The Use of Biodegradable Mulches in Pie Pumpkin Crop Production in Two Diverse Climates

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Abstract
The use of plastic biodegradable mulch (BDM) in many vegetable crops such as tomato (Solanum lycopersicum L.), broccoli (Brassica oleracea L. var. italica), and pepper (Capsicum annuum L.) has been proven to be of equal benefit as polyethylene (PE) mulch. However, there are limited research findings on the performance of BDM with a large fruited crop such as pumpkin (Cucurbita pepo L.) where the fruit can rest directly on the mulch for an extended period. To investigate whether heavy fruit might cause the mulch to degrade more quickly than expected, thereby, influencing weed control, fruit yield, and fruit quality including mulch adhesion on fruit, we carried out a field experiment in 2015 and 2016 at two locations in the United States with distinctive climates, Mount Vernon, WA and Knoxville, TN. Three plastic mulches marketed as biodegradable (BioAgri, OrgaNix, and Naturecycle), one fully biodegradable paper mulch (WeedGuardPlus), and one experimental plastic BDM consisting of polyactic acid and polyhydroxyalkanoates (Exp. PLA/PHA) were evaluated against PE mulch and bare ground where ‘Cinnamon Girl’ pie pumpkin was the test crop. There was significant weed pressure in the bare ground plots at both locations over both years, indicating viable weed seed banks at the field sites. Even so, weed pressure was minimal across mulch treatments at both locations over both years because the mulches remained sufficiently intact during the growing season. The exceptions were Naturecycle in 2015 at both locations because of the splitting of the mulch and consequently higher percent soil exposure (PSE), and the penetration of all the plastic mulches at Knoxville by nutsedge (Cyperus sp. L.); nutsedge did not penetrate WeedGuardPlus. At Mount Vernon, overall pumpkin yield across both years averaged 18.1 t·ha⁻¹, and pumpkin yield was the greatest with PE, Exp. PLA/PHA, BioAgri, and Naturecycle (19.9–22.8 t·ha⁻¹), intermediate with Organix and WeedGuardPlus (15.3–18.4 t·ha⁻¹), and the lowest for bare ground (8.7 t·ha⁻¹). At Knoxville, overall pumpkin yield across both years averaged 17.7 t·ha⁻¹, and pumpkin yield did not differ because of treatment (15.3–20.4 t·ha⁻¹). The differences in yield between treatments at Mount Vernon were likely because of differences in the soil temperature. At 10 cm depth, the average soil temperature was 1 °C lower for bare ground and WeedGuardPlus as compared with PE mulch and plastic BDMs (20.8 °C). In contrast, soil temperatures were generally higher (25.2 to 28.3 °C) for all treatments at Knoxville and more favorable to crop yield compared with Mount Vernon. Forty-two percent to 59% of pumpkin fruit had mulch adhesion at harvest at Mount Vernon, whereas only 3% to 12% of fruit had mulch adhesion at Knoxville. This difference was because of the location of fruit set—at Mount Vernon, most of the fruit set was on the mulch whereas at Knoxville, vine growth was more extensive and fruit set was mostly in row alleys. Fruit quality differences among treatments were minimal during storage across both locations and years except for total soluble solids (TSS) in 2016, which was lower for bare ground and WeedGuardPlus compared with all the plastic mulches. Taken overall, these results indicate that pie pumpkin grown with BDM has fruit yield and quality comparable to PE mulch; however, adhesion of some BDMs on fruit could affect marketable yield. Furthermore, paper mulch appears to prevent nutsedge penetration.

Polyethylene mulch has been used in agriculture for more than 60 years and contributes to crop yield and quality by reducing weed pressure and herbicide use, moderating soil temperature, and conserving soil moisture (Emmert, 1957; Ibarra-Jimenez et al., 2006; Kasirajan and Ngouajio, 2012; Lamont, 2005). In 2011, PE mulch was applied on nearly 20 million ha in China with use projected to grow 7% or more annually (Liu et al., 2014). At nearly the same time, in 2012, an estimated 89.2 thousand t of PE mulch was used in North America, and the projected use is estimated to be 106 thousand t in 2017 (MarketsandMarkets, 2012).

Despite its many benefits, PE mulch is difficult to recycle as it is contaminated with soil and/or vegetation (up to 50% by weight) (Kasirajan and Ngouajio, 2012). Currently, only 10% of agricultural plastics are recycled (Grossman, 2015; Levitan and Barros, 2003), mostly because not all facilities will accept PE because of the difficulty of removing adhering soil and plant debris (Levitan and Barros, 2003). PE mulch removal and disposal in a landfill is costly, up to $584/ha (Galinato and Walters, 2012; Galinato et al., 2012). The lack of affordable recycling and disposal choices has left farmers with few end-of-life options for PE mulch at the end of the growing season. Thus, many farmers dispose used PE mulches in landfills, or stockpile it on-site, whereas others till it into the soil or burn it on-site (Kasirajan and Ngouajio, 2012).

Mulch that can be tilled into the soil after crop harvest and thereafter biodegrades in the soil may provide farmers with an environmentally beneficial and low-cost disposal option. Several BDM alternatives to PE mulch have been developed, including paper and plastic BDMs. Although paper mulch has been shown to fully biodegrade in soil (Haapala et al., 2014; Li et al., 2014), it tends to breakdown too rapidly during the growing season, especially along the sides of the bed where there is direct soil contact (Merfield, 2000; Miles et al., 2012). Also, brown paper mulch (WeedGuardPlus: Sunshine Paper Co., Aurora, CO) has been shown to lower soil temperature by 0.5 and 1 °C compared with bare ground in open field and high tunnel tomato production systems, respectively, resulting in lower yields compared with black PE mulch (Cowan et al., 2014). Plastic BDM has been reported to perform similarly to PE mulch with regard to soil temperature and yield. Studies in Spain (Anzalone et al., 2010; Martín-Closas et al., 2008) and the United States (Cowan et al., 2014) found that tomato yield is similar when plants are grown with black plastic and brown paper BDMs compared with black PE mulch in most years. In one study, the percentage of ripe fruit was lower for brown paper and black plastic BDMs compared with black PE mulch only in 1 year of a 3-year study (Anzalone et al., 2010). Waterer (2010) compared the field performance of black and clear BioTelo (consisting of Mater-Bi polymeric resin; Novamont, Novara, Italy) and...
black and clear PE mulch for the production of five warm season vegetable crops ['Na- 
vajo’ sweet corn (Zea mays L.), ‘Goldrush’ zucchini (C. pepo), ‘Fastbreak’ muskmelon 
(Cucumis melo L. var. reticulatus), ‘Redstart’ pepper, and ‘Dusky’ eggplant (Solanum mel-
ongena L.)] over three cropping seasons in Saskatchewan, Canada. No significant dif-
ferences in soil temperature, crop growth, or yield responses were found for the BDMs as 
compared with the same color of PE mulch, whereas mulch adhesion on fruit was not 
mentioned.

Weed control is the primary function of mulch; thus, a BDM must remain intact on 
the soil surface long enough to provide a barrier to weed seed germination and 
growth. The critical period of weed control for tomato is 4–5 weeks after transplanting 
(Weaver and Tan, 1983). During this time, competition with weeds may decrease plant 
size and the number of marketable fruit. PE mulch and two plastic BDMs (both Mater-Bi 
based) gave similar weed suppression throughout the tomato production season, 
despite 15% of the bed becoming exposed because of mulch deterioration for BDMs 
(Minuto et al., 2008). Cowan et al. (2014) likewise found that tomato yield was not 
reduced by weed growth that occurred when soil was exposed over the course of the 
growing season because of mulch deteriora-
tion. Pumpkin has a relatively long growing 
season, and the critical period for weed 
control has been estimated to last until 4–6 
weeks after planting (Schonbeck, 2015).

When growing fruit rest on BDMs, prob-
lems can arise with the durability of the 
mulch because of the weight and pressure 
imposed by the fruit, and the quality of the 
fruit because of adhering mulch fragments. 
Limpus (2012) reported that melon, tomato, 
pepper, and eggplant fruit resting on the 
surface of plastic BDMs can cause the mulch 
to split, although growers did not indicate the 
splitting to be widespread. BDM fragments 
did adhere to the surface of the tomato and 
pepper fruit, but the adhering mulch was 
easily removed. However, C.A. Miles (un-
published data) reported BDM fragments adhering to the surface of watermelon (Cit-
rullus lanatus) fruit that could not be wiped 
off.

Fruit quality is another important consid-
eration for crops grown with BDM. There 
was no difference in fruit TSS because of 
mulch when Rangarajan and Inglall (2006) 
measured the quality of ‘Athena’ muskmelon 
grown with four plastic BDMs and a PE 
mulch. Filippi et al. (2011) evaluated melon 
grown with two BDMs (black and green, both 
Mater-Bi based) and a PE mulch in Italy in 
2004, and then again with three plastic BDMs 
two green and one black) and a PE mulch in 
2005. BDMs produced higher yield than PE 
mulch, whereas fruit TSS and percent dry 
matter (DM) content were higher with BDMs 
in 2004, but not in 2005.

Although several studies have evaluated 
BDM deterioration, weed pressure, and crop 
yield and quality, no studies have used pie 
pumpkin as a test crop. Pie pumpkin and 
similar cucurbit crops are economically im-
portant crops and are grown worldwide. The 
selection of pie pumpkin as the test crop in 
this study allowed for nearly identical plant-
 ing and harvest dates at Mount Vernon and 
Knoxville test sites, despite their major cli-
mate differences. Pumpkin leaves and stems 
have enlarged, rigid and sharp thichomes that 
are abrasive and could contribute to mulch 
tearing. As pumpkin fruit mature and become 
heavier, there can be substantial fruit-to-
mulch contact that might accelerate mulch 
deterioration through splitting, and/or lead 
to mulch adhesion on fruit and fruit quality 
losses.

The fruit is often stored for several 
months, especially by fresh-market growers, 
and it is uncertain if a BDM has an impact on 
the quality of stored fruit. The objectives 
of the current study were to evaluate the 
deterioration of five BDMs throughout two 
pie pumpkin growing seasons (June—Sep-
tember in 2015 and 2016) in two diverse regions of the United States (Mount Vernon, WA and 
Knoxville, TN), and to compare these BDMs 
with PE mulch and bare ground for weed 
control and impact on pie pumpkin total fruit 
yield, marketable yield, and fruit quality at 
harvest and during 8-week storage.

Materials and Methods

Experimental locations. This study was 
carried out at two locations in 2015 and 2016: 
the Washington State University (WSU) 
Northwestern Washington Research and Ex-
tension Center at Mount Vernon, WA 
(48°43′24″N, 122°39′09″ W, elevation 6 m) and 
the University of Tennessee, East Ten-
nessee AgResearch and Education Center at 
Knoxville, TN (35°52′52″N, 83°55′27″W, 
elevation 270 m). The Mount Vernon field site 
was located in the maritime Pacific Northwest, 
where the summer climate is mild and humid 
with 15 °C average daily temperature, 82% 
relative humidity (RH), and 150 mm rainfall
At both locations, missing plants in the field were replaced up to 4 weeks after seeding/ transplanting, when transplant size was equivalent to the size of plants in the field.

**Fertilizer and irrigation.** Fertilizer application was performed according to recommended practices for pumpkin in each region. At Mount Vernon, fertilizer was applied before planting at the rate of 117 kg N/ha, 51 kg P/ha, 48 kg K/ha, 16 kg S/ha, and 11 kg Ca/ha in 2015; and 120 kg N/ha, 52 kg P/ha, 50 kg K/ha, 16 kg S/ha, and 12 kg Ca/ha in 2016. At Knoxville both years, fertilizer was applied before planting and additionally through fertigation (four times in 2015 and six times in 2016), for total nutrient application of 89.6 kg N/ha, 24.5 kg P/ha, 107.8 kg K/ha, and 14.5 kg Ca/ha in 2015; and 112.2 kg N/ha, 24.5 kg P/ha, 138.4 kg K/ha, and 28.7 kg Ca/ha in 2016. At both locations, drip irrigation tape (T-Tape, Model 508-08-340, 0.20 mm, 20 cm emitter spacing, 4.23 L/min/100 m flowrate, San Diego, CA) was laid simultaneously with mulch during bed shaping. Drip irrigation rate was based on moisture sensors (ST; Decagon Devices, Inc., Pullman, WA) installed at each location in row 3 of the PE mulch treatment in one replicate block at 10 and 20 cm depths, and data were recorded with data loggers (EM50G; Decagon Devices, Inc.).

**Weather data.** Air temperature, solar radiation, RH, and rainfall data were collected from the WSU AgWeatherNet station located ≈140 m from the field site at Mount Vernon. At Knoxville, air temperature and rainfall were collected from the U.S. National Oceanic and Atmospheric Administration station located 12 km from the field site, and solar radiation was collected from the Plant Sciences Unit weather station located near the field site, and RH was recorded from a weather station (VP-3; Decagon Devices, Inc.) installed 10 m away from the experimental site. Soil temperature and moisture sensors (ST; Decagon Devices, Inc.) were installed in row 3 of each plot in one replicate block at 10 cm and 20 cm depths and data were recorded at 60 s intervals and averaged hourly using data loggers (EM50G; Decagon Devices, Inc.) at both locations.

**Weed management.** The planting holes in mulch treatments and a 5 cm diameter area around each plant in the bare ground treatment were hand weeded as needed throughout the growing season at both locations. At Mount Vernon, herbicides (Curb EC 3.5 L-ha⁻¹, Gramoxone SL 2.3 L-ha⁻¹, In-Place 239.6 g L⁻¹, Glyn Star Original 372.7 mL-ha⁻¹, and R-56 190 mL-ha⁻¹) were applied to alleys posttransplanting in 2015. No herbicide was applied pre- or posttransplanting in 2016. At Knoxville both years, postemergence herbicides (2.34 L-ha⁻¹, Dual II Magnum 1.47 L-ha⁻¹, and Command 1.86 L-ha⁻¹; RoundUp WeatherMax, Monsanto, St. Louis, MI) were applied to alleys between the raised beds. The bare ground plots were the weedy control for the whole growing season in 2015 and until most of the critical weed control period had passed in 2016. In 2016, weed pressure became severe in bare ground plots at both locations, thus those plots were hand weeded 35 and 56 d after transplanting at Mount Vernon and 30 d after planting at Knoxville.

### Table 1. Mulch treatments evaluated in 'Cinnamon Girl' pumpkin grown at Mount Vernon, WA and Knoxville, TN in 2015 and 2016. Thickness, ingredient(s) and biobased content information was obtained from each mulch manufacturer.

| Mulch treatment | Manufacturer | Color | Thickness (mm) | Key product ingredient(s) | Biobased (%) |
|-----------------|--------------|-------|----------------|--------------------------|--------------|
| BioAgri | BioBag Americas, Inc., Dunedin, FL | Black | 0.0180 | Mater-Bi grade EF04P (starch–copolyester blend) | 20–25 |
| Exp. PLA/PHA | Experimental film | Black | 0.0250 | IngeoPLA®/Mirel amorphous PHA | 86 |
| Naturecycle | Custom Bioplastics, Burlington, WA | Black | 0.0254 | Starch–polyester blend | ≥20 |
| Organix | Organix Solutions, Maple Grove, MN | Black | 0.0178 | BASF Ecovio M2351 (PBAT + PLA) | 10 |
| Polyethylene | FilmIntech, Allentown, PA | Black | 0.0254 | Polyethylene | <1 |
| WeedGuardPlus | Sunshine Paper Co. | Black | 0.2400 | Cellulose | 100 |

²Composition (%) of mulch that is from biological products or renewable materials; biobased content can be important, for example the USDA National Organic Program requires a biodegradable mulch to be 100% biobased to allow its use in organic agriculture.

²Not available in market, prepared for this study by Metabolix, Inc., Cambridge, MA.

PLA = polylactic acid; PHA = poly(hydroxyalkanoate); PBAT = poly(butylene adipate-co-terephthalate).
results

Weather data. At Mount Vernon, the 2-year average daily air temperature for the pumpkin growing season (June–September) was 17 °C, RH was 76%, total solar radiation was 2260 MJ m⁻² (9% greater in 2015 than 2016), and total rainfall was 140 mm (90 mm in 2015 and 190 mm in 2016) (Table 2). At Knoxville, the 2-year average daily air temperature was 25 °C, RH was 80%, total solar radiation was 1907 MJ m⁻² (14% greater in 2015 than 2016), and total rainfall was 239 mm (354 mm in 2015 and 123 mm in 2016). During pumpkin storage at Mount Vernon in 2015 and 2016 (September–November), the average ambient temperature was 18 and 15 °C, and the average RH was 78% and 71%, respectively (Fig. 1). At Knoxville during pumpkin storage, the average ambient temperature was 18 and 22 °C, and the average RH was 82% and 61% in 2015 and 2016, respectively.

The 2-year average soil temperature during the pumpkin growing season at Mount Vernon was 20.5 °C at 10 cm depth (1.8 °C higher in 2015 than 2016) (Table 2). At Knoxville, the 2-year average soil temperature was 26.8 °C at 10 cm depth (2.0 °C lower in 2015 than 2016). In 2015 at Mount Vernon, soil temperature was 3 °C lower for bare ground and WeedGuardPlus, and 1.8 °C lower for all plastic BDMs, compared with PE (23.3 °C). In 2016, soil temperature was 1 °C lower for bare ground, WeedGuardPlus and Organix as compared with all other plastic mulches (20 °C on average). In 2015 at Knoxville, soil temperature also was the lowest for bare ground and WeedGuardPlus (25.3 °C on average), but was the highest for Organix (26.9 °C). In 2016, soil temperature was the lowest for WeedGuardPlus (26.7 °C) compared with all other treatments (27.8 °C on average). Soil temperature at 20 cm depth was similar as at 10 cm, and followed the same trends (data not reported).

Percent soil exposure. PSE differed because of treatment and year, and because of interacting effects of treatment and year; treatment and location; and treatment, year, and location (P < 0.0001 for all). However, PSE did not differ because of location, and there was no interaction between location and year. PSE increased over sampling time at both locations over both years (P < 0.05 for all). At Mount Vernon in 2015, PSE was the highest for Naturecycle compared with other mulch treatments, and reached 61% by the end of the season (Fig. 2). PSE for PE, Exp. PLA/PHA, WeedGuardPlus, and Organix was low throughout the growing season and reached 0.3% to 8% by the end of the season. In 2016, PSE was low for all the mulch treatments (0% to 6.5%). At Knoxville in 2015, Naturecycle reached 100% PSE 3 weeks after pumpkin sowing, WeedGuardPlus reached 100% PSE 1 month before harvest, and BioAgri reached 36% PSE at the end of the growing season (Fig. 2). PSE for PE, Exp. PLA/PHA and Organix was low throughout the growing season and reached 2% to 7% by the end of the season. In 2016, PSE was the lowest for PE mulch (5.5%), whereas PSE for all other mulch treatments was 14.3% to 25%.

Weed measurement. Predominant weeds at Mount Vernon were pigweed (Amaranthus sp. L.), chickweed (Stellaria media L.), and common lambsquarer (Chenopodium sp. L.), whereas predominant weeds at Knoxville were nutedge (Cyperus sp.), carpetweed (Mollugo sp. L.), and goosegrass (Galium aparine L.). At Mount Vernon in 2015, dry weight of weeds was not measured at 2 weeks after transplanting, but at midseason and 2 weeks before harvest, there were weeds (388 and 475 g m⁻², respectively) only in bare ground except 0.1 g m⁻² of weeds in Naturecycle 2 weeks before harvest (P = 0.04 and P < 0.0001, respectively). Also, in 2016, there were weeds (dry weight 15 g m⁻²) only in bare ground treatment 2 weeks after transplanting (P < 0.0001). At Knoxville in 2015, dry weight of weeds was higher for the bare ground treatment and Naturecycle 2 weeks after transplanting (59 and 9 g m⁻², respectively) (P = 0.0005), midseason (199 and 33 g m⁻², respectively) (P < 0.0001), and 2 weeks before harvest (71 and 25 g m⁻², respectively) (P = 0.0002) compared with all other treatments, where there were minimal weeds (0–13 g m⁻²). In 2016, dry weight of weeds was high for the bare ground treatment 2 weeks after transplanting (91 g m⁻²) (P < 0.0001), midseason (56 g m⁻²) (P < 0.0001), and 2 weeks before harvest (168 g m⁻²) (P < 0.0001), whereas there were minimal weeds in all the mulched treatments (0.8–17 g m⁻²).

Table 2. Environmental and soil temperature data during the pumpkin growing season at Mount Vernon, WA and Knoxville, TN in 2015 and 2016.

| Environmental parameters | Mount Vernon<sup>2</sup> | Knoxville<sup>3</sup> |
|---------------------------|--------------------------|----------------------|
| Average daily air temperature (°C) | 17.4 | 16.4 | 24.9 | 25.9 |
| Average daily maximum air temperature (°C) | 23.7 | 22.2 | 30.3 | 32.5 |
| Average daily minimum air temperature (°C) | 11.5 | 11.2 | 19.6 | 20.8 |
| Total solar radiation (MJ m⁻²) | 2,359 | 2,161 | 2,033 | 1,781 |
| Relative humidity (%) | 75.7 | 77.1 | 81.6 | 77.9 |
| Total rainfall (mm) | 90 | 190 | 354 | 123 |

<sup>2</sup>Data from Washington State University AgWeatherNet Station located =40 m from the field site.
<sup>3</sup>All 2015 data were collected from the National Oceanic and Atmospheric Administration Station at McGhee Tyson Airport, located 12 km from field site, except solar radiation, which was recorded at the Plant Sciences Unit Weather Station located near the experiment, and humidity, which was acquired from sensors (VP-3; Decagon Devices, Inc.) at the field site. 5 Aug. to 16 Sept. 2015. In 2016, all data were collected at a Decagon Weather Station, located 10 m from the field site.
<sup>z</sup>Data at Mount Vernon were pigweed (Amaranthus sp. L.), carpetweed (Stellaria media L.), and common lambsquarer (Chenopodium sp. L.), whereas predominant weeds at Knoxville were nutedge (Cyperus sp.), carpetweed (Mollugo sp. L.), and goosegrass (Galium aparine L.). At Mount Vernon in 2015, dry weight of weeds was not measured at 2 weeks after transplanting, but at midseason and 2 weeks before harvest, there were weeds (388 and 475 g m⁻², respectively) only in bare ground except 0.1 g m⁻² of weeds in Naturecycle 2 weeks before harvest (P = 0.04 and P < 0.0001, respectively). Also, in 2016, there were weeds (dry weight 15 g m⁻²) only in bare ground treatment 2 weeks after transplanting (P < 0.0001). At Knoxville in 2015, dry weight of weeds was higher for the bare ground treatment and Naturecycle 2 weeks after transplanting (59 and 9 g m⁻², respectively) (P = 0.0005), midseason (199 and 33 g m⁻², respectively) (P < 0.0001), and 2 weeks before harvest (71 and 25 g m⁻², respectively) (P = 0.0002) compared with all other treatments, where there were minimal weeds (0–13 g m⁻²). In 2016, dry weight of weeds was high for the bare ground treatment 2 weeks after transplanting (91 g m⁻²) (P < 0.0001), midseason (56 g m⁻²) (P < 0.0001), and 2 weeks before harvest (168 g m⁻²) (P < 0.0001), whereas there were minimal weeds in all the mulched treatments (0.8–17 g m⁻²).
**Fruit yield.** Pumpkin yield differed because of treatment \((P < 0.0001)\), and the yield was influenced by interacting effects of treatment and location \((P = 0.009)\), and location and year \((P < 0.0001)\). However, the yield did not differ because of location and year, and there were no interactions between treatment and year; and treatment, location, and year. At Mount Vernon, overall mean pumpkin yield for both years was 18.1 t·ha\(^{-1}\), whereas yield was higher in the PE, Exp. PLA/PHA, BioAgri, and Naturecycle treatments compared with the bare ground and WeedGuardPlus treatments (Table 3). At Knoxville, overall mean pumpkin yield for both years was 17.7 t·ha\(^{-1}\), and yield did not differ because of treatment. The average pumpkin yield at Mount Vernon for all treatments combined was higher in 2015 than in 2016 (20.1 and 16.1 t·ha\(^{-1}\), respectively), but was lower in 2015 than in 2016 at Knoxville (15.7 and 19.7 t·ha\(^{-1}\), respectively).

The number of fruit per hectare differed because of treatment and location, and there were interactions between treatment and location, location and year \((P < 0.0001)\) for all, and treatment, location, and year \((P = 0.015)\). However, the number of fruit did not differ because of year, and there was no interaction between treatment and year. At Mount Vernon for both years combined, the number of fruit per hectare was higher in the PE treatment than for the other treatments, and the number of fruit in all four plastic BDM treatments was significantly higher than the WeedGuardPlus treatment; the bare ground treatment had fewer fruit than all other treatments (Fig. 3). At Knoxville, the number of fruit per hectare did not differ because of mulch treatment. At Mount Vernon, the average number of fruit for all the treatments combined was higher in 2015 than in 2016 (15,891 and 12,901 fruit/ha, respectively), whereas at Knoxville, the average number of fruit for all the treatments was lower in 2015 than in 2016 (10,390 and 14,157 fruit/ha, respectively).

**Mulch adhesion.** Percentage of fruit with mulch adhesion differed because of treatment and location, and there was an interaction between treatment and location \((P < 0.0001)\) for all. All other two-way and three-way interactions were insignificant. At both locations over both years, there was no mulch adhesion on fruit in the PE mulch treatment. At Mount Vernon, 0.4% of the fruit in the Exp. PLA/PHA treatment had mulch adhesion, whereas all the other BDM treatments had 3% to 12% fruit with mulch adhesion. At Knoxville, most of the pumpkin fruit set was outside the mulched bed because of the longer vine growth, and there was no significant difference in the yield of pumpkins with mulch adhesion; 6% of the total yield for the five mulch treatments had mulch fragments adhered to the fruit.

**Postharvest fruit quality.** TSS of fruit did not differ because of treatment, but differed because of year \((P < 0.0001)\) and location \((P = 0.02)\). There was an interaction between treatment and year \((P = 0.04)\), and location and year \((P < 0.0001)\). However, there was no interaction between treatment and location, and treatment, location and year. TSS was not influenced by the interaction of mulch treatment and sampling interval. Overall TSS was higher at Mount Vernon \((8.10 \text{ Brix})\) than Knoxville \((7.89)\), and higher in 2015 \((8.13)\) than 2016 \((7.87)\). Although TSS in 2015 did not differ because of mulch treatment, in 2016 TSS was higher in fruit grown on PE, Organix, Naturecycle, and BioAgri than for fruit grown on bare ground across both locations (Table 4). TSS increased from harvest to 2 weeks of storage and then declined over the storage period, such that TSS at 8 weeks was the same as TSS at harvest (data not shown). DM of fruit did not differ because of mulch treatment either year, and did not differ over 8 weeks of storage (data not presented).

**Discussion.** PE mulch and plastic BDMs raised soil temperature by 1 to 1.8 °C at 10 cm depth compared with bare ground and WeedGuardPlus, which is in line with Cowan et al. (2014) and Miles et al. (2012). Deterioration of the BDMs varied by location and year. In 2015, deterioration of Naturecycle was substantial and started primarily along the center fold line shortly after laying, even before planting, because of heavy rainfall coupled with strong wind. Naturecycle in 2016 had the same formulation as in 2015, but was not folded, and very low PSE occurred. This observation suggests that the higher PSE in 2015 was due to the fold. PSE for WeedGuardPlus and BioAgri tended to be greater at Knoxville than Mount Vernon in 2015, likely because of heavy rainfall at Knoxville early in the season. Changes in the physicochemical properties of the mulches due to environmental weathering during the 2015 crop growing season are reported elsewhere (Hayes et al., 2017). In 2016, PSE at both locations was relatively low for all treatments by the end of

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**Table 3. Total fruit yield (t·ha\(^{-1}\)) for 'Cinnamon Girl' pumpkin in 2015 and 2016 (years combined), and fruit yield with mulch adhesion (t·ha\(^{-1}\)) in 2016 at Mount Vernon, WA and Knoxville, TN.**

|                      | Mount Vernon | Knoxville |
|----------------------|--------------|-----------|
| Bare ground          | 8.70 d       | 15.27     |
| BioAgri              | 20.86 ab     | 18.79     |
| Exp. PLA/PHA\(^a\)   | 20.90 ab     | 16.34     |
| Naturecycle          | 19.92 ab     | 17.28     |
| Organix              | 18.38 bc     | 19.86     |
| Polyethylene         | 22.75 a      | 20.39     |
| WeedGuardPlus        | 15.28 c      | 16.16     |
| Total pumpkin yield  |              |           |
| with mulch adhesion  |              |           |

|                      | Mount Vernon | Knoxville |
|----------------------|--------------|-----------|
| NA                   | NA           |           |
| 8.13 b               | 1.29         |
| 0.32                 |              |
| 1.30                 |              |
| 1.79                 |              |
| 0                    |              |
| 0.82                 |              |
| 0.07                 |              |

\(^a\)Treatment means compared using Fisher’s least significant difference at \(\alpha = 0.05\). Treatment means followed by the same letter within a column are not significantly different.

\(^\text{Experimental film made with polylactic acid (PLA)/polyhydroxyalkanoate (PHA) polymers.}\)

NA = not applicable.
The season (±7% at Mount Vernon and ±25% at Knoxville) compared with 2015, where PSE in some plots reached 63% and 100% by the end of the season at Mount Vernon and Knoxville, respectively. Knoxville had higher average air and soil temperature (7.5 and ≈5 °C higher, respectively) compared with Mount Vernon. Other studies have found that BDM deterioration increases with increased solar radiation, temperature, rainfall, and humidity (Kijchavengkul et al., 2008; Miles et al., 2012).

There were essentially no weeds in any of the mulch treatments at Mount Vernon and very few weeds at Knoxville in both years because mulches remained sufficiently intact during the growing season. One exception was Naturecycle in 2015, where weed pressure at both locations corresponded to the high PSE of this mulch. Another exception at Knoxville was with nutseed, which penetrated all the plastic BDMs and the PE mulch in both years. Only the paper mulch, WeedGuardPlus, provided a satisfactory barrier to nutseed, similar to the findings of Cirujeda et al. (2012b), Haapala et al. (2015), and Shogren and Hochmuth (2004). As plastic mulches are more pliable and much thinner than paper mulches, the needle-like growing tip of nutseed could penetrate all the plastic mulches. In the early growing season, black plastic mulch controls weeds by limiting light reaching weed seeds and seedlings, resulting in reduced viable weed seeds in the bed. Therefore, even if mulch starts degrading after the first weed flush is suppressed, weed severity will be reduced. There was heavy weed pressure in the bare ground plots at both locations in both years, indicating that there was a significant weed seed bank in the plots and the mulches indeed provided a barrier to weed emergence and/or growth. Other studies have also found that plastic BDMs controlled weeds equal to PE mulch (Anzalone et al., 2010; Cowan et al., 2014; Miles et al., 2012).

Total average pumpkin yield for both years at Mount Vernon was the highest with black plastic mulches (PE, Exp. PLA/PHA, BioAgri, and Naturecycle), likely because of higher soil temperatures beneath them compared with the lighter colored WeedGuardPlus mulch and bare ground treatments. Similarly, Haapala et al. (2015) saw increased yield of cucumber (Cucumis sativus) from soil warming due to dark-colored paper and plastic BDMs compared with bare ground or lighter colored paper. However, at Knoxville, total pumpkin yield did not differ because of mulch treatments, where the average soil temperature was higher than at Mount Vernon, and was similar among all mulch treatments. These results suggest that mulching may not increase crop yield during the summer in warmer regions provided that there is satisfactory weed control. The overall average pumpkin yield was higher at Mount Vernon in 2015 compared with 2016, and likely was because of higher solar radiation (9% higher), air temperature (1 °C higher), and soil temperature (1.8 °C higher) in 2015 than in 2016. At Knoxville, the overall average pumpkin yield was lower in 2015 than in 2016, because strong spring storms with heavy rains, wind, and hail not long after planting slowed plant growth initially in 2015. In addition, Knoxville had higher air temperature (1 °C higher) and soil temperature (1.8 °C higher) in 2016 than in 2015. Miles et al. (2012) reported that increased soil temperature under the mulch treatment appeared to favor tomato yield. Many other studies have reported crop yield to be similar for plastic BDMs and PE mulch, e.g., lettuce (Lactuca sativa) (Brault et al., 2002), melon (Filippi et al., 2011; Iapichino et al., 2014; Shogren and Hochmuth, 2004), tomato (Cirujeda et al., 2012a; Cowan et al., 2014; Martin-Clossas et al., 2008; Moreno and Moreno, 2008), and cucumber (Wortman et al., 2016).

Lower TSS in fruit grown on bare ground than in plastic mulched beds at both locations in 2016 was likely because of the environmental differences noted previously. Although, it is also possible that low TSS in fruit grown on bare ground was because of less plant vigor, and lower nutrient and water uptake, but these measurements were not taken in this study. Cowan et al. (2014) also found higher TSS in tomato fruit grown on PE and BDMs compared with bare ground. This result suggests that mulches can improve fruit TSS compared with bare ground. We observed that mulch fragments tended to continue to adhere on fruit over the 8 weeks of storage. There was no difference in the storage quality because of mulch treatment, but TSS was not measured specifically for fruit with mulch adhesion. Pumpkin marketable yield was reduced at Mount Vernon both years because of adhesion of BDM (except Exp. PLA/PHA) on fruit at places where the fruit rested on the mulch during the growing season. By contrast, mulch adhesion was relatively low at Knoxville because most of the pumpkin fruit set was outside the mulched bed because of longer vine growth. Observations at both locations indicated that adhered mulch could be wiped off fruit in the early morning, when fruit were damp from morning dew; however, as the temperature increased, and the mulch dried on the fruit, the mulch became more difficult to remove. Adhesion of BDM can be an important issue for crops such as pumpkin.
or watermelon where fruit rest on the mulch surface and remain in direct contact during the growing season. Labor cost increases when adhered mulch must be cleaned from the fruit, and marketable yield decreases if these fruit have to be discarded because of quality concerns. Also, mulch adhesion on fruit increases the risk of plastics entering the food processing stream and impairing the quality and food safety of the products and byproducts. The main outcomes from the current study indicate that total yield and quality of pumpkin grown with BDMs are comparable to PE mulch, however, fruit that rest for prolonged times on BDMs may have mulch adhesion that can reduce marketable yield, and paper mulch can prevent nodule settlement.

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