Biodegradable Plastic and Fabric Mulch Performance in Field and High Tunnel Cucumber Production

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SUMMARY. Polyethylene mulch use is common in vegetable production, but disposal of mulch is problematic for growers and of significant environmental concern. Biodegradable fabrics and plastic films are compostable and can be incorporated into the soil at the end of the growing season, but questions remain about the durability, performance, and rate of decomposition of these products after soil incorporation. Three trials were conducted in field and high tunnel cucumber (*Cucumis sativus*) cropping systems to compare performance and decomposition after use among two bioplastic films and four experimental spunbond, nonwoven biofabrics. Soil temperature and moisture, mulch durability and deterioration, weed suppression, and crop yield data were collected in each growing season. All biomulches were soil incorporated after the growing season and recovered up to 11 months after incorporation to estimate relative rates of decomposition. One bioplastic film increased field soil temperature by 2 °C in 2013, but temperatures under the biofabrics were not different from bare soil. Bioplastics and biofabrics increased soil moisture relative to bare soil. Bioplastic films were less durable and deteriorated sooner than biofabrics, especially in the field environment (as early as 34 days after transplanting). All biomulches suppressed weed emergence relative to bare soil, but weeds were visibly growing beneath the most translucent biofabric. Marketable yield of cucumber was trending highest in the most durable and opaque biofabric (1827 g·m⁻²), but was not significantly different from weed-free bare soil (1251 g·m⁻²). Relative rate of mulch decomposition up to 11 months after soil incorporation was not different among bioplastic and biofabric products. Results suggest that the tested biofabrics will be most useful to growers when soil warming is not necessary (e.g., warm climates), but moisture conservation and weed control are critical (e.g., organic cropping systems). Moreover, biofabrics are permeable and may be useful to growers dependent on sprinkler irrigation or rainfall to meet crop water demands.

Intensive cultivation of fruits and vegetables typically includes the use of polyethylene (PE) mulch (Lamont, 2005), partly because of its low cost and proven potential to increase yields and improve crop growth (Cirujeda et al., 2012). However, disposal of petroleum-based plastic mulches is a significant environmental concern that has led many growers to consider alternatives. Popular alternatives to PE mulches include organic mulches derived from agricultural or urban byproducts and waste [e.g., straw and newspaper mulches (Monks et al.,

1997)], paper-based mulches (e.g., WeedGuardPlus; Sunshine Paper, Aurora, CO), or biodegradable plastic films and fabrics (Miles et al., 2012). Of these options, biofabrics and bioplastic films have demonstrated the greatest potential as commercial alternatives to PE mulch (Miles et al., 2012).

Bioplastic films have similar physical properties to PE and are typically effective in increasing soil temperatures relative to bare soil, which contributes to increased crop growth rate and yield

(Cowan et al., 2014; Martin-Closas et al., 2008; Miles et al., 2012; Ngouajio et al., 2008). In contrast, most bioplastic films have lower tensile strength and mechanical resistance compared with PE (Martin-Closas et al., 2008). As a result, bioplastic films often degrade faster than PE during the growing season and are more susceptible to rips, tears, and holes during installation. Early deterioration of bioplastic films reduces their capacity for season-long weed suppression (Martin-Closas et al., 2008; Miles et al., 2012; Moreno and Moreno, 2008; Ngouajio et al., 2008; Waterer, 2010). Despite the potential shortcomings in season-long durability, fruit and vegetable crop yield is often similar between bioplastic and PE films (Martin-Closas et al., 2008; Miles et al., 2012; Moreno and Moreno, 2008; Weber, 2003).

Biofabrics are a relatively new concept and not yet commercially available. These mulches are typically spunbond, nonwoven fabrics composed of polylactic acid or polylactic acid in combination with polyhydroxyalkanoate (Cowan et al., 2014). One line of experimental biofabrics (SB-PLA-10/11/12; Natureworks, Blair, NE) was recently tested in vegetable cropping systems and some desirable characteristics were observed (Cowan et al., 2014; Miles et al., 2012). The fabrics were more durable than bioplastic films during the growing season (e.g., less visible deterioration and rips, tears, and holes) and the black biofabrics provided season-long weed suppression. By contrast, white translucent biofabrics did not provide acceptable weed control (Cowan et al., 2014). While bioplastic films tend to absorb and transfer solar radiation to the soil resulting in warmer temperatures, biofabrics, like organic mulches (e.g., straw), are less-effective conductors of heat and may even decrease soil temperatures (Larsson and Båth, 1996). As a result, crop yield increases, especially in cooler

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
0.0929	ft ²	m ²	10.7639
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.0254	mil	mm	39.3701
305.1517	oz/ft ²	g·m ⁻²	0.0033
(°F - 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

climates, are often greater for bioplastic films than for biofabrics (Cowan et al., 2014; Miles et al., 2012; Olsen and Gounder, 2001). In the absence of soil warming, the potential benefits of biofabrics are soil moisture retention and season-long durability and weed suppression. However, there is a concern that the more durable biofabrics may also be slow to decompose or biodegrade in the soil after the growing season (Cowan et al., 2013).

Decomposition of biodegradable mulch after the growing season is an important issue for growers. Slow degradation of a mulch (or any organic material) after soil incorporation can lead to accumulation of residue that may interfere with normal field operations (e.g., planting) or create an imbalance of carbon:nitrogen that contributes to nitrogen immobilization during subsequent growing seasons (Martens, 2001). Paper-based mulches decompose within 12 months of soil incorporation but are not durable enough to endure an entire field-based growing season (Li et al., 2014). Bioplastic films are slower to degrade than paper-based mulch, but certain products can be visibly degraded 13–24 months after soil incorporation, depending on local climatic conditions. A recently developed biofabric (i.e., SB-PLA-10) did not deteriorate during the growing season, but also showed little to no signs of biodegradation 13–24 months after soil incorporation (Cowan et al., 2013; Li et al., 2014). Thus, a balance is needed between durability during the growing season and rapid degradation after soil incorporation. Unfortunately, few biodegradable mulch products possess this necessary balance of properties.

Field performance (e.g., weed suppression and soil moisture retention) and soil decomposition of biodegradable mulches will also be influenced by the production environment. High tunnel production of fruits and vegetables is increasingly common. High tunnels create a microclimate that is markedly different from the field environment. In high tunnels, air and soil temperatures are warmer, wind speed is reduced or eliminated, direct solar radiation is reduced, and precipitation is eliminated (Miles et al., 2012; Wien, 2009). Moreover, reduced surface soil moisture throughout the high tunnel contributes to reduced weed emergence and growth, which may reduce

the need for weed suppression from a given mulch product (Cowan et al., 2014). However, weed emergence within high tunnels will be greatest within the crop row where irrigation water is delivered from drip tape; thus, weed suppressive characteristics of biomulch are still important in high tunnels. Deterioration of biodegradable mulches in high tunnels is slowed during the growing season (Miles et al., 2012); however, the rate of decomposition of the mulch after soil incorporation was not different between field and high tunnel environments (Li et al., 2014). The latter result is somewhat surprising given the typical differences in soil moisture and temperature between field and high tunnel environments (e.g., warmer but drier in the high tunnel).

The objective of this study was to evaluate the field performance, durability, and decomposition following soil incorporation of four experimental spunbond, nonwoven biofabrics in comparison with two commercially available bioplastic mulch films and a bare soil control across field and high tunnel cucumber cropping systems.

Materials and methods

Three trials were conducted at the University of Illinois Sustainable Student Farm in Urbana, IL (lat. 40.08°N, long. 88.22°W; elevation = 221 m; loam soil texture: 31% sand, 45% silt, and 24% clay) in 2013 and 2015. Two trials in 2013 were conducted in the field and a high tunnel using ‘Marketmore 76’ fresh-market cucumber as the test crop. The experimental site was rotated into tomato (*Solanum lycopersicum*) and pepper (*Capsicum annuum*) production in 2014. A third trial was performed in 2015 to replicate the field cucumber experiment, but the high tunnel experiment was not replicated because of poor crop performance in 2013. The high tunnel is Gothic style, 30 ft wide by 96 ft long, and included roll-up sides that remained up unless nighttime air temperatures outside of the tunnel were forecast below 5 °C. Weather conditions across years are summarized in Table 1.

Each trial was arranged as a randomized complete block design with four replicate blocks and seven experimental treatments including four experimental spunbond, nonwoven biofabrics of varying thickness and

color (3M Co., Saint Paul, MN), Eco Film bioplastic mulch film (Cortec Corp., Saint Paul, MN), Bio Telo bioplastic mulch film (Dubois Agrinovation, Saint-Remi, QC, Canada), and a bare soil control. A summary of mulch properties is provided in Table 2. Experimental units were 40 ft² (4 ft wide × 10 ft long) and included five cucumber plants spaced 2 ft apart.

Before laying mulches, the experimental area was rototilled and raised beds were shaped (≈2.5 ft across top of bed). Drip tape irrigation line (Aqua-Traxx; Toro Co., Bloomington, MN) with 6-inch emitter spacing was placed along the middle of each raised bed. Pieces of mulch were cut to length, laid on top of the raised beds, and 2.5 inches of mulch edge was buried. Six- to eight-week-old greenhouse-grown cucumber seedlings were transplanted into 3 × 3-inch square holes, which had been cut through the mulch. Cucumber plants were transplanted on 31 May in the field and on 7 Aug. in the high tunnel in 2013. In 2015, cucumber plants were transplanted in the field on 29 May.

Cucumber plants were pruned to one primary stem during the vegetative growth stage by removing secondary stems or “suckers.” In 2013, plants were first pruned 3 weeks after transplanting and pruned on a weekly basis thereafter until fruit production began. In 2015, plants were only pruned one time at 6 weeks after transplanting. Although pruning is atypical in field cucumber production, limiting the vegetative biomass was necessary to maintain the identity of plants within a given treatment and to maintain researcher access to biomulches and soil for data collection throughout the season. Weeds between the rows of mulch were controlled with straw mulch and hand weeding. Cucumber was drip irrigated at varying rates and intervals (depending on growing environment, growth stage, and weather) to maintain soil moisture in the top 3 inches of the profile above 15% volumetric soil moisture. Water volume applied at each irrigation interval was uniform across treatments. Crop nutrition was supplemented during the growing season with water-soluble fish emulsion delivered via drip irrigation lines. Cultural practices followed U.S. Department of Agriculture (USDA) National Organic Program guidelines. Squash bugs (*Anasa tristis*)

Table 1. Average monthly high and low temperatures and total monthly precipitation (P) from the Illinois State Water Survey weather station at Urbana, IL, in 2013 and 2015.

Month	2013			2015		
	High (°C) ^z	Low (°C)	P (mm) ^z	High (°C)	Low (°C)	P (mm)
May	23.9	11.9	95.0	25.1	13.1	154.2
June	27.7	15.9	159.3	28.0	17.3	229.1
July	27.7	17.3	89.7	29.0	18.1	106.2
August	29.0	16.7	9.1	28.7	16.4	80.3
September	28.1	13.7	17.3	28.3	14.7	163.6
October	18.9	6.3	91.2	20.3	7.4	39.4

^z(1.8 × °C) + 32 = °F, 1 mm = 0.0394 inch.

Table 2. Properties of bioplastic and biofabric mulches used in 2013 and 2015 field and high tunnel cucumber trials at Urbana, IL.

Mulch	Manufacturer ^z	Polymer	Color	Thickness ^y	Pro-degradants
BK-1-270 ^x	3M Co.	PLA ^w	Black	0.6 mm	No
BK-2-360 ^x	3M Co.	PLA	White/black ^v	0.3 mm	No
BK-5-350 ^x	3M Co.	PLA	Black	0.45 mm	Yes
BK-6-300 ^x	3M Co.	PLA	Black	0.45 mm	Yes
Eco Film	Cortec Corp.	Unknown	Black	0.75 mil	—
BioTelo	Dubois	Mater-bi [®]	Black	0.60 mil	—
Agrinovation					

^z3M Co., Saint Paul, MN; Cortec Corp., Saint Paul, MN; Dubois Agrinovation, Saint-Remi, QC, Canada.

^y1 mm = 0.0394 inch, 1 mil = 0.0254 mm.

^xProprietary 3M Co. biologically based product.

^wPolylactic acid.

^vWhite side facing up.

in cucumber were managed with as-needed applications of pyrethrum.

On a weekly (2013) or biweekly (2015) basis, the following data were collected: counts of emerged weed seedlings, soil moisture, and mulch deterioration. Weed counts and measures of mulch deterioration were collected within three randomly placed 30 × 60-cm quadrats in each plot. Weeds emerging through the mulch material were counted and then all weeds were removed from the entire experimental unit to limit any weed-induced yield loss. Volumetric soil moisture was measured within crop holes (to avoid damage to the mulch) to a 3-inch depth in all experimental units using a soil moisture sensor (ML2x Theta Probe Sensor; Delta-T Devices, Cambridge, UK). Mulch deterioration was visually estimated with a rating where 0% indicated a fully intact mulch and 100% a fully deteriorated mulch. Temperature data loggers (HOBO Pendant; Onset Computer, Bourne, MA) were buried at a depth of 2 inches for continuous measurement of soil temperature throughout the growing season in four of seven (2013; treatments included BK-1-270, BK-5-350, Bio Telo, and bare soil) or all experimental treatments (2015) in

each trial. Ripe fruit was harvested up to three times per week, graded into marketable [meeting a minimum of U.S. No. 2 standards for cucumbers (USDA)] and nonmarketable (e.g., insect infested, scabbed, or rotten) categories, counted, and weighed. Field cucumber harvest occurred between 10 July and 8 Aug. in 2013 and between 10 July and 6 Aug. in 2015. High tunnel cucumber harvest in 2013 occurred between 6 Sept. and 24 Oct.

At the end of the field and high tunnel growing season in 2013, drip irrigation line and soil temperature loggers were removed from experimental units and aboveground crop residues were flail mowed. Mulches left on the soil surface were also flail mowed and then immediately incorporated into the top 10 to 15 cm of soil with a rotary tiller. To quantify subsequent decomposition of the mulches, mulch residues in the field and high tunnel soils were sampled within 1 month of incorporation of the mulch (baseline) and one (high tunnel) or two (field) additional times, for up to 11 months after soil incorporation. Five (baseline) or eight (subsequent samplings) large soil cores (10 cm diameter by 15 cm depth) were taken at random from each experimental

unit and soil in the samples was sieved (0.25-inch mesh) to recover mulch residues. Recovered mulch was then washed, dried at room temperature to constant mass, and weighed. The relative rate of mulch decay was then calculated as

$$\frac{\ln(M_{t2}) - \ln(M_{t1})}{t_2 - t_1}$$

where M is the mass of a recovered biomulch at a given time (t_x).

All data were analyzed with a generalized linear mixed model analysis of variance [Proc Mixed (SAS version 9.3; SAS Institute, Cary, NC)]. Repeated measures analysis was used for measures of soil moisture, mulch deterioration, and recovered biomulch mass. Data from each environment (high tunnel or field) and year were analyzed separately and fixed effects in each model included biomulch treatment, sampling date, and their interaction. Sampling date was included as a repeated effect and block was the random effect. The model for analysis of soil temperature, total weed emergence, crop yield, and relative rate of mulch decay was identical except the repeated measures were dropped.

Preliminary data analysis pooled across both years and environments commonly resulted in three- and four-way interactions among fixed effects for year, environment, sampling date, and biomulch treatment. Limiting data analysis to individual years and environments helped to minimize confounding effects (e.g., different transplant dates between environments), simplify interpretation of results, and to provide meaningful recommendations to growers. The one exception was marketable yield of field cucumber, and in this case data were pooled across years; year and the interaction of year by treatment were included as fixed effects in the model.

All data were tested for assumptions of analysis of variance, and data for visible deterioration, weed emergence, and mulch decomposition were $\ln(x + 1)$ transformed to improve normality. Data were back-transformed for presentation in figures and tables and standard errors were estimated from the raw data before transformation (standard errors cannot be back-transformed). Differences among least squares means were determined using the Tukey–Kramer

multiple comparisons test at a significance level of $\alpha = 0.05$.

Results and discussion

SOIL TEMPERATURE. Soil temperature during the first month after transplanting was greatest beneath one bioplastic compared with biofabrics and bare soil across both environments in 2013. Soil temperature in field cucumber was up to 2.1 °C warmer beneath Bio Telo compared with BK-5-350 (Table 3). Differences in the high tunnel were similar where soil temperature was 1.9 °C warmer beneath Bio Telo compared with BK-5-350. Soil temperature beneath biofabrics was not different from bare soil in either field or high tunnel cucumber. Field soil temperatures were trending higher beneath bioplastic films compared with biofabrics and bare soil in 2015, but differences were not significant ($P = 0.15$).

Previous studies have demonstrated increased soil temperatures beneath bioplastic films relative to bare soil (Larsson and Bth, 1996; Olsen and Gounder, 2001). Because biofabrics are relatively new, less is known about their impact on soil physical properties. However, Miles et al. (2012) reported between 1 and 3.6 °C lower soil temperatures throughout the growing season beneath SB-PLA-10 (a white, experimental spunbond, nonwoven biofabric) compared with bioplastic and PE films in a Texas field environment. Consistent with the results of this study, soil temperatures beneath the biofabrics were not different from bare soil in either environment (field and high tunnel). The physical and mechanical properties of plastic, regardless of the polymer used to produce it, are excellent for absorbing and conducting heat to soil as long as the film and soil are in close contact (Lamont, 2005; Larsson and Bth, 1996). In contrast, biofabrics can absorb thermal radiation, but the mechanical and physical properties of the fabrics often limit direct contact with the soil surface. This lack of contact interferes with conductance of thermal energy. In cooler climates where soil warming is desirable, bioplastic films may be the most suitable alternative to PE mulch. However, biofabrics may be a better alternative to PE mulch in warmer climates or in cool season crops where increased soil temperatures are less beneficial or even deleterious to

crop growth and yield. It is interesting to note that soil temperature did not vary among any of the biofabrics (Table 3) despite differences in color (black vs. white; Table 2). Color of bioplastic and PE films has significant effects on soil temperature (Daz-Prez and Batal, 2002), and the lack of observed differences among biofabrics in this study may be related to the low potential for thermal conductance in biofabrics.

SOIL MOISTURE. Surface soil moisture, averaged across the season, increased beneath all biomulches compared with bare soil in all trials; however, bioplastics conserved up to 5.2% more soil moisture than BK-1-270 in the high tunnel (absolute percent, not relative; Table 4). In the field, soil moisture was up to 8.2% greater beneath biomulches compared with bare soil and there were not consistent differences between bioplastics and biofabrics. These results suggest that all mulches and films can be effective in conserving surface soil moisture; thus, growers should consider other performance factors (e.g., soil temperature, durability, and weed suppression) when choosing a biomulch. However, the permeable nature of biofabrics may be more suited to the field where they may help to mitigate evaporative soil water loss, and also allow precipitation to penetrate to the soil surface. In this way, biofabrics perform similar to organic mulches (e.g., straw mulch) where soil moisture following a rain event is often greater than that beneath PE film (Larsson and Bth, 1996).

MULCH DETERIORATION. Deterioration of bioplastic films increased over time in the field (Fig. 1). By 69 d after transplanting (DAT) in 2013, visible deterioration of Bio Telo and Eco Film had reached 28.7% and 8.9%, respectively. Bio Telo was more durable in the field in 2015 (2.3% deteriorated at 68 DAT), but Eco Film was less durable (19.2% deteriorated at 68 DAT). Improved durability of Bio Telo in 2015 may be because of differences in pruning methods between years. Cucumbers in 2015 were not pruned until 6 weeks after transplanting, compared with 3 weeks after transplanting in 2013, and the resulting increase in leaf area during that time may have reduced ultraviolet degradation of Bio Telo in 2015. Moreover, warmer temperatures and greater precipitation in 2015 likely

Table 3. Soil temperatures during the first month after transplanting in biomulch treatments at 5 cm (2.0 inches) beneath the soil surface in field (2013 and 2015) and high tunnel (2013 only).

Biomulch	Soil temp (�C)*		
	2013		2015
	Field	High Tunnel	Field
BK-1-270 ^y	23.3 b ^x	27.2 b	23.4 a
BK-2-360 ^y	—	—	23.9 a
BK-6-300 ^y	—	—	23.4 a
BK-5-350 ^y	23.3 b	26.9 b	23.5 a
Eco Film ^w	—	—	24.4 a
Bio Telo ^v	25.4 a	28.8 a	24.3 a
Bare soil	23.4 b	27.0 b	23.4 a
SE	0.2	0.5	0.3

^z(1.8 C) + 32 = F.

^yExperimental biofabric (3M Co., Saint Paul, MN).

^xDifferent letters within a column indicate significant differences as determined by the Tukey–Kramer multiple comparisons test at a rejection level of $\alpha = 0.05$.

^wBioplastic (Cortec Corp., Saint Paul, MN).

^vBioplastic (Dubois Agrinovation, Saint-Remi, QC, Canada).

Table 4. Volumetric soil moisture among biomulch treatments in field (2013 and 2015) and high tunnel (2013 only) cucumber. Soil moisture values were averaged over the course of all sampling intervals in a season due to a lack of interactions between sampling date and biomulch treatment.

Biomulch	Soil moisture (%)		
	2013		2015
	Field	High tunnel	Field
BK-1-270 ^z	31.3 a ^y	23.1 bc	22.0 ab
BK-2-360 ^z	30.2 a	26.6 ab	19.9 b
BK-6-300 ^z	30.9 a	25.4 ab	20.5 b
BK-5-350 ^z	30.9 a	26.5 ab	21.7 ab
Eco Film ^x	30.2 a	28.1 a	23.1 a
Bio Telo ^w	30.7 a	28.3 a	20.0 b
Bare soil	25.3 b	20.8 c	14.9 c
SE	0.5	1.5	0.6

^zExperimental biofabric (3M Co., Saint Paul, MN).

^yDifferent letters within a column indicate significant differences as determined by the Tukey–Kramer multiple comparisons test at a rejection level of $\alpha = 0.05$.

^xBioplastic (Cortec Corp., Saint Paul, MN).

^wBioplastic (Dubois Agrinovation, Saint-Remi, QC, Canada).

increased vegetative growth and leaf area that could have contributed to reduced ultraviolet degradation of Bio Telo (Table 1). In contrast to bioplastics, deterioration of biofabrics was negligible throughout the growing season (Fig. 1). Deterioration of bioplastics in the high tunnel also increased over time, but visible deterioration did not exceed

Fig. 1. Visible deterioration of biomulches in field cucumber observed between 21 and 69 d after transplanting in 2013 (top) and between 12 and 68 d after transplanting in 2015 (bottom). The error bar in the bottom left corner of each figure represents $\pm$ SE of least squares means estimated from raw data before transformation. BK-1-270, BK-2-360, BK-6-300, and BK-5-350 experimental biofabrics manufactured by 3M Co. (Saint Paul, MN). Eco Film bioplastic manufactured by Cortec Corp. (Saint Paul, MN). Bio Telo bioplastic manufactured by Dubois Agrinovation (Saint-Remi, QC, Canada).

3% at any point during the growing season for any of the products (Fig. 2).

In similar studies, deterioration of bioplastic films was consistently greater and occurred faster than that of biofabrics (Cowan et al., 2013; Miles et al., 2012). By season end, Cowan et al. (2013) observed visible deterioration of bioplastics between 10% and 70%, depending on the product. In contrast, the biofabric SB-PLA-11 showed no

signs of visible deterioration at any point during the growing season. Miles et al. (2012) reported similar trends and also found increased visible deterioration of bioplastics in the field relative to the high tunnel. Slower deterioration in the high tunnel is likely due to protection from the full weathering effects of precipitation, wind, and ultraviolet light. Crop species may also have a significant effect on the rate

of biomulch deterioration. Deterioration of Bio Telo ranged from 0.3% to 3.8% by 33 DAT in field cucumber production of this study, but Wortman et al. (2015) reported 25.6% deterioration of Bio Telo in field pepper production by 35 DAT. This observed difference may be partly because of differences in canopy architecture and growth habit of cucumber (vining and sprawling) and pepper (erect). Cucumber and other sprawling crops may serve to protect biomulches from the elements (e.g., wind, radiation, and precipitation) that contribute to deterioration.

Rips, tears, and holes in mulches eventually spread and contribute to widespread deterioration of mulches that can limit their utility in vegetable crops. Results from this study and others suggest that biofabrics are more durable and suited to the harsh conditions of the field, whereas bioplastic films are less durable and will deteriorate before season end unless used in a more protected environment, such as a high tunnel. Early deterioration of mulch in organic cropping systems, where weed seedbank abundance is usually greater than in conventional systems (Wortman et al., 2010), may result in intense weed competition, moisture stress, and reduced crop yield and quality. Thus, mulch durability will likely be a greater priority among organic growers who rely on biomulches to provide season-long weed suppression in the absence of chemical control options.

WEED EMERGENCE. No weeds emerged through biomulches in either environment in 2013, but 117 weeds/m² emerged in bare soil plots throughout the growing season in the field compared with only 12 weeds/m² in the high tunnel bare soil plots. Results were similar in 2015, where 474 weeds/m² emerged in bare soil plots compared with 27 weeds/m² in the BK-6-300 biomulch and zero in the remaining biomulches. Limited weed emergence in the high tunnel suggests weed suppressive characteristics of biodegradable mulches may be more important when used in the field, where weed emergence and growth is more common because of regular precipitation (Cowan et al., 2014). The dry environment in the high tunnel, especially as the growing season progresses, limits the emergence of many weed species to within a narrow band of soil where drip irrigation is delivered.

Although weeds which did not penetrate the mulch were not counted as emerged, weed growth was observed in both years and environments beneath BK-2-360. Results from this and other trials demonstrate the importance of opacity in a biodegradable mulch product, especially in the field where weed emergence and competition is typically more intense (Cowan et al., 2014). Weed growth observed under BK-2-360 in this study is consistent with Miles et al. (2012) and Cowan et al. (2014) who both reported increased weed growth beneath a translucent biofabric (SB-PLA-10). Weed growth beneath translucent mulches can lead to mulch deterioration and supplemental weed control (e.g., hand weeding) may be required to avoid crop yield loss (Ngouajio et al., 2008; Waterer, 2010). However, weed suppression by BK-1-270 suggests that season-long weed suppression is feasible in high tunnel and field environments if the mulch is sufficiently opaque.

CROP YIELD. Marketable cucumber yield was not influenced by biomulch treatment in the high tunnel and production was limited to only 108 g·m⁻² because of heat stress and a subsequent aphid infestation shortly after transplanting. Differences in marketable yield of cucumber among biomulch treatments in the field was approaching significance ($P = 0.09$), and plants were generally more productive than in the high tunnel (1307 g·m⁻²). Although marketable yield was trending highest in BK-1-270, it was not significantly different from other biomulch products or bare soil (Fig. 3). Similarly, biomulch treatments did not affect the proportion of total cucumbers graded as marketable (data not shown).

The lack of significant yield differences between biomulches and weed-free bare soil observed in this study is atypical, as most studies have demonstrated consistent crop yield increases in response to application of paper, plastic, and fabric biomulches relative to bare soil (Cowan et al., 2014; Miles et al., 2012). Moreover, many studies have found that crop yields—including strawberry (*Fragaria ×ananassa*), watermelon (*Citrullus lanatus*), lettuce (*Lactuca sativa*), and pepper—in biomulch are comparable to PE film (Jenni et al., 2004; Olsen and Gounder, 2001; Shogren and Hochmuth, 2004; Weber, 2003). In the absence of

Fig. 2. Visible deterioration of biomulches in high tunnel cucumber observed between 36 and 78 d after transplanting in 2013. The error bar in the bottom left corner of the figure represents $\pm$ SE of least squares means estimated from raw data before transformation. BK-1-270, BK-2-360, BK-6-300, and BK-5-350 experimental biofabrics manufactured by 3M Co. (Saint Paul, MN). Eco Film bioplastic manufactured by Cortec Corp. (Saint Paul, MN). Bio Telo bioplastic manufactured by Dubois Agrinovation (Saint-Remi, QC, Canada).

Fig. 3. Field cucumber marketable yield averaged across 2013 and 2015. Differences among biomulch treatments were only approaching significance ($P = 0.09$). Error bars represent $\pm$ SE of least squares means; BK-1-270, BK-2-360, BK-6-300, and BK-5-350 experimental biofabrics manufactured by 3M Co. (Saint Paul, MN). Eco Film bioplastic manufactured by Cortec Corp. (Saint Paul, MN). Bio Telo bioplastic manufactured by Dubois Agrinovation (Saint-Remi, QC, Canada); 1 g·m⁻² = 0.0033 oz/ft².

strong yield differences among bio-mulch products, growers will likely choose the most economical product or one that provides the greatest secondary benefits (Cirujeda et al., 2012). Secondary benefits important to growers might include, soil moisture conservation, weed suppression, rapid soil decomposition of biomulch, and minimal cost and effort involved in mulch removal and disposal. Finally, it is important to note that the lack of differences could be partly because of the relatively small plot size employed in this study (400 ft², five plants/plot). Plot size was limited by the availability of experimental biofabrics, but the variability in yield data highlight the challenge of detecting field-scale yield differences in small plots.

DECOMPOSITION OF BIOMULCHES IN SOIL. The amount of biomulch recovered from soil (grams per square meter of surface area) varied according to biomulch product and sampling date, but there was no interaction between the two effects. Biofabrics are thicker and heavier than bioplastics and the mass of mulch recovered from soil decreased over time (Fig. 4), but there was no detectable difference in the relative rate of decay among biomulches (data not shown).

The rate of soil decomposition observed for the biofabrics tested in this study was faster than what has been reported for similar experimental products. Cowan et al. (2013) found that bioplastic films were between 65% and 100% visibly degraded 13 months after soil incorporation, whereas a biofabric (SB-PLA-11) showed no signs of decomposition. Similarly, Li et al. (2014) observed no decrease in the surface area of a biofabric (SB-PLA-10) recovered from soil 6, 12, and 18 months after soil incorporation. The rate of decomposition of biomulches in soil is variable across diverse climates, but is less affected by the local production environment (i.e., high tunnel or field). Consistent with the results of this study, Li et al. (2014) found no difference in the decomposition of mulches after soil incorporation in the high tunnel and field. However, the rate of decomposition of bioplastic films was much greater at the Texas location—characterized by warm daily maximum temperatures and a greater abundance of soil fungi—compared with the cooler climate in Washington State (Li et al., 2014).

Fig. 4. Biomulch residue recovered from the top 15 cm (5.9 inches) of the soil profile from field (top) and high tunnel (bottom) cucumber between 0 and 11 months after soil incorporation of flail mowed biomulches. The error bar in the bottom left corner of each figure represents $\pm$ SE of least squares means estimated from raw data before transformation. BK-1-270, BK-2-360, BK-6-300, and BK-5-350 experimental biofabrics manufactured by 3M Co. (Saint Paul, MN). Eco Film bioplastic manufactured by Cortec Corp. (Saint Paul, MN). Bio Telo bioplastic manufactured by Dubois Agrinovation (Saint-Remi, QC, Canada); 1 g·m⁻² = 0.0033 oz/ft².

The similar rate of decomposition observed among all biodegradable fabrics and plastics tested in these trials is a promising result in the development of biofabrics. Previous studies on a line of experimental biofabrics (SB-PLA-10/11/12) highlighted the durability and capacity for soil moisture conservation and weed suppression, but a lack of decomposition observed after soil incorporation

would not be acceptable for most growers (Cowan et al., 2013, 2014; Li et al., 2014; Miles et al., 2012). One difference between the experimental biofabrics developed by 3M and the SB-PLA experimental line previously tested is the addition of a “prodegradant” into the composition of two of the 3M fabrics (BK-1-270 and BK-2-360; Table 2). The purpose of the prodegradant is to expedite the rate of

material degradation after soil incorporation of biofabrics. This proprietary prodegradant is biologically based and completely compostable. However, there was no difference in the relative rate of decomposition among any of the 3M fabrics, which suggests there are likely other factors (e.g., thickness or density) influencing the enhanced decomposition of the 3M biomulches relative to similar products. Although the mechanism is unclear at this point, to our knowledge this is the first evidence of comparable relative rates of decomposition between bioplastic films and spunbond, nonwoven biofabrics.

Conclusions

Bioplastic films usually increased soil temperature, but the biofabrics were not different from bare soil. In contrast, all biomulches (bioplastics and biofabrics) increased soil moisture relative to bare soil throughout the growing season. Bioplastic films were less durable and deteriorated sooner than biofabrics, especially in the field. Despite differences in soil temperature, moisture, and mulch deterioration among treatments, significant yield differences were not detected. Relative rate of biomulch decay in soil was not different among bioplastic and biofabric mulches. This is the first study to demonstrate significant soil decomposition of a biofabric mulch before 12 months after soil incorporation. Slow decomposition is one factor that has limited widespread adoption of biomulches in vegetable production. However, this study demonstrates potential progress toward a renewable product that will provide growers with the desirable agricultural benefits of mulch without the potentially deleterious effects of residue accumulation in the soil over time. Although yield benefits may not have been demonstrated, weed control and moisture conservation represent important production cost savings.

Results of this study suggest that biofabrics may be most useful in cool-season crops or warmer climates and in high tunnels where soil warming is usually adequate, but moisture conservation and weed control are still critical. If soil-incorporated residues do not accumulate to deleterious levels, biofabrics may be an attractive option for certified organic vegetable growers as a more durable and weed suppressive alternative to bioplastic films (the 3M experimental products

tested are manufactured from entirely renewable materials and would currently be an allowed input under the USDA National Organic Program). White PE film may provide similar agricultural benefits without warming the soil, but the permeability of biofabrics may appeal to growers without drip irrigation who rely on rainfall or sprinkler irrigation to meet crop water demands. Moreover, the biodegradability of biofabrics should appeal to the increasing number of growers seeking ways to reduce time, labor, and environmental impact associated with PE mulch removal and disposal.

Literature cited

- Cirujeda, A., J. Aibar, Á. Anzalone, L. Martín-Closas, R. Meco, M.M. Moreno, A. Pardo, A.M. Pelacho, F. Rojo, A. Royo-Esnal, M.L. Suso, and C. Zaragoza. 2012. Biodegradable mulch instead of polyethylene for weed control of processing tomato production. *Agron. Sustain. Dev.* 32:889–897.
- Cowan, J.S., D.A. Inglis, and C.A. Miles. 2013. Deterioration of three potentially biodegradable plastic mulches before and after soil incorporation in a broccoli field production system in northwestern Washington. *HortTechnology* 23:849–858.
- Cowan, J.S., C.A. Miles, P.K. Andrews, and D.A. Inglis. 2014. Biodegradable mulch performed comparably to polyethylene in high tunnel tomato (*Solanum lycopersicum* L.) production. *J. Sci. Food Agr.* 94:1854–1864.
- Díaz-Pérez, J.C. and K.D. Batal. 2002. Colored plastic film mulches affect tomato growth and yield via changes in root-zone temperature. *J. Amer. Soc. Hort. Sci.* 127:127–136.
- Jenni, S.D., D. Breult, and K.A. Stewart. 2004. Degradable mulches as an alternative for weed control in lettuce produced on organic soils. *Acta Hort.* 638:111–118.
- Lamont, W.J. 2005. Plastics: Modifying the microclimate for the production of vegetable crops. *HortTechnology* 15:477–481.
- Larsson, L. and A. Båth. 1996. Evaluation of soil temperature moderating and moisture conserving effects of various mulches during a growing season. *Acta Agriculturae Scandinavica Section B Soil Plant Sci.* 46:153–160.
- Li, C., J. Moore-Kucera, C. Miles, K. Leonas, J. Lee, A. Corbin, and D. Inglis. 2014. Degradation of potentially biodegradable plastic mulch films at three diverse U.S. locations. *Agroecol. Sustainable Food Systems.* 38:861–889.
- Martens, D.A. 2001. Nitrogen cycling under different soil management systems. *Adv. Agron.* 70:143–192.
- Martin-Closas, L., A.M. Pelacho, P. Picuno, and D. Rodríguez. 2008. Properties of new biodegradable plastics for mulching, and characterization of their degradation in the laboratory and in the field. *Acta Hort.* 801:275–282.
- Miles, C., R. Wallace, A. Wszelaki, J. Martin, J. Cowan, T. Walters, and D. Inglis. 2012. Deterioration of potentially biodegradable alternatives to black plastic mulch in three tomato production regions. *HortScience* 47:1270–1277.
- Monks, C.D., D.W. Monks, T. Basden, A. Selders, S. Poland, and E. Rayburn. 1997. Soil temperature, soil moisture, weed control, and tomato (*Lycopersicon esculentum*) response to mulching. *Weed Technol.* 11:561–566.
- Moreno, M.M. and A. Moreno. 2008. Effect of different biodegradable and polyethylene mulches on soil properties and production in a tomato crop. *Sci. Hort.* 116:256–263.
- Ngouajio, M., R. Auras, R.T. Fernandez, M. Rubino, J.W. Counts, and T. Kijchavengkul. 2008. Field performance of aliphatic-aromatic copolyester biodegradable mulch films in a fresh market tomato production system. *HortTechnology* 18:605–610.
- Olsen, J.K. and R.K. Gounder. 2001. Alternatives to polyethylene mulch film—A field assessment of transported materials in capsicum (*Capsicum annuum* L.). *Austral. J. Expt. Agr.* 41:93–103.
- Shogren, R.L. and R.C. Hochmuth. 2004. Field evaluation of watermelon grown on paper-polymerized vegetable oil mulches. *HortScience* 39:1588–1591.
- Waterer, D. 2010. Evaluation of biodegradable mulches for production of warm-season vegetable crops. *Can. J. Plant Sci.* 90:737–743.
- Weber, C.A. 2003. Biodegradable mulch films for weed suppression in the establishment year of matted-row strawberries. *HortTechnology* 13:665–668.
- Wien, H.C. 2009. Microenvironmental variations within the high tunnel. *HortScience* 44:235–238.
- Wortman, S.E., I. Kadoma, and M.D. Crandall. 2015. Assessing the potential for spunbond, nonwoven biodegradable fabric as mulches for tomato and pepper crops. *Sci. Hort.* 193:209–217.
- Wortman, S.E., J.L. Lindquist, M.J. Haar, and C.A. Francis. 2010. Increased weed diversity, density and above-ground biomass in long-term organic crop rotations. *Renew. Agr. Food Syst.* 25:281–295.