
| July | 22.4 | 22.1 |
| Aug. | 15.5 | 2.8 |
| Sept. | 37.1 | 53.6 |

*Environmental data (air temperature, relative humidity, precipitation, and nontreatment soil temperature)
data were collected from a weather station located 0.7 km from the experimental sites and were summarized
every 15 min from June through September of both years. Data courtesy of WSU AgWeatherNet.

**Soil temperature data for the bare ground treatment in Sept. 2014 and in 2015 are not presented due
to a logger malfunction; Sept. 2015 data also not reported due to a logger malfunction in the WeedGuardPlus,
Experimental Prototype, and PE treatments.
differed because of treatment across all sampling dates ($P = 0.0008$) and weeds significantly increased from strawberry planting to the end of the last sampling date in all treatments ($P < 0.0001$) (Fig. 2). By the end of the season, weed cover was greatest in the bare ground treatment (95%) followed by WeedGuardPlus (50%). Percent weed cover was intermediate in the Exp. Prototype (34%) and PE (25%), whereas Bio360 had the lowest weed cover (15%) (Fig. 2).

**Fruit yield.** Marketable yield and fruit number differed by cultivar, treatment, and year (Table 3). In 2014, ‘Albion’ marketable yield was the same across all mulch treatments and was higher than yield from the bare ground treatment ($P < 0.0001$). ‘Albion’ marketable yield in 2015 was lower than 2014, but was highest from plots treated with PE and plastic BDMs (Exp. Prototype and Bio360), intermediate for WeedGuardPlus, and lowest for bare ground plots ($P < 0.0001$). Marketable fruit number in ‘Albion’ was greater for all mulch treatments than the bare ground treatment in 2014. Bare ground plots of ‘Albion’ also had the lowest marketable fruit number in 2015, whereas plants treated with WeedGuardPlus had a lower leaf biomass than other mulch treatments. Leaf biomass was lowest in the bare ground control. Crown biomass did not differ due to the cultivar in 2015, with plants from all mulched plots producing higher biomass than bare ground.

**Fruit quality.** Only SSC showed a cultivar, year, and treatment difference, whereas fruit pH only differed due to year, and TA differed due to treatment only in ‘Seascape’ in 2015 (Table 4). ‘Albion’ SSC only differed in 2015 ($P = 0.05$), where it was higher in fruit harvested from the PE treatment when ‘Seascape’ marketable yield was greatest from plants treated with the Exp. Prototype and lowest in the bare ground plots in 2014, with the remaining treatments being similar ($P = 0.05$). In 2015, marketable yield was greatest in the PE treatment followed by Bio360 and the Exp. Prototype, WeedGuardPlus, and the bare ground. ‘Seascape’ marketable fruit number only responded to treatments in 2015, where the pattern was the same as 2015 marketable yield. Unmarketable berry weight showed a year effect and was not different in 2014, averaging 49 and 65 g/plot for ‘Albion’ and ‘Seascape’, respectively ($P$ value = 0.56 for ‘Albion’ and 0.675 for ‘Seascape’). In 2015, ‘Albion’ unmarketable berry weight was greatest in the PE treatment (46 g/plot) followed by WeedGuardPlus (31 g/plot), with Bio360 and Exp. Prototype being similar to PE and WeedGuardPlus (39 and 37 g/plot, respectively); unmarketable berry weight was lowest in the bare ground treatment (12 g/plot) ($P < 0.0001$). The trend of differences in unmarketable berry weight was similar in ‘Seascape’, with unmarketable berry weight greatest in the PE treatment (59 g/plot) followed by WeedGuardPlus (43 g/plot), with Bio360 and Exp. Prototype being similar to PE and WeedGuardPlus (50 g/plot for both treatments); unmarketable berry weight was lowest in the bare ground treatment (15 g/plot) ($P < 0.0001$).

**Dry biomass.** Plant biomass differed because of cultivar, year, and treatment (Table 4). There was a year and cultivar effect for root biomass and a treatment effect only in 2015 for ‘Seascape’. ‘Seascape’ root biomass was greatest under Bio360 mulch followed by WeedGuardPlus and PE, Exp. Prototype, and the bare ground control. There was no cultivar effect in both years of the study for leaf biomass, but there were effects due to year and treatment. Leaf biomass was higher across all treatments compared with bare ground control in 2014. In 2015, plants treated with plastic BDMs (Bio360 and Exp. Prototype) responded similarly to the PE treatment, whereas plants treated with WeedGuardPlus had a lower leaf biomass than other mulch treatments. Leaf biomass was lowest in the bare ground control. Crown biomass did not differ due to the cultivar in 2014 and was higher in the PE and Exp. Prototype treatments than the bare ground and Bio360 treatments, but was similar to WeedGuardPlus. In 2015, crown biomass differed by cultivar. ‘Albion’ treated with PE had the highest crown biomass and was similar to Bio360 and the Exp. Prototype, whereas crown biomass was similar among WeedGuardPlus, Bio360, and Exp. Prototype treatment plots. ‘Seascape’ crown biomass in 2015 was less responsive than ‘Albion’, with plants from all mulched plots producing higher biomass than bare ground.

**Fruit quality.** Only SSC showed a cultivar, year, and treatment difference, whereas fruit pH only differed due to year, and TA differed due to treatment only in ‘Seascape’ in 2015 (Table 5). ‘Albion’ SSC only differed in 2015 ($P = 0.05$), where it was higher in fruit harvested from the PE treatment when...
Table 3. Marketable fruit yield and number in ‘Albion’ and ‘Seascape’ strawberry grown with different mulch treatments in Mount Vernon, WA in 2014 and 2015.

| Treatment          | Albion Marketable fruit yield/plot (g) | Albion Marketable fruit number/plot | Seascape Marketable fruit yield/plot (g) | Seascape Marketable fruit number/plot |
|--------------------|----------------------------------------|-------------------------------------|-----------------------------------------|---------------------------------------|
|                    | 2014 | 2015 | 2014 | 2015 | 2014 | 2015 | 2014 | 2015 |
| Bio360             | 253 a 181 b 15 ab 311 ab 190 b 32 18 b |                                    |                                         |                                       |
| WeedGuardPlus      | 259 a 137.5 b 17 a 11 c 316 ab 144 c 30 13 c |                                    |                                         |                                       |
| Exp. prototype     | 281 a 181.9 a 20 a 14 b 340 a 202 b 32 18 b |                                    |                                         |                                       |
| Plastic (PE)       | 295 a 200.7 a 22 a 17 a 322 ab 239 a 32 22 a |                                    |                                         |                                       |
| Bare ground (control) | 126 b 80.0 c 9 b 6 d 257 b 96 d 25 8 d |                                    |                                         |                                       |

Table 4. Dry biomass of ‘Albion’ and ‘Seascape’ strawberry grown with different mulch treatments in Mount Vernon, WA in 2014 and 2015. Data are presented by year and cultivar when there was an interaction due to year or cultivar.

| Treatment          | Root biomass (g) | Crown biomass (g) |
|--------------------|------------------|-------------------|
|                    | 2014 2015 | 2014 2015 | 2014 2015 |
| Bio360             | 295 a 200.7 a 22 a 17 a 322 ab 239 a 32 22 a | 2014 2015 |
| WeedGuardPlus      | 281 a 181.9 a 20 a 14 b 340 a 202 b 32 18 b | 2014 2015 |
| Exp. prototype     | 295 a 200.7 a 22 a 17 a 322 ab 239 a 32 22 a | 2014 2015 |
| Plastic (PE)       | 295 a 200.7 a 22 a 17 a 322 ab 239 a 32 22 a | 2014 2015 |
| Bare ground (control) | 126 b 80.0 c 9 b 6 d 257 b 96 d 25 8 d | 2014 2015 |

Table 5. Total soluble solids concentration (SSC, %), juice pH, and titratable acidity (as percent citric acid; CA, %) of ‘Albion’ and ‘Seascape’ strawberry grown with different mulch treatments in Mount Vernon, WA in 2014 and 2015.

| Treatment          | Albion SSC (%) | Albion pH | Albion CA (%) | Seascape SSC (%) | Seascape pH | Seascape CA (%) |
|--------------------|----------------|----------|---------------|-----------------|------------|-----------------|
|                    | 2014 2015 | 2014 2015 | 2014 2015 | 2014 2015 | 2014 2015 | 2014 2015 |
| Bio360             | 2.3 8.1 6.5 a 3.4 4.7 b 3.7 abc 2.7 a | 2.3 8.1 6.5 a 3.4 4.7 b 3.7 abc 2.7 a | 2.3 8.1 6.5 a 3.4 4.7 b 3.7 abc 2.7 a |
| WeedGuardPlus      | 2.3 8.1 6.5 a 3.4 4.7 b 3.7 abc 2.7 a | 2.3 8.1 6.5 a 3.4 4.7 b 3.7 abc 2.7 a | 2.3 8.1 6.5 a 3.4 4.7 b 3.7 abc 2.7 a |
| Exp. prototype     | 2.3 8.1 6.5 a 3.4 4.7 b 3.7 abc 2.7 a | 2.3 8.1 6.5 a 3.4 4.7 b 3.7 abc 2.7 a | 2.3 8.1 6.5 a 3.4 4.7 b 3.7 abc 2.7 a |
| Plastic (PE)       | 2.3 8.1 6.5 a 3.4 4.7 b 3.7 abc 2.7 a | 2.3 8.1 6.5 a 3.4 4.7 b 3.7 abc 2.7 a | 2.3 8.1 6.5 a 3.4 4.7 b 3.7 abc 2.7 a |
| Bare ground (control) | 2.3 8.1 6.5 a 3.4 4.7 b 3.7 abc 2.7 a | 2.3 8.1 6.5 a 3.4 4.7 b 3.7 abc 2.7 a | 2.3 8.1 6.5 a 3.4 4.7 b 3.7 abc 2.7 a |

Discussion

Yield, plant biomass, and fruit quality of day-neutral strawberry grown with plastic BDMs were overall comparable to plants grown with PE mulch, whereas many of these variables were reduced for plants grown without mulch and were intermediate for plants grown with the paper BDM (WeedGuardPlus). Marketable yield and fruit number were greater in 2014 relative to 2015 because of the warmer, drier conditions during the 2015 June and July production period, which were less favorable for day-neutral strawberry production. Unmarketable berry weight was only different in 2015, but was overall high across both years because of tarnished plant bug (Lygus lineolaris) feeding and rigorous culling for size. However, unmarketable berry weight was greater for all mulched treatments among both cultivars in 2015, which may be due to microclimate effects impacting crop development and is an area recommended for further study. Nevertheless, bare ground plots consistently had the lowest marketable yield and fruit number, which was consistent with previous studies that show productivity of strawberry and other horticultural crops are enhanced through mulch application because of reduced competition from weeds and a modified soil environment that is more favorable to plant growth and development (Anzalone et al., 2010; Diaz-Perez et al., 2005; Forcella et al., 2003; Moore, 1963; Touchalàume et al., 2016; Waterer, 2010).

The current study showed cultivars can respond differently to BDM treatments. In general, ‘Albion’ appeared less sensitive to type of mulch application, with marketable yield and fruit number from plants treated with plastic BDMs being equal to those grown with PE mulch. Reduced yield from plants treated with the Exp. Prototype plastic BDM in 2015 can be attributed to greater weed pressure and resultant plant competition that may have been exacerbated by the warmer and drier environmental conditions that year. ‘Seascape’ had less consistent trends with regard to marketable yield and fruit number across the years of the study. Marketable yield was similar for all mulch treatments in 2014 but was strongly impacted by mulch treatment in 2015 when yield was greatest in plants treated with PE mulch, followed by the plastic BDM treatments, paper BDM, and was lowest in nonmulched plots. Taken together, these results suggest cultivar genetics may influence how day-neutral strawberry plants respond to different mulch treatments and that some cultivars may be more adaptable to systems that use BDMs. Similar to the yield results, plant biomass tended to be the lowest in bare ground, intermediate in the paper BDM treatment, and the greatest in PE and plastic BDM treatments. ‘Albion’ appeared less sensitive to mulch treatments with regard to root biomass, whereas ‘Seascape’ appeared less sensitive in regard to crown biomass, and both cultivars showed a similar response for leaf biomass. These results highlight how cultivar genetics lead to different developmental responses after mulch application and that environmental and weed pressure conditions of 2015 elicited more plant growth responses to mulch treatments when contrasted to 2014.

Root and leaf biomass were overall greater in 2015, which may have been an adaptive
response to the environmental conditions and come at the cost of decreased fruit production. Perennial plants augment growth and development during periods of environmental stress, such as temperature and moisture stress, and mulching can alleviate plant stress by suppressing weeds, enhancing soil moisture, and improving soil temperatures.

Kumar and Dey (2011) found that 'Chandler' strawberry plants grown with PE mulch, straw mulch, or bare ground had higher root growth when plants received irrigation (100%, 80% and 60% of volume of water) and lower root growth under rainfed conditions in a subtemperate climate in India. Soil moisture content at 0–25 cm was 2.8% to 12.8% higher under PE mulch than bare ground. In a separate study by Taparauskienë and Miseckaité (2014) in a subhumid area of Lithuania, soil moisture content at 0–40 cm depth was higher under straw mulch (18.0%) than under PE mulch (16.5%) or bare ground (16.2%), whereas strawberry fruit yield was 60% higher from plants grown with PE mulch than bare ground and 56% greater relative to plants grown with straw mulch.

Several studies have found that fruit quality is maintained or unchanged as a result of plastic BDM use (Blick et al., 2010; Costa et al., 2014). However, Morr et al. (2015) found increased production of secondary metabolites (anthocyanins, flavanols, and polyphenols) and greater antioxidant activity in strawberry grown with plastic BDM (with Mater-Bi as the primary feedstock) relative to those grown with PE mulch. While the current study did not measure these secondary metabolites, there was an overall trend of lower SSC in fruits harvested from the bare ground treatment relative to mulched treatments. This difference may be due to the diurnal absorption and reradiation of heat energy from the dark-colored mulches, which could impact soil and canopy temperatures. Mulches may also change the quality and quantity of light energy being reradiated into the plant canopy, which may impact plant development and resultant fruit quality. Research has shown that mulch color can impact strawberry crop development and quality attributes of fruit. For example, in strawberry production in central Colombia, silver color mulch resulted in lower fruit pH, SSC, TA, and dry biomass compared with red, blue, yellow, green, and black mulch treatments; the ratio of SSC to TA was highest with black mulch; fresh fruit weight and fruit length were highest with red mulch, which might be the result of absorbing more red and far-red light by phytochrome (Casierra-Posada et al., 2011; Kasperbauer et al., 2001). Wang et al. (1998) found that fruit of ‘Northeaster’ strawberry grown with red mulch had higher TA than fruit grown with black mulch.

All mulches reduced weed pressure relative to bare ground both years in the cooking study. This result is consistent with other studies that show plastic BDMs can provide efficacious weed suppression depending on their formulation and compatibility with the cropping system (Anzalone et al., 2010; Cowan et al., 2014; Miles et al., 2012). Despite rapid changes in PVC of the Exp. Prototype in 2014, weed cover was comparable to the other mulched treatments and indicates weed suppression was adequate for the experimental conditions. Because of the rapid degradation of the Exp. Prototype in 2014, the mulch manufacturer re-formulated the mulch product, and consequently, the Exp. Prototype deteriorated less rapidly in 2015 (the specifics of the reformation were not disclosed, as this was proprietary information of the mulch manufacturer). Exp. Prototype is made up of thermoplastic starch (TPS) and polyhydroxyalkanoate, which have been shown to have comparably high rates of above-ground disintegration (Cowan et al., 2013). Despite this, TPS has been successfully used in BDMs in strawberry production in Brazil (Blick et al., 2010). Bio360 (formerly BioTelo) was observed to have high rates of PVC in both years of the experiment and was comparable to the PE control. Percent weed cover was low for Bio360 and was comparable to PE. This result was similar to a study with tomato (Lycopersicum esculentum) in Washington that included BioAgri mulch, which has a similar formulation as Bio360 (Miles et al., 2012). The starch in Bio360 is characterized as highly biodegradable while the PBAT component is characterized as having a low to moderate rate of biodegradation in soil (Brodhagen et al., 2015).

For WeedGuardPlus, PVC was reduced and percent weed cover increased in 2015 due to the occurrence of several windy days in July 2015 (maximum wind gusts surpassed 12.9 km·h⁻¹, WSU AgWeatherNet, 2017), which caused the WeedGuardPlus mulch to rip and tear along the buried edges of the raised bed, creating more exposed surfaces for degradation. Weber (2003) reported similar experiences when using Planters Paper in establishing matted-row strawberry in New York, where degradation occurred rapidly along buried edges of the planting beds and allowed wind to rip fragments of the mulch off the beds. Similarly, studies with WeedGuardPlus in tomato grown in Washington confirm this material is susceptible to ripping and has low rates of PVC later in the growing season (Cowan et al., 2014; Miles et al., 2012). Performance of WeedGuardPlus, however, varied based on location and production system, and was found to have higher deterioration in open-field production in Washington relative to Texas, and lower deterioration in a high tunnel environment relative to open-field (Li et al., 2014). The primary feedstock in WeedGuardPlus is cel lulose, a plant-derived polysaccharide that is intrinsically biodegradable and is characterized as having a moderately high rate of biodegradation in soils (Brodhagen et al., 2015; Sivan, 2011). These findings underscore that the environment and cropping system must be considered when selecting a BDM, as mulch performance will vary based on these factors. Additionally, while complete biodegradation is an important feature of BDMs, paper-based mulches may be too quick to degrade and consequently may not provide adequate soil surface coverage for strawberry, depending on the production environment and growers’ goals.

**Conclusion**

The plastic BDMs studied in this experiment performed comparably to standard PE mulch and may provide a suitable alternative to PE mulch in plasticulture systems of day-neutral strawberry in the PNW. Bio360 was most similar to PE mulch in terms of PVC, weed suppression, and yield, indicating this material is compatible with commercial strawberry production systems and could replace PE mulch. Re-formulations of the Exp. Prototype could make it more compatible with the requirements of day-neutral strawberry production and additional testing of reformulated and new plastic BDMs (e.g., BASF Ecovio) is recommended. The question of in-soil biodegradation of these materials should also be pursued in future research, as there has been limited evaluation of in-soil biodegradation of plastic BDMs across different production systems and soil environments. It is important to note that while PE and paper BDMs are allowed in organic production, use of plastic BDMs is presently not permitted (Miles et al., 2017). Plastic BDMs may be a tool that enhances the sustainability of conventional strawberry production as a replacement for PE, but are also chemically and physically different from PE. Soil fumigation and concurrent BDM application is not allowed and producers should speak with mulch manufacturers if they have questions regarding how certain on-farm practices may impact plastic BDM performance. Overall, plastic BDMs are a promising tool for day-neutral strawberry growers and continued research on plastic BDMs as an alternative to PE could assist growers in reducing plastic waste generation while maintaining the profitability of their farm enterprises.

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