Deterioration of Potentially Biodegradable Alternatives to Black Plastic Mulch in Three Tomato Production Regions

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Abstract. Four potentially biodegradable mulch products (BioAgri, BioTelo, WeedGuardPlus, and SB-PLA-10) were evaluated during 2010 in three contrasting regions of the United States (Knoxville, TN; Lubbock, TX; and Mount Vernon, WA) and compared with black plastic mulch and a no-mulch control for durability, weed control, and impact on tomato yield in high tunnel and open field production systems. WeedGuardPlus, BioTelo, and BioAgri had the greatest number of rips, tears, and holes (RTH) and percent visually observed deterioration (PVD) at all three sites ($P \leq 0.05$), and values were greater in the open field than high tunnels, likely as a result of high winds and greater solar radiation and rainfall. SB-PLA-10 showed essentially no deterioration at all three sites and was equivalent to black plastic in both high tunnels and the open field. Weed growth at the sites did not differ in high tunnels as compared with the open field ($P > 0.05$). Weed growth at Knoxville and Mount Vernon was greatest under SB-PLA-10 ($P \leq 0.02$), likely as a result of the white, translucent nature of this test product. Tomato yield was greater in the high tunnels than open field at all three sites ($P \leq 0.03$), except for total fruit weight at Knoxville ($P \leq 0.53$). Total number of tomato fruit and total fruit weight were lowest for bare ground at both Knoxville (150×10^4 fruit/ha and $29 \text{ t} \cdot \text{ha}^{-1}$; $P \leq 0.04$) and Mount Vernon (44×10^4 fruit/ha and $11 \text{ t} \cdot \text{ha}^{-1}$; $P \leq 0.008$). At Knoxville, the other mulch treatments were statistically equivalent, whereas at Mount Vernon, BioAgri had among the highest yields (66×10^4 fruit/ha and $16 \text{ t} \cdot \text{ha}^{-1}$). There were no differences in tomato yield resulting from mulch type at Lubbock.

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plastic mulch covered $\approx 162,000$ ha in the United States alone (P. Bergholtz, personal communication). Disadvantages of plastic mulches include their long-term persistence in the environment as well as the economic costs of yearly removal and disposal. These costs hinge on available labor, equipment, and infrastructure (Olsen and Gounder, 2001; Schonbeck, 1995) and in 2004 were estimated to be $\approx \$250$ per hectare (Shogren and Hochmuth, 2004).

The recycling of agricultural plastics is available in limited areas of the United States. Major obstacles to the recycling of agricultural plastics include: 1) contamination resulting from soil and mixing of different plastic (resin) types; 2) high cost of long-distance transport of plastic wastes from remote collection sites; and 3) high price of the recycled resin as compared with virgin resin on the open market (Garthe and Kowal, 1993). As a result of the difficulty and expense of agricultural plastic recycling, many growers choose to dispose of this waste through local landfills (Olsen and Gounder, 2001; Shogren, 2000). However, some growers burn their plastic waste (Shogren and Hochmuth, 2004), which has deleterious effects on environmental and human health.

The ideal agricultural mulch would be made from renewable, natural, and sustainable raw products; have low overall environmental impact (for raw materials, manufacturing, and disposal); be affordable (in purchase, application, removal, and disposal); suppress weeds; sustain crop yields; and retain functionality throughout the cropping season (Miles et al., 2009). Costs associated with mulch removal and disposal could be avoided if degradable or biodegradable mulches were tilled into the soil after harvest (Anderson et al., 1995; Olsen and Gounder, 2001). Environmental costs could also be reduced if the mulches were compostable.

Degradable plastic agricultural mulches were first introduced in the 1980s, but those products were photodegradable rather than biodegradable, and they disintegrated or fragmented into smaller pieces of plastic (Riggle, 1998). A major issue at the time these products entered the market was a lack of consensus regarding the definition of “degradable.” In the last decade, U.S. stakeholders (researchers, manufacturers, marketers, etc.) have created standards to define degradation and established widely accepted testing strategies to evaluate the behavior of degradable products [American Society for Testing and Materials/Institute for Standards Research (ASTM, 2004)]. According to ASTM D 883-11 (ASTM, 2011), “degradation” is “a deleterious change in the chemical structure, physical properties, or appearance of a plastic” irrespective of cause, whereas “biodegradation” “results from the action of naturally-occurring micro-organisms such as bacteria, fungi, and algae.” Although there are currently ASTM standards for measuring biodegradation in specific environments such as accelerated bioreactor landfill conditions [D 5526-94(2011)e1 (ASTM, 2011c), D 7475-11 (ASTM, 2011d)], anaerobic digesters

Since its introduction to agriculture in the 1950s, polyethylene plastic has become the standard mulch used by specialty crop growers to control weeds, conserve soil moisture, increase crop yield, modify soil temperature, and shorten the time to harvest (Hill et al., 1982; Schonbeck, 1998; Schonbeck and Evanylo, 1998; Shogren, 2000). Plastic mulch has contributed significantly to the economic viability of farmers worldwide (Takakura and Fang, 2001); by 2006, it was estimated that

[D 5511-11 (ASTM, 2011b)], controlled composting [D 5338-11 (ASTM, 2011a), D 5988-03 (ASTM, 2003), D 6340-98(2007) (ASTM, 2007b)], marine environment [D 6691-09 (ASTM, 2009)], and municipal sewage sludge [D 5210-92(2007) (ASTM, 2007a), D 6340-98(2007) (ASTM, 2007b)], currently there is none for biodegradation in the soil environment, although one is under development [R. Narayan, personal communication; ASTM WK 29802, 2012 (ASTM, 2011f)]. In contrast to degradation and biodegradation, “deterioration” is the loss of physical or mechanical strength as observed through physical testing, microscopic imaging, or visual assessment and may be the result of abiotic and/or biotic factors.

The use of degradable or biodegradable mulches could reduce or eliminate costs associated with plastic mulch removal and disposal as well as decrease the total amount of disposed plastic waste. However, there are many questions and concerns regarding the efficacy, degradability, and potential residues of biodegradable petroleum-based mulches (Greer and Dole, 2003; Hochmuth, 2001; Shogren, 2000). As a result, alternative mulches such as paper and starch have been created from non-petroleum feedstocks. Numerous paper mulch products have been tested over the last century with variable results (Brault and Stewart, 2002; Flint, 1928; Knavel and Mohr, 1967; Shogren, 2000). The density and fiber orientation of paper mulches may impact light penetration, which can influence both weed seed germination and growth beneath the mulch. Weeds growing under paper mulch can push the mulch off the soil surface resulting in tearing (Miles et al., 2005). Use of paper mulch is further limited by its heavier weight, which is two to four times greater than that of plastic mulch and incurs increased costs and labor for shipping and handling. In addition, paper mulch can be very difficult to lay with mechanical mulch laying equipment (Sorkin, 2006). However, as a result of its natural fiber composition, paper mulch remains of high interest to growers concerned about the negative impacts of non-degradable plastic mulch.

Mulch film products composed primarily of starch are relatively new to the market, are similar in appearance (weight, density, and texture) and handling properties compared with standard polyethylene mulches, and may be a viable alternative to polyethylene-based mulch (Kijchavengkul et al., 2008; Rangarajan et al., 2003). New experimental materials such as spunbond (SB) polylactic acid (PLA) have recently been developed as potential alternatives to polyethylene mulches (Wadsworth et al., 2009). However, it is unclear how starch- and PLA-based mulch alternatives perform in high tunnel (HT) and open field (OF) production systems across diverse environments. The objective of this study was to evaluate and compare three mulch products marketed as biodegradable (two starch-based and one cellulose-based), and one experimental PLA-based product, to black plastic mulch under two production systems (HTs and OF) in

three contrasting regions (Knoxville, TN; Lubbock, TX; Mount Vernon, WA) in the United States. Mulch deterioration, weed control attributes, and impact on tomato yield were the principal performance factors measured.

Materials and Methods

Plot establishment and maintenance

This study was conducted in 2010 at three distinct and diverse field sites: the University of Tennessee, Knoxville East Tennessee Research & Education Center (lat. 35°52'52" N, long. 83°55'27" W, elevation 270 m) located in the subtropical southeast with a hot and humid summer climate (22 °C average daily temperature and 73% average relative humidity) and Dewey silt loam, a fine kaolinitic thermic Typic Paleudults with 6.8 soil pH and 13 g organic matter/kg soil; the Texas A&M AgriLife Research & Extension Center at Lubbock (lat. 33°41'38" N, long. 101°49'51" W, elevation 993 m) located on the High Plains with a hot and dry summer climate (22.5 °C average daily temperature and 59% average relative humidity) and Acuff clay loam, a fine mixed thermic Aridic Paleustolls with 7.4 soil pH and 12 g organic matter/kg soil; and the Washington State University Mount Vernon Northwestern Washington Research & Extension Center (lat. 48°43'24" N, long. 122°39'09" W, elevation 6 m) located in the Pacific Northwest with a cool, humid summer climate (15 °C average daily temperature and 83% average relative humidity) and Skagit silt loam, a fine-silty mixed nonacid mesic Typic Fluvaquents with 6.5 soil pH and 26 g organic matter/kg soil. Soil pH was determined by saturated paste, NAPT # S-1.10, and soil percent organic matter was measured by loss on ignition, NAPT # S-9.20.

The study included four replicates of two main plots (HTs and OF) with randomized subplots of four degradable mulch treatments plus black plastic mulch and hand-weeded bare ground as control treatments (Table 1). At Knoxville and Lubbock, the experimental design was a split plot with no blocking or randomization of main plot treatments resulting from space, shading, and environmental constraints; at both of these locations, main plots were located immediately adjacent to each other. At Mount Vernon, the study design was a randomized complete block split plot. At all three sites, each subplot measured 1.8 m wide × 4.3 m long in one center bed of each HT and corresponding OF block, and the crop was ‘Celebrity’ tomato. High tunnel models were selected based on grower preferences in each region and included Windjammer Series 5000 (Cold Frame; Griffin Greenhouse & Nursery Supplies, Knoxville, TN) measuring 29.3 m long × 9.2 m wide at Knoxville; ClearSpan ‘Colossal’ (ClearSpan, Windsor, CT) measuring 29.3 m long × 9.2 m wide at Lubbock; and, Haygrove ‘Solo’ (Haygrove Ltd., U.K.) measuring 36.5 m long × 8.4 m wide at Mount Vernon. Plastic covering was DuraFilm Super 4 (AT Films, Inc., Edmonton, Alberta, Canada) with 92% optical transmission at Knoxville; PolyMax Clear Woven

Greenhouse Covering (FarmTek, Dyersville, IA) with 88% light transmission at Lubbock; and Tufflite IV (Berry Plastics Corp., Evansville, IN) with unspecified light transmission at Mount Vernon. Beds measured 0.6 to 0.9 m wide and spacing between bed centers was 1.8 m at all three sites. Before mulch application, the beds were mechanically tilled and drip tape was centered on the bed. Drip tape at Knoxville and Mount Vernon was T-Tape (Deere & Company, Moline, IL), 508-8-340 low flow (0.5 LPH), 1.6 cm diameter, 0.2 mm wall thickness, and 20 cm emitter spacing; at Lubbock, it was Netafim (Tel Aviv, Israel) Typhoon 636 0125F, 0.9 LPH, and 31 cm emitter spacing. Mulch treatments were laid by hand on the dates indicated in Table 2 and coincided with climatic conditions appropriate for tomato transplanting at each site. To lay mulches, furrows were formed at the edge of the bed, mulch was laid in each plot with the sides placed within the side furrows, and soil was backfilled by hand to keep the mulch tight over the bed surface.

A hand-operated bulb planter was used to create 10-cm diameter holes 0.6 m apart in a single continuous row in each bed with seven holes per subplot. Tomato seedlings 6 to 9 weeks old were transplanted on the dates listed in Table 2. Planting dates were similar for HTs and the OF at Lubbock and Mount Vernon because tunnels were newly erected just in time for the OF season. At all three sites, tomato plants were pruned to one or two central leaders and staked using a Florida Weave training system (Kelbert et al., 1966). At Knoxville, water was applied by irrigation twice per week at 67 m³·ha⁻¹ per application from transplanting until the end of the growing season. At Lubbock, plants received 268 m³·ha⁻¹ of water by drip irrigation at transplanting, and thereafter water was applied twice per week at 134 m³·ha⁻¹ per application until the end of the growing season, except when rain fell daily from 27 June through 12 July and totaled 210 mm; all plots, including those inside the HTs, remained under water for more than 1 week. At Mount Vernon, water was applied by drip irrigation once per week at 134 m³·ha⁻¹ per application starting at transplanting and then twice per week at 66 m³·ha⁻¹ per application from 12 Aug. until the end of the growing season.

Insect and disease management practices varied by site. At Knoxville, late blight was managed with four sprays of copper hydroxide (Champ WG; Albaugh, Inc., Ankeny, IA) applied at 3.4 kg·ha⁻¹ on 4, 17, and 30 June and 14 July using the SOLO 430-1G handheld sprayer (Newport News, VA). At Lubbock, Natural Guard® Insecticidal Soap (Voluntary Purchasing Group, Inc., Bonham, TX) was applied on 24 and 28 May and 1, 4, 7, 11, 15, 18, and 23 June at 20 mL·L⁻¹; and both spinetoram (Radiant®; Dow AgroSciences, Indianapolis, IN) and azadirachtin (Aza-Direct®; Gowan Co., Yuma, AZ) were applied at 4.0 mL·L⁻¹ and 6.2 mL·L⁻¹, respectively, on 18 June and 7 July for thrips, whitefly, and mite control. Sprays at Mount Vernon included four applications of Pyganic Crop

Table 1. Mulch treatments evaluated in high tunnel and open field tomato culture at Knoxville, Lubbock, and Mount Vernon in 2010.

Mulch product	Company	Mulch composition
BioAgri® Ag-Film	BioBag, Palm Harbor, FL	Cornstarch and non-disclosed biopolymers; biodegradable and compostable; 0.02 mm; black
BioTelo Agri	Dubois Agrinovation, Waterford, Ontario, Canada	Cornstarch and non-disclosed biopolymers; biodegradable and compostable; 0.02 mm; black
Weed Guard Plus®	Sunshine Paper Co. LLC, Aurora, CO	Cellulosic; biodegradable control; 0.23 mm; black
SB-PLA-10	NatureWorks LLC, Blair, NE	Experimental nonwoven spunbond, white, translucent, 100% poly(lactic acid); 0.64 mm; white
Plastic	Pliant Corp., Schaumburg, IL	Standard agricultural polyethylene plastic (control); 0.03 mm; black

Protection EC 1.4 (MGK Company, Minneapolis, MN) on 11 June, 9 and 19 July, and 4 Aug. at a rate of 15.6 mL·L⁻¹ (5.8 L·100 m⁻¹) for aphid and thrips control and two applications of NuCop 50 WP (Albaugh, Inc., Ankeny, IA) at 3.4 kg·ha⁻¹ in 138 L·ha⁻¹ on 20 Aug. and 3 Sept. to delay onset of late blight. In addition, Organic BioLink Cal Plus (Westbridge, Vista, CA) was applied to tomato foliage (0.7 L·ha⁻¹) on 8 and 22 Sept. for blossom end rot control.

Organic fertilizers were used at all three sites. At Knoxville, Soybean Meal (7N–0.9P–0.8K) (Foothills Farmers Co-Op, Maryville, TN) was broadcast-applied at 33.6 kg N/ha to bed centers and incorporated. Schafer's liquid fish fertilizer (2N–0.9P–0.2K) (Thomson, IL) was applied at 1.12 kg N/ha/d every 15 d from 14 May to 15 July for a total of five applications. At Lubbock, composted cattle manure mixed with cotton burrs was broadcast-applied over the entire trial site on 27 Oct. 2009 at 40 kg N/ha and incorporated to a depth of 15 cm. During the growing season, Fish Emulsion Fertilizer (5N–0.4P–0.8K) (Fertilome®, Voluntary Purchasing Group, Bonham, TX) was applied at 5.6 kg·ha⁻¹ biweekly through drip irrigation beginning at transplanting for a total of 10 applications. At Mount Vernon, Par 4 (9N–1.3P–5.8K) (North Pacific Ag Products, Portland, OR) was broadcast-applied at 90 kg N/ha to bed centers and incorporated to ≈15 cm. Converted Organics (4.5N–0.9P–0.8K) fertilizer (Converted Organics of California LLC, Gonzales, CA) was injected into the drip irrigation system weekly at 1.12 kg N/ha/d every 10 d beginning at transplant until 13 Aug. (six applications) and every 7 d, from 27 Aug. to 24 Sept. (four applications).

Data collection

Air and soil temperatures, percent relative humidity, photosynthetically active radiation (PAR), and average wind and wind gust speeds were recorded every 15 min from time of transplanting through final harvest using a Hobo U30-NRC weather station (Onset Computer, Bourne, MA) located within the center of each main plot in one replicate block at each site. Soil temperature was measured 5 cm from the center plant at a depth of 5 cm in each plot. Within a designated 1.5 m × 0.6-m bed area in the center of each plot in every replication, total number of RTH, not including the holes punched for transplanting, were counted twice per month at Lubbock and Mount Vernon. PVD, in which 0% represented completely intact and 100% represented fully deteriorated, was assessed in the same plot area twice per month at Knoxville and Mount Vernon. Mulch was removed from

Table 2. Tomato planting dates and growing environment characteristics in high tunnels (HT) and the open field (OF) at Knoxville, Lubbock, and Mount Vernon during 2010.^z

	Knoxville		Lubbock		Mount Vernon	
	HT	OF	HT	OF	HT	OF
Mulch laying	23 Mar.	4 May	7 May	7 May	25 May	25 May
Tomato planting	26 Mar.	5 May	7 May	7 May	27 May	3 June
Mulch removal	11 Aug.	11 Aug.	8 Oct.	8 Oct.	18 Oct.	8 Oct.
No. d mulch in place	141	99	154	154	146	136
GDD ^y (base 10 °C)	1795	1463	1799	1661	1007	740
Avg. daily maximum air temp. (°C)	34.2	33.5	31.9	32.6	24.2	21.1
Avg. daily minimum air temp. (°C)	17.5	18.7	24.7	18.9	10.5	9.7
Avg. soil temp. at 5 cm depth						
BioAgri	26.2	27.0	26.2	25.6	18.9	17.7
BioTelo	27.0	26.8	25.9	26.6	19.3	18.1
SB-PLA-10	26.5	26.6	24.9	24.6	18.7	17.0
Weed Guard Plus	25.7	26.3	26.9	26.6	18.3	16.7
Black plastic	27.8	27.3	27.2	28.2	19.8	18.9
Bare ground	26.9	26.7	24.9	25.2	18.7	16.8
Avg. solar radiation ^x (μmol·m ⁻² ·s ⁻¹)	369	513	315	486	324	397
Relative humidity (%)	74.1	79.2	66.2	66.7	79.7	81.3
Avg. wind speed ^w (km·h ⁻¹)	0	1.9	0.2	6.4	1.1	3.3
Total rainfall (mm)	0	156	NA ^v	333.5 ^u	0	235.5 ^v

^zAt Knoxville, data collected in the high tunnel from 9 Apr. until 11 Aug. as a result of sensor malfunction and 6 May until 11 Aug. in the open field; at Lubbock, data collected in the high tunnel from 9 June until 8 Oct., and in the open field from 17 May to 2 Sept. as a result of weather monitoring sensor delays and malfunctions; at Mount Vernon, data collected from 25 May to 8 Oct.

^yGrowing degree-days (GDDs) calculated base 10 °C as [(T_{max}+T_{min})/2]-10] with negative daily degree-days converted to zero.

^xAverage solar radiation is photosynthetically active radiation (μmol·m⁻²·sec⁻¹) for the period of time mulch was in place.

^wWind speed measured above the tomato canopy: 150 cm above soil surface at Knoxville, 245 cm at Lubbock, and 160 cm at Mount Vernon.

^vNA = not available.

^uAt Lubbock, 210 mm (63% of total) occurred 27 June through 12 July, resulting in significant flooding within the high tunnel plots for 1 week.

^vMount Vernon precipitation data from AgWeatherNet station at WSU Mount Vernon NWREC (<<http://www.weather.wsu.edu>>).

HT = high tunnel; OF = open field.

an area measuring 0.6 m × 1 m at tomato first-flower (one fully open flower on every plant in each main plot) and after final harvest at Knoxville and Mount Vernon. Weeds were counted and fresh weights recorded and included those growing through RTHs as well as those found under the mulch. Total number of fruit (fruit/ha) and total fruit weight (kg·ha⁻¹) were measured for the seven plants per plot over the entire harvest period at all three sites.

Statistical analyses

All data were subjected to analysis of variance (ANOVA) using PROC MIXED in SAS (Statistical Analysis System Version 9.2 for Windows™; SAS Institute, Cary, NC). At Knoxville and Lubbock, data were analyzed as a completely randomized split plot design. At Mount Vernon, data were analyzed as a randomized complete block split plot design. Statistical analyses at all three locations compared production system (main plots), mulch (subplots), and production system × mulch

interactions. At Knoxville and Lubbock the Kenward and Roger (1997) method was used to determine denominator df (DDFM) for F-tests in the analysis, whereas at Mount Vernon, the Satterthwaite (1946) method was used to determine DDFM. Treatment means were compared for significant differences using Fisher's least significant difference test at alpha level 0.05. Main effects are presented for weed management and fruit yield data as a result of no significant production system × mulch interactions. However, as a result of a high incidence of significant production system × mulch interactions, RTH and PVD data were analyzed separately by production system using PROC GLM in SAS. Weed measurements and fruit yield data were analyzed as a split plot using PROC MIXED in SAS as a result of no significant production system × mulch interactions. At all three field sites, a hand-weeded bare ground treatment was included in the mean comparisons for fruit yield to relate the bare ground means to previously established regional yields.

Some data required transformation before analysis to meet the assumptions of normality and homogeneity of variance for ANOVA; the most appropriate transformation was selected using the range method described by Kirk (1982).

Results

Environmental comparison. The length of time that mulch was in place was indicative of the length of the cropping season and was 40% longer in HTs than in the OF at Knoxville, equivalent at Lubbock, and 7% longer in HTs than the OF at Mount Vernon (Table 2). At Knoxville, environmental data were only measured for 123 d in the HT (87% of the study period) and 96 d in the OF (97% of the study period) as a result of equipment malfunctions. Nevertheless, measured growing degree-days (base 10 °C) in HTs were 23% greater as compared with the OF. At Lubbock, environmental data were only measured for 121 d in the HT (79% of the study period) and 108 d in the OF (70% of the study period) again resulting from equipment malfunctions. Measured growing degree-days were 8% greater in HTs than in the OF, and this finding may have been the result of the greater number of measurement days. At Mount Vernon, growing degree-days were measured 136 d in both HTs (93% of the study period) and the OF (100% of the study period) as a result of late arrival of the weather monitoring equipment. Similar to Knoxville, there were 36% more growing degree-days in the HT than the OF at Mount Vernon.

The average soil temperature at 5 cm was 8.2 °C lower at Mount Vernon than at Knoxville and Lubbock (Table 2). Soil temperatures were similar in HTs and OFs at Lubbock and Knoxville, whereas at Mount Vernon, the average soil temperature was 1.5 °C warmer in the HT than the OF. Average soil temperatures tended to be highest for black plastic mulch at all three sites in both HTs and the OF and lowest for paper mulch at Knoxville and Mount Vernon and for SB-PLA-10 mulch and bare ground at Lubbock. In all cases, soil temperature was elevated under black plastic mulch as compared with bare soil, a difference of 1.7 °C on average. The average soil temperature was similar to or greater than the average air temperature in all cases except Lubbock HTs where the average mulch soil temperature was 2.3 °C lower than the average air temperature, potentially as a result of decreased solar radiation in the HT.

Average solar radiation (*PAR*) was decreased 28%, 35%, and 18% in HTs vs. the OF during the same measurement period at Knoxville, Lubbock, and Mount Vernon, respectively. Reduced *PAR* in HTs compared with the OF at Knoxville and Lubbock was likely the result of dust coating the HT plastic covering at those sites. Relative humidity was 7% and 2% lower in HTs than the OF at Knoxville and Mount Vernon, respectively, but approximately equivalent at Lubbock. Average wind speed (km·h⁻¹) was two- to 32-fold lower in HTs compared with the OF

at all three sites with maximum wind gust speeds exceeding 30 km·h⁻¹ in the OF during 24 d at Knoxville, 70 d at Lubbock, and 14 d at Mount Vernon. The maximum wind gust speed exceeded 30 km·h⁻¹ in HTs only during 1 d and only at Mount Vernon.

Mulch deterioration. The number of RTH at Lubbock and Mount Vernon differed as a result of production system ($P \leq 0.05$) and mulch treatment ($P \leq 0.05$), and there were significant ($P \leq 0.05$) interactions between production system and mulch treatment on most rating dates; thus, the data are presented separately by HTs and the OF (Table 3). At Lubbock HTs, the number of RTH ranged from 0 to 1.5 early in the season and did not differ by mulch treatment. By midseason, WeedGuardPlus had significantly greater RTH ($P = 0.003$) than the other treatments except BioAgri. At the end of the season, the number of RTH was greatest for WeedGuardPlus followed by BioTelo and BioAgri ($P < 0.0001$). In the OF, BioTelo and BioAgri had more RTH than other treatments at the beginning of the season ($P < 0.0003$), but by the end of the season, WeedGuardPlus had more RTH than any other treatment ($P < 0.0001$). At the end of the season, the average number of RTH in HTs was similar to the average number in the OF for all mulch treatments except BioTelo, which had two times the number of RTH in the HT as compared with the OF.

In HTs at Mount Vernon, BioTelo had a higher number of RTH than did the other mulches later in the season ($P \leq 0.001$), but the RTH was not significantly different from BioAgri and/or WeedGuardPlus RTH during the season. In the OF, WeedGuardPlus, BioTelo, and BioAgri had the highest number of RTH during the season ($P \leq 0.01$), although at the end of the season, WeedGuardPlus had a greater number of RTH than the other mulches ($P < 0.0001$). At Mount Vernon, the final average number of RTH for mulch treatments in HTs (11.06) was approximately equal to that in the OF at Lubbock (10.12), whereas the average number in the OF at Mount Vernon (28.98) was more than twice as much as at Lubbock (10.12). On four dates a coalescence of RTH caused the numbers of RTH to be fewer than on the preceding rating date.

At both Knoxville and Mount Vernon, PVD differed as a result of mulch treatment ($P \leq 0.05$) and there was a significant interaction between production system and mulch type ($P \leq 0.05$); therefore, PVD data (Fig. 1) from both sites are presented separately for HTs and the OF. In HTs at Knoxville, PVD range was 0% to 3.6% at the beginning of the season ($P = 0.16$) and 0% to 21.4% at the end of the season ($P = 0.37$). BioAgri and BioTelo had the greatest PVD midseason ($P = 0.04$), but none of the PVD values were significantly different at the end of the season ($P = 0.37$). In the OF at Knoxville, PVD range was 0.5% to 2.5% at the beginning of the season ($P = 0.11$) and 0.5% to 33.3% at the end of the season ($P = 0.0003$). Whereas PVD for BioTelo at Knoxville was greater than the other treatments early in the

season ($P \leq 0.003$), it was similar ($P \leq 0.005$) to BioAgri and WeedGuardPlus from midseason onward. In HTs at Mount Vernon, PVD range was 0% to 0.8% at the beginning of the season ($P = 0.06$) and 0% to 11.8% at the end of the season ($P = 0.0004$). In the OF at Mount Vernon, PVD range was 0% to 3.3% at the beginning of the season ($P = 0.005$) and 1.3% to 34.0% at the end of the season ($P = 0.003$). Throughout the season in both HTs and the OF at Mount Vernon, WeedGuardPlus had the greatest PVD followed by BioTelo and BioAgri ($P \leq 0.001$). At both Knoxville and Mount Vernon, SB-PLA-10 showed very little PVD in HTs and the OF throughout the season (0% to 1.3%) and the PVD was not significantly different from black plastic PVD on any of the evaluation dates. There was an increase in black plastic PVD midseason in the HT at Knoxville as a result of inadvertent tearing by workers in the field. Overall average PVD was 58% greater at the end of the season in the OF than in HTs at Knoxville but two and a half times greater at Mount Vernon.

Weed assessment. Number of weeds and weed fresh weight at tomato first flower and final harvest did not differ as a result of production system at either Knoxville or Mount Vernon ($P > 0.05$); however, the values did differ by mulch treatments at both sites (Table 4). There was no significant interaction between production system and mulch treatment at either Knoxville or Mount Vernon ($P > 0.05$). At both Knoxville and Mount Vernon, SB-PLA-10 had the greatest number of weeds at first flower ($P < 0.0001$) and final harvest ($P \leq 0.02$) as well as the greatest weed fresh weight at first flower ($P < 0.0001$) and final harvest ($P \leq 0.009$). The other mulch treatments at Knoxville and Mount Vernon did not differ significantly from each other for weed number and weight at either first flower or final harvest, although BioTelo was not significantly different from SB-PLA-10 at final harvest at Mount Vernon.

Fruit yield. There was no significant interaction in tomato fruit number or weight ($P > 0.05$) between production system and mulch treatment at any of the sites. Total tomato fruit number was 42% greater in HTs than in the OF at Knoxville ($P < 0.0001$); however, there was no difference in total fruit weight ($P = 0.53$) by production system at Knoxville (Table 5). At Lubbock, tomato fruit number was 74% greater in HTs than in the OF ($P = 0.02$) and total fruit weight was 60% greater ($P = 0.03$). At Mount Vernon, tomato fruit number was five times greater in HTs than in the OF ($P = 0.0008$) and total fruit weight was nine times greater ($P = 0.0005$). Mulch treatment affected total number of tomato fruit and fruit weight at Knoxville ($P = 0.04$ and $P = 0.04$, respectively) and Mount Vernon ($P = 0.008$ and $P = 0.004$, respectively) but not at Lubbock ($P = 0.46$ and $P = 0.23$, respectively). Total fruit number and yield were lowest for bare ground at both Knoxville (150×10^4 fruit/ha and $29 \text{ t} \cdot \text{ha}^{-1}$) and at Mount Vernon (44×10^4 fruit/ha and $11 \text{ t} \cdot \text{ha}^{-1}$). At Knoxville, none of the other

Table 3. Comparison of average number of rips, tears and holes (RTH) per bed area (1.5 m × 0.6 m) in mulch treatments and field production systems (high tunnel or open field) at Lubbock and Mount Vernon in 2010.^z

	No. of RTH per bed area (1.5 m × 0.6 m) ^y							
	28 May	7 June	22 June	19 July	—	—	—	8 Oct.
Lubbock								
High tunnel								
BioAgri	0.0	0.0	1.3	1.5 ab ^x	—	—	—	13.3 a
BioTelo	0.8	0.8	1.0	1.0 bc	—	—	—	17.0 a
WeedGuardPlus	0.0	0.0	1.5	4.0 a	—	—	—	23.5 a
SB-PLA-10	0.0	0.0	0.0	0.0 c	—	—	—	0.0 b
Black plastic	0.0	0.0	0.0	0.0 c	—	—	—	0.0 b
<i>P</i> value	0.06	0.06	0.41	0.003	—	—	—	<0.0001
Open field								
BioAgri	2.8 x	1.8 x	4.0 x	7.5 xy	—	—	—	13.3 x
BioTelo	4.3 x	6.5 x	7.0 x	8.3 x	—	—	—	7.8 y
WeedGuardPlus	0.0 y	0.0 y	0.0 y	4.5 y	—	—	—	29.5 x
SB-PLA-10	0.0 y	0.0 y	0.0 y	0.0 z	—	—	—	0.0 z
Black plastic	0.3 y	0.5 y	0.5 y	0.0 z	—	—	—	0.0 z
<i>P</i> value	0.0003	<0.0001	<0.0001	<0.0001	—	—	—	<0.0001
Mount Vernon								
	16 June	30 June	14 July	28 July	16 Aug.	2 Sept.	15 Sept.	29 Sept.
High tunnel								
BioAgri	1.8 ab	3.0 a	2.5 a	7.3 ab	7.8 ab	12.8 a	14.0 b	15.8 b
BioTelo	3.8 a	3.8 a	4.3 a	9.5 a	15.5 a	22.5 a	26.3 a	28.5 a
WeedGuardPlus	0.3 bc	2.0 a	2.3 a	4.5 b	5.8 b	6.0 b	9.8 b	9.5 c
SB-PLA-10	0.0 c	0.0 b	0.0 b	0.0 c	0.0 c	0.0 c	0.0 c	0.0 d
Black plastic	0.3 bc	0.0 b	0.0 b	0.0 c	0.8 c	1.3 c	1.5 c	1.5 d
<i>P</i> value	0.03	0.006	0.0004	0.0004	0.0001	<0.0001	<0.0001	<0.0001
Open field								
BioAgri	0.5 yz	1.3 y	2.0 yz	9.3 y	10.5 y	19.5 x	20.8 x	21.8 x
BioTelo	1.5 xy	1.8 y	6.0 x	13.0 y	18.3 y	17.0 xy	28.3 x	33.5 x
WeedGuardPlus	4.8 x	5.0 x	6.8 x	7.3 y	7.5 y	11.5 xy	25.0 x	72.8 w
SB-PLA-10	0.0 z	0.0 z	0.5 z	0.8 z	1.5 z	2.8 z	3.0 z	3.0 z
Black plastic	0.8 yz	0.8 yz	2.8 xy	6.3 y	5.5 yz	10.0 y	10.5 y	13.8 y
<i>P</i> value	0.007	0.002	0.003	0.01	0.02	0.006	0.0002	<0.0001

^zTomatoes were planted 7 May in high tunnels and open field at Lubbock and 27 May in high tunnels and 3 June in open field at Mount Vernon.

^yNo transformation met the assumptions of normality; therefore, data were non-parametrically transformed using PROC RANK (Statistical Analysis System Version 9.2 for Windows™; SAS Institute, Cary, NC), and analysis was for each production system separately using PROC GLM in SAS (Statistical Analysis System Version 9.2 for Windows™). All RTH data presented in this table are non-transformed.

^xMeans within a column followed by the same letter are not significantly different ($P > 0.05$) as determined by Fisher's protected least significant difference test.

mulch treatments was significantly different from one another but at Mount Vernon, BioAgri tended to have the highest yield (66×10^4 fruit/ha and $16 \text{ t} \cdot \text{ha}^{-1}$). At Lubbock, the highest yield appeared to be in WeedGuardPlus (477×10^4 fruit/ha and $55 \text{ t} \cdot \text{ha}^{-1}$) and SB-PLA-10 (503×10^4 fruit/ha and $56 \text{ t} \cdot \text{ha}^{-1}$); whereas these differences were not significant, likely as a result of large variation between plants within a treatment, they represented an increase of 27% and 33%, respectively, compared with the lowest yielding treatments (bare ground and black plastic).

Discussion

At all three sites, mulch deterioration was greater in the OF than in HTs. Soil and air temperatures were elevated in HTs as compared with the OF at Mount Vernon but did not result in accelerated mulch degradation. Deterioration was likely greater in the OF than HTs as a result of higher wind speed (blowing soil particles potentially abraded mulch), greater solar radiation, and increased rainfall. In our study, the greatest mulch deterioration occurred at Knoxville and at Mount Vernon, the sites with the highest relative humidity (average 77% and 81%, respectively). Whereas Lubbock received one major

rain event during the study (210 mm from 27 June to 12 July), the moisture drained from the site relatively quickly so that plots were dry within a few weeks. Thus, overhead moisture may play a larger role than temperature or incident radiation in the deterioration of these mulch products. Other studies have also found that potentially biodegradable products (corn starch, paper, and/or PLA-based) exhibited different levels of deterioration (decreased molecular weight and increased water solubility) as a result of increased environmental moisture, temperature, and light (Hakkarainen, 2002; Ho et al., 1999; Kijchavengkul et al., 2008).

At all three sites, mulch deterioration as measured visually in the field through RTH and PVD was greatest for the three commercially advertised biodegradable mulches, WeedGuardPlus, BioAgri, and BioTelo, and was insignificant for the experimental SB-PLA-10 mulch and black plastic. Deterioration of starch and paper-based mulches started earlier in the OF than in HTs at Knoxville, whereas at Mount Vernon, only paper-based mulch deterioration was earlier in the OF compared with HTs. WeedGuardPlus deteriorated at the soil interface at all three sites and was susceptible to wind blowing beneath it, occasionally lifting it off the bed. To keep paper mulch in place, it was necessary to move

soil from the alley onto the side of the bed once or twice during the season.

Greater deterioration of BioAgri and BioTelo at Knoxville may be the result of a combination of high solar radiation, high overhead moisture, and high temperature at this site. BioTelo and BioAgri deteriorated at all sites in a longitudinal fashion, that is, rips and tears became elongated down the length of the bed. Although it was possible to have only a small number of RTH measured for mulch products, over the course of the growing season, these could extend down the entire length of the plot, exposing a significant area of soil. Additionally, the number of RTH can decrease over time when individual RTHs coalesce. Furthermore, it took more time to count RTH (30 to 60 s/plot) than to visually rate PVD (5 to 30 s/plot) as the season progressed. Thus, we found RTH was not as effective or reliable as PVD to evaluate mulch deterioration.

For effective weed control, biodegradable mulches must remain intact for a significant portion of the growing season. At Knoxville, mulch deterioration generally remained below 10% until early July, which was more than halfway through the tomato production season, and final mulch deterioration was 20% to 30%. At Mount Vernon, deterioration

Fig. 1. Percent visual degradation (PVD) per bed area (1.5 m × 0.6 m) of mulch treatments in high tunnels (HT) and the open field (OF) at Knoxville and Mount Vernon in 2010. Bars represent the SEM; value ranges for treatments with limited degradation are small thus error bars are not evident.

Table 4. Total weed number and fresh weight (g) per 0.6 m² associated with mulch treatments at tomato first flower and final harvest at Knoxville and Mount Vernon in 2010.

	Knoxville				Mount Vernon			
	First flower		Final harvest		First flower		Final harvest	
	Weed no. (plot) ^z	Weed wt (g/plot) ^z	Weed no. (plot) ^y	Weed wt (g/plot)	Weed no. (plot) ^x	Weed wt (g/plot) ^v	Weed no. (plot) ^v	Weed wt (g/plot) ^v
Field location								
High tunnel	11.3	15.0	3.4	41.6	14.6	233.3	1.0	0.9
Open field	9.2	13.6	3.0	54.1	20.2	140.2	1.3	0.8
<i>P</i> value	0.38	0.84	0.50	0.51	0.30	0.06	0.50	0.72
Mulch treatment								
BioAgri	2.3 b ^u	4.6 b	0.0 b	0.0 b	15.0 b	71.5 b	0.5 b	0.3 b
BioTelo	2.1 b	1.9 b	0.0 b	0.0 b	8.4 b	92.3 b	1.5 ab	1.3 ab
WeedGuardPlus	1.8 b	0.7 b	0.0 b	0.0 b	12.3 b	40.8 b	1.0 b	0.7 b
SB-PLA-10	123.7 a	190.8 a	16.0 a	47.4 a	85.1 a	1012.3 a	8.7 a	6.3 a
Black plastic	0.3 b	0.5 b	0.0 b	0.0 b	10.6 b	132.0 b	0.5 b	0.3 b
<i>P</i> value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.02	0.009

^zKnoxville weed number data and weed weight data at first flower were square root transformed for analysis and means separation; means presented are backtransformed.

^yKnoxville weed number data at final harvest were log₁₀ transformed for analysis and means separation; means presented are backtransformed.

^xMount Vernon first flower weed number data were log₁₀ transformed for analysis and means separation; means presented are backtransformed.

^vMount Vernon first flower weed weight data were square root transformed for analysis and means separation; means presented are backtransformed.

^vMount Vernon final harvest weed number and weight data were reciprocal transformed for analysis and means separation; means presented are backtransformed.

^uMeans within a column followed by the same letter are not significantly different (*P* > 0.05) as determined by least square means in the PROC MIXED model (SAS Version 9.2 for Windows™; SAS Institute, Cary, NC).

of all mulches except WeedGuardPlus remained below 5% throughout the tomato production season. WeedGuardPlus in HTs had low deterioration by the end of the season, ≈10%, but had higher deterioration in the OF, ≈30%. At Lubbock, mulch deterioration in both HTs and the OF as measured by RTH

was equivalent to mulch deterioration in the HTs at Mount Vernon. At Knoxville and Mount Vernon, weed number and weight declined between first flower and final harvest, likely as a result of competition under SB-PLA-10 and weed death from lack of light under the other mulches. These results

indicate that all of the potentially biodegradable mulches included in this study likely have an adequate lifespan in the field, and weed growth did not increase with mulch deterioration later in the season. The HTs had no effect on weed number or weight compared with the OF at any of the three sites, indicating

Table 5. Total number of tomato fruit ($10^4/\text{ha}$) and weight ($\text{t}\cdot\text{ha}^{-1}$) associated with production system and mulch treatment at Knoxville, Lubbock, and Mount Vernon in 2010.^z

	Knoxville		Lubbock		Mount Vernon	
	Total fruit no. ($10^4/\text{ha}$)	Total fruit wt ($\text{t}\cdot\text{ha}^{-1}$)	Total fruit no. ($10^4/\text{ha}$)	Total fruit wt ($\text{t}\cdot\text{ha}^{-1}$)	Total fruit no. ($10^4/\text{ha}$)	Total fruit wt ($\text{t}\cdot\text{ha}^{-1}$)
Production system						
High tunnel	226 a ^y	38	549 a	58 a	94 a	24 a
Open field	160 b	36	315 b	37 b	18 b	3 b
<i>P</i> value	<0.0001	0.53	0.02	0.03	0.0008	0.0005
Mulch treatment						
BioAgri	201 y	38 y	408	44	66 x	16 w
BioTelo	192 y	37 y	403	45	64 xy	16 wx
WeedGuardPlus	197 y	38 y	477	54	55 xyz	13 xyz
SB-PLA-10	202 y	39 y	503	56	50 y	12 yz
Black plastic	216 y	41 y	408	42	56 xy	13 wxy
Bare ground	150 z	29 z	395	42	44 z	11 z
<i>P</i> value	0.04	0.04	0.46	0.23	0.008	0.004

^zTotal fruit number and total weight of fruit were calculated based on seven plants in each plot; spacing was 1.8 m between beds and 0.6 m in the bed.

^yMeans within a column followed by the same letter are not significantly different ($P > 0.05$) as determined by Fisher's protected least significant difference test.

weed management strategies will likely not need to change as a result of production system.

Tomato yield was substantially improved at all three sites when tomatoes were grown in HTs rather than the OF, indicating that HTs can improve tomato yield across a wide diversity of environmental conditions. Tomato was planted earlier in HTs than OF at Knoxville as a result of warmer temperatures in the HTs; this practice leads to an earlier harvest, which enables growers to capture a higher price. HTs had little impact on soil temperature or maximum air temperature in the hot climates of Knoxville and Lubbock, perhaps as a result of reduced solar radiation in the HTs; thus, temperatures were not increased to levels detrimental to tomato production at either location. Individual fruit weight was decreased in HTs at Knoxville as compared with the OF, potentially as a result of hastened fruit maturity as a result of increased maximum temperature and disease pressure (data not shown). At Lubbock, the difference in yield between HTs and the OF was likely the result of protection from wind that damaged plants by "sandblasting" (abrasion caused by wind-blown soil particles). In the relatively cool summer climate of Mount Vernon, HTs increased soil temperature and maximum air temperatures, resulting in increased accumulation of growing degree-days (base 10°C) and temperatures more optimal for tomato production when compared with the OF. In general, the hot dry climate of Lubbock appears to favor tomato production, whereas the humid climate of Knoxville favors disease, whereas the cool climate of Mount Vernon limits heat units. Tomato yields were improved with mulch treatments compared with bare ground at Knoxville and Mount Vernon, whereas at Lubbock, WeedGuardPlus and SB-PLA-10 tended to have the highest tomato yield. In the hot dry climate of Lubbock, soil temperature was lower under SB-PLA-10 treatment and was likely more conducive for tomato production. In the more humid environments of Knoxville and Mount Vernon, increased soil temperature appeared to favor tomato yield.

Of the three commercial biodegradable mulches included in this study, only

WeedGuardPlus is currently allowable in certified organic systems in the United States. Although BioAgri and BioTelo are allowed in certified organic systems in Canada and the European Union, they are not allowed in the United States as a result of the presence of non-allowable additive(s) in their formulation (USDA, 2012). One advantage of SB-PLA-10 or similar biodegradable products that remain intact in the field could be in removal at the end of the season and placement in a composting facility where 100% biodegradation is expected (Lunt, 2000). BioTelo and BioAgri partially degrade in the field and so their removal is not practical. Although composting mulch would not reduce time and labor costs, it could reduce environmental impact. WeedGuardPlus has been shown to be 100% biodegradable in a greenhouse study (Hayes et al., 2011). However, it is unknown at this time whether BioTelo and BioAgri will fully biodegrade in the soil or if biodegradation occurs within an acceptable timeframe to satisfy most growers. Additional studies are needed to further elucidate the biodegradation potential within a soil environment of potentially biodegradable mulches. Hence, a field study is underway to measure mulch biodegradation after soil incorporation at the end of the cropping season (Moore-Kucera et al., 2011).

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