Biodegradable Biobased Mulch Film

Crops

Summary of Petitioned Use

Biodegradable biobased mulch film is currently allowed under the National Organic Program (NOP) regulations at 7 CFR 205.601(b)(2)(iii) for use as mulch in organic crop production with the annotation: "Must be produced without organisms or feedstock derived from excluded methods." This technical report is limited in scope to address specific questions posed by the National Organic Standards Board (NOSB) Crops Subcommittee in support of the substance's sunset review.

The definition for biodegradable biobased mulch film at 7 CFR 205.2 includes criteria for compostability, biodegradation, and biobased content. NOP Policy Memo 15-1 (National Organic Program 2015) clarified that in order to meet the definition, all polymer feedstocks must be biobased. A subsequent report prepared for the NOP (OMRI 2015) found that there are no 100% biobased mulch films currently available, and that the biobased content of currently available biodegradable films in the marketplace ranged from 10-20%, with the remaining content being comprised of polymers derived from fossil fuels as well as inorganic materials such as dyes and processing aids. Although these mulches, referred to herein as biodegradable mulch films (BMFs), do not meet the requirement for 100% biobased polymer content specified in NOP Policy Memo 15-1, they are discussed in this technical report since they have undergone field research related to the focus questions requested by the subcommittee, whereas very little field research on 100% biobased biodegradable mulch film is reported in the literature.

A transdisciplinary research project funded by the USDA's National Institute of Food and Agriculture Specialty Crop Research Initiative (SCRI) titled "Biodegradable Mulches for Specialty Crops Produced Under Protective Covers" was carried out between 2010 and 2013. The project was conducted by a team of scientists from several universities and extension centers to evaluate biodegradable mulches for specialty crops produced in high tunnels and open fields in three different regions of the U.S. (USDA 2009). Several of the publications resulting from this project, referred to herein as SCRI 1, are referenced throughout this report. The USDA awarded a second SCRI grant in 2014 for another four years of the project, this time titled "Performance and Adoptability of Biodegradable Plastic Mulch for Sustainable Specialty Crop Production" (USDA 2014). This additional segment of the project is thus ongoing and is half way complete. It is herein referred to as SCRI 2.

Focus Areas Requested by NOSB Crops Subcommittee

1. What is the effect on overall soil health, including soil biology, when this material biodegrades?

The question of how BMFs affect soil quality once they degrade is a very new topic of research; few studies have been carried out or are still in progress (Flury 2016; Li, Moore-Kucera and Lee, et al. 2014). The reason is the relatively recent development of these materials. The beneficial effects of using non-biodegradable plastic mulch films on soil conditions and crop performance are widely accepted and have led to their widespread use since their commercial introduction in the 1960s (Kasirajan and Ngouajio 2012; Li, Guo and Wei 1999). However, due to concerns over environmental pollution and high costs associated with plastic mulch waste, BMFs have been developed, including some from biobased feedstocks, beginning in the 1990s. There have been numerous studies on the extent of the biodegradability of BMFs both under laboratory conditions and in the soil or in compost. However, their long-term effects on soil quality are only beginning to be evaluated.

As part of the SCRI 1 project, Li, Moore-Kucera and Miles, et al. (2014) evaluated *in-situ* degradation of four different BMFs in three different geographical regions, each under two different cropping systems. The

BMFs included two different, black, starch-based mulches; an experimental, white, nonwoven spunbond mulch made from 100% polylactic acid (PLA) feedstock (biobased but lower degradability); and a cellulose (paper) mulch. The variability in degradation results led the authors to recommend that localized degradation tests be carried out to determine suitability of a particular BMF to a site. Another report from the same SCRI 1 project found similarly high variability in soil quality index among sites, production systems and time of sampling after mulch integration into the soil (Li, Moore-Kucera and Lee, et al. 2014). These findings suggest that the effects of BMF degradation on soil quality will vary substantially based on a combination of factors, including the type of BMF used, location, cropping system and time since mulch incorporation. Moore-Kucera (2012) also reported that while the SCRI 1 group found enhanced enzymatic potential under cellulose-based mulch compared to no mulch after one year, soil biological responses to all the treatments were variable among locations, mulch type and cropping system, with no visible trends in N mineralization potential. The authors concluded that soil conditions such as temperature, moisture and pH may affect soil quality more than incorporation and degradation of BMFs over time (Moore-Kucera 2012).

Various indicators can be used to assess soil quality or health. Soil health has been compared to ecosystem health in terms of functionality (Arias, et al. 2005), stability and resilience under conditions of disturbance or stress (van Bruggen and Semenov 2000). Indicators used to assess soil health include soil organic matter (SOM) content and mineralization; microbial biomass, diversity and activity (Arias, et al. 2005); as well as soil enzyme activity (Alkorta, et al. 2003). Functional indicators include control of plant diseases, insect pests and weeds; symbiotic associations between microorganisms and plants; recycling of nutrients; and improved plant growth or crop production (Arias, et al. 2005). Physical and chemical indicators include soil structure and associated water- and nutrient- holding capacity, water infiltration rate, bulk density, pH, electrical conductivity, ion-exchange capacity, and aggregate stability and slaking. The presence of environmental toxins and contaminants is another important component of soil health. Several of these indicators are discussed below where information is available and relevant to the degradation of biodegradable mulch films.

Microbial biomass and soil organic matter

Microbial utilization of BMF as a carbon source can have multiple disparate and interconnected effects on soil quality. According to the American Society for Testing and Materials (ASTM), biodegradable plastics by definition undergo degradation by naturally occurring soil microorganisms, for which the plastic polymers serve as an energy source (Li, Moore-Kucera and Miles, et al. 2014). In the first stage of degradation, mulch films fragment into small particles by various abiotic and biotic mechanisms. The abiotic forces include photodegradation, oxidation and hydrolysis. Biodegradation begins to occur when microbial enzymes break the polymer chains into shorter lengths via chemical cleavage, which begins to affect the polymers' original properties. The last stage of degradation occurs when the macromolecules have been reduced in size enough to be incorporated into microorganisms' physiological cycles, known as bioassimilation. The products of microbial degradation of BMF under aerobic conditions therefore include microbial biomass, water, and carbon dioxide. Methane is an additional metabolite under anaerobic conditions (César 2014; Kasirajan and Ngouajio 2012).

The ratio of microbial biomass carbon to total organic carbon has been used both as a measure of microbial activity and to examine soil carbon equilibrium, meaning the amount of carbon inputs compared to the outputs. Changes to this ratio are often seen in the initial stages after carbon inputs are added and the ratio usually then falls back to original levels over time (Anderson and Domsch 1989). Ardisson et al. (2014) used respiration to measure biodegradation of BMFs in a laboratory setting, and reported a lack of reliable methods for measuring biomass carbon or carbon residues produced during biodegradation of BMFs at the time of their study (Ardisson, et al. 2014). However, one of the current SCRI 2 project goals is to determine how BMFs contribute to the carbon cycle, including the fractions that are bioassimilated, lost to the atmosphere as CO_2 via respiration, or converted into stable soil organic carbon: humus. The group postulates that the addition of new carbon to the soil in the form of BMF could help improve soil quality by increasing content of soil organic matter (see Figure 1) (English, et al. 2016).

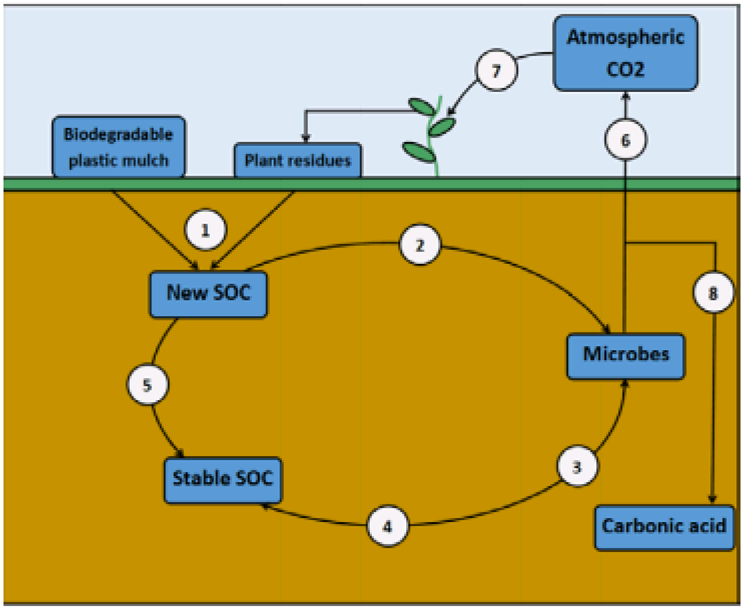

Figure 1. Soil Carbon Cycle (English, et al. 2016)

1) Small pieces of biodegradable plastic mulch and plant residue enter the soil where they become new soil organic carbon (SOC).
2) Microbes decompose SOC at a rate determined by soil pH, temperature, moisture, and oxygen availability.
3) Microbes decompose SOC at a rate determined by soil pH, temperature, moisture, and oxygen availability.
4) Incomplete decomposition can lead to the synthesis of stable compounds that enter the stable SOC pool.
5) Stable SOC is formed when new SOC chemically adheres to minerals, or gets incorporated into aggregates.
6) During decomposition, microbes incorporate some carbon into their cells and respire some in the form of CO_2.
7) Plants take up CO_2 during photosynthesis and incorporate it into biomass.
8) Depending on the pH and moisture content of the soil, some CO_2 is leached into the soil as carbonic acid.

Li et al. (2004) used microbial biomass carbon as an indicator of soil quality measured under non-biodegradable plastic mulch treatments of varying durations (0 days, 30 days, 60 days and one entire growing season). They found that mulching soils promoted microbial biomass C, but decreased soil organic matter (SOM) (Li, Song, et al. 2004). This may be due to the introduction of carbon-rich substrate accelerating the mineralization of native soil organic matter (Kuzyakov 2010). SOM mineralization is beneficial in the sense that soil nutrients are liberated and become bio-available for plants (Moreno and Moreno 2008). Mineralization of SOM also means that nutrients become subject to loss by leaching or volatilization, and CO_2 gas from microbial respiration is released into the atmosphere. Increased SOM mineralization can also occur due to increased soil temperature under mulch film (Li, Song, et al. 2004; Leirós, et al. 1999), although Moreno & Moreno (2008) observed the opposite. They reported decreased microbial biomass carbon and SOM mineralization (or CO_2 respiration) under BMF as compared to bare soil one year after mulch introduction, which they attributed to increased temperatures (although they observed greater soil microbial biomass and SOM mineralization under BMFs than non-biodegradable plastic mulches). Another report from the SCRI 1 project evaluated changes in microbial biomass under the different mulches and cropping systems and found elevated microbial biomass under starch-based mulches in high-tunnel production systems as compared to open fields after 18 months (Li, Moore-Kucera and Lee, et al. 2014).

Determining the net effect of BMF biodegradation on soil quality in terms of soil carbon is a complex question because the carbon and nitrogen cycles are dynamic processes. Kuzyakov (2010) explored the interactions between the living (e.g., microbial) and non-living organic matter, and advocated for the inclusion of such interactions in models describing carbon and nitrogen dynamics. The interaction between carbon and nitrogen pools with microbial biomass changes and enzyme activity are only beginning to be explored in relation to BMF degradation and its impacts on soil quality.

Microbial community structure

Van Bruggen and Semenov (2000) suggested that the amplitude and duration of soil microbial community responses to various stressors at different intensities could serve as good indicators of soil health. As part of the SCRI 1 project, Moore-Kucera, Cox et al. (2014) found the structure of soil fungal communities involved in the degradation of BMFs at three different locations to be unaltered by mulch treatment after 6 months,. The authors also noted that the composition of the fungal communities was different at each location (Moore-Kucera, Cox, et al. 2014). Kapanen et al. (2008) found no change in the diversity of ammonia-oxidizing bacteria in the soil one year after incorporating starch-based BMFs into the soil at the end of a crop season. Ammonia-oxidizing bacteria have been used as an indicator of soil health for their important role in the global nitrogen cycle, and particularly in agricultural soils (Kapanen, et al. 2008).

Nitrogen mineralization and nutrient balance

Utilization of BMF as a carbon source can be limited if the levels of nitrogen or phosphorus in the soil are insufficient for microorganisms to produce proteins and nucleic acids (Brodhagen, et al. 2015). Microbes immobilize available soil nitrogen when they convert carbon (from soil organic matter or in this case BMF) to biomass. As with any substrate with a high C:N ratio, microbial decomposition can deplete the available nitrogen in the soil as it is immobilized in the utilization of the more abundant carbon source. This can lead to nitrogen deficiency for growing plants, including during the next growing season if mulch fragments remain in the soil (Li, Moore-Kucera and Lee, et al. 2014). However, such a phenomenon has not been observed with the degradation of BMFs according to current scientific literature.

Ardisson et al. (2014) carried out laboratory analyses on the nitrification potential of soil to which a BMF had been applied. Nitrification, or inhibition thereof, has been identified as another important indicator of soil health, as it is a critical two-part step carried out by soil microbes to convert organic nitrogen to nitrate which can be taken up by plants. The inhibition of nitrification indicates adverse impacts on soil health. Their study consisted of the ISO 17556 biodegradation of plastics test, followed by the ISO 14238 test of nitrification inhibition to detect whether biodegradable plastics might adversely affect ecosystems in this way. They found no inhibition of nitrification based on the application of Mater Bi, a commercially available mulch made from a blend of polycaprolactone-based co-polyester and starch, as compared to untreated soil and cellulose-treated soil. They also found the greatest depletion of nitrate associated with the BMF treatment, suggesting microbial assimilation of nitrogen during its utilization of the BMF carbon source (Ardisson, et al. 2014). No significant changes to properties that affect soil nutrient profiles, such as cation exchange capacity and absorption sites, have been observed in the SCRI 2 project after two years of data collection (Flury 2016). However, Flury (2016) notes that soil quality changes slowly over time, and thus the effects of the BMF application are likely to take a long time to detect.

Soil Quality Indices

As part of the SCRI 1 project, Li, Moore-Kucera and Lee, et al. (2014) observed five soil quality indicators over the course of 18 months at the three biogeographic locations, with four different BMFs and under two production systems. The indicators were: pH, electrical conductivity, total organic carbon, microbial biomass and ß-glucosidase activity. The authors concluded that the mulch treatments had only minor impacts on soil quality index (SQI) scores based on the indicators chosen, and that the scores were more dependent on production system (high tunnel vs. open field) and timing (rapid microbial growth was followed by decline – possibly due to lack of additional carbon inputs into the bags of soil where the BMFs were buried), rather than mulch treatment. The authors note that improvements in SQI could have been due to factors other than the mulch treatments, and the overall drop in SQI after 18 months with the cellulose and starch-based mulches led the authors to suggest the need for longer-term studies on the effects of BMFs on soil quality.

A broad range of soil quality indicators are being evaluated as part of the SCRI 2 study: bulk density, infiltration rate, penetration resistance, pH, organic carbon, electrical conductivity, nitrate, respiration (in situ and potential), soil water and heat flow dynamics, leaching, soil microbial community, structure, slaking and macro- and micronutrients in soil under BMF treatments. Although the project is in its second year of a 5-year study, it does not yet have conclusive data to suggest whether and how the BMF affects soil quality, since soil quality changes slowly over time (Flury 2016).

Ecotoxicity and pathogen persistence

Ardisson et al. (2014) describe testing for ecotoxicity as the second tier in evaluating the safety of BMFs, after the first tier of determining the extent of their degradability. General statements are made in the scientific literature regarding the safety of the by-products resulting from the biodegradation of BMFs, referring to water, biomass, carbon dioxide and methane (Kasirajan and Ngouajio 2012). One study found no evidence of ecotoxicity in the soil during the biodegradation of a starch-based BMF over the course of a year by measuring the reproduction potential of *Vibrio fischeri* and *Enchytraeus albidus* ISO/CD 16387 with a kinetic luminescence bacteria test (Kapanen, et al. 2008).

There is a lack of evidence in the scientific literature for ecotoxic effects of BMF degradation on soil microbial communities. Brodhagen et al. (2015) noted that the growth of microbial cells during BMF degradation can result in the secretion of organic acids that alter the pH of the surrounding environment, which could help facilitate further polymer break down. However, the authors also cite the potential accumulation of mycotoxins produced by some of the fungi involved in the biodegradation of BMFs as a topic needing future research (Brodhagen et al. 2015).

In general the effects of BMFs on soil health are not yet well understood and need further study (Flury 2016). Kasirajan and Ngouajio (2012) highlight microclimate modification along with soil physical, chemical and biological properties; soil moisture, weed control, soil nutrients, and pest and disease management as areas where information is needed with regard to the effects of BMFs. Substantial research efforts to address such questions are underway with the SCRI 2 project.

2. **What is the cumulative effect of the continued use of this biodegradable biobased mulch film, on soil nutrient balance, soil biological life, and soil tilth, when used in the same area of the field for 3-5-10 years?**

The cumulative, long-term effects of biodegradable biobased mulch film on soil nutrient balance, soil biological life and soil tilth are not currently known. As discussed above, research into the impacts of BMFs on soil is recent, and most studies have been short-term (less than two years). The SCRI 2 project does include a longer-term (5-year) study on repeated incorporation of BMFs at fixed field sites in Washington and Tennessee to detect any adverse effects on soil quality from fragments or mulch residues that don't biodegrade quickly, and may therefore accumulate in the soil (Inglis 2016).

Mere degradation, fragmentation or partial decomposition could result in accumulation in the environment, which is why ASTM D6400 standards outline requirements for microbial utilization of biodegradable mulches (Narayan 2012). A series of surveys and focus groups conducted between 2009 and 2012 of specialty crop growers, Extension personnel, and agricultural input suppliers reported that many operators who have used biodegradable mulch films have not been satisfied with them due to unpredictable or incomplete degradation, though there is continued interest in their use. Uncertainty of the long-term impact on soil was cited as one barrier to the adoption of BMFs (Goldberger and Miles 2012). However, other reports suggest farmer satisfaction with the performance of BMFs over several growing seasons due to the many benefits and despite higher up-front costs (Rangarajan and Leonard 2007; KMVT 2016).

Brodhagen et al. (2015) looked at the potential for long-term accumulation of fragments with continued use of BMFs that pass the ISO 17088 (2012) and ASTM D6400-12 (2012) composting standards. They report that the biodegradability standards of these tests would permit the accumulation of small plastic fragments (< 2.0 mm), as well as up to 49% of the concentration of regulated metals allowed for sludges, fertilizers and composts. A new testing standard under consideration for aerobically biodegradable plastics in a soil environment, ASTM WK29802 (2014), would result in similar conditions: persistence of 10% of the plastic mass after 2 years for each constituent present in the material at a concentration of more than 1%. With their assumptions, the authors calculate that, if any portion of the remaining 10% represents recalcitrant polymers, metals or untested components, they will accumulate with repeated applications in the soil in a manner that can be estimated. In their report, Brodhagen et al. (2015) calculate theoretical accumulations of biodegradable mulch films based on various factors including degree of biodegradability, and estimate that with 0.1 volume fraction of a plastic mulch film remaining at the end of 1 year in soil (1 being equal to no degradation, 0 being equal to complete degradation), after 30 years the volume fraction would be around 2.4 ppt (parts per thousand). The authors note that the aggregate effects on soil quality and ecosystem health from the accumulation of the persisting fraction of mulch films over repeated cropping cycles has not been systematically studied. Although no long term studies on BMFs are reported in the literature, Brodhagen et al. (2015) cite one 2014 report from China where use of non-biodegradable agricultural plastic for two decades resulted in the accumulation of >300 kg polyolefins/ha in the topsoil. Research and development of BMFs continue to improve degradability and increase the biobased content, and one report projects that BMFs will replace polyethylene mulch films in the next 8 years (Grand View Research, Inc. 2016). Thus, increased rates of use and modifications to BMF products' composition are additional factors to consider when evaluating their long-term, cumulative effects.

3. What effect does the breakdown of these polymers have on soil and plant life as well as livestock that would graze either crop residues or forages grown the subsequent year after this mulch film was used?

There is a lack of specific evidence in the current scientific literature to show that the breakdown of BMF polymers adversely affects soil and plant life or subsequently grazing livestock. Starch and polylactic acid (PLA)-based BMFs have been reported to degrade into harmless products when placed in contact with soil microbiota (Kasirajan and Ngouajio 2012). One study found the degradation products of various blends of starch and polycaprolactone to be non-toxic to earthworms, *Eisena fetida* (Nishioka, et al. 1994). One study found no significant difference in levels of heavy metals (Pb, Ni Cu, Cd and Cr) in the edible portion of crops grown in soil where a starch-based BMF had been incorporated over 6 consecutive years versus soil without the mulch film (Yang and Chin-Hsiang 1999).

As part of the SCRI 1 project, Cowan, Miles and Inglis (2013) reported on the deterioration of three biodegradable mulches in a broccoli production system. Degradation rates differed between the mulch products during the growing season, and fragmentation increased for all products following incorporation into the soil, reaching maximum levels at days 132 and 299, respectively. Although fragment numbers declined after this, their size did not, suggesting the existence of a threshold fragment size for biodegradation during this period. The authors reported that crop yields were improved under all mulch treatments as compared to no mulch, measured at the end of the second year after the first year's mulch had been incorporated into the soil. They reported no impact, adverse or beneficial, on crop yields due to the incorporation of the mulch into the soil.

Although these studies did not uncover significant impacts of BMF degradation products on soil or plant life, it is generally accepted that any such impacts are poorly understood and need further study. Regarding livestock that that would graze crop residues or forages grown subsequent to the use of BMFs, Brodhagen et al. (2015) report that it is unknown what effect the ingestion of plastics has on terrestrial organisms. It has been noted that plastics can absorb pesticides and other contaminants such as mycotoxins in the environment, which could be ingested with the plastic and bioaccumulate. Insects have been observed to accumulate flame retardants from plastics (Gaylor, Harvey and Hale 2012), and plastic ingestion by seabirds has been cited as a probable source of polychlorinated bisphenol (PCB) burden in their bodies (Ryan, Connell and Gardner 1988) (Yamashita, et al. 2011). That being said, BMFs in agriculture are used predominantly in the production of fresh market fruits and vegetables in systems such as high or low tunnels and open field row crops. It is therefore less likely that areas of livestock production would overlap with areas where BMFs are used.

As part of the SCRI 2 project, various BMFs were used in organically managed experimental fields where pie pumpkins were grown. Mulch adhesion to the pumpkins was noted with several of the different BMFs, with pronounced adhesion at the site in Western Washington, rendering the affected pumpkins unmarketable (Miles, Ghimire, et al. 2015).

4. Are there different cropping systems, climate, soil types or other factors that affect the decomposition rate (Examples would be long cold winters, or exceptionally dry conditions, such as found in a desert)?

Decomposition rate is likely the most extensively studied topic when it comes to biodegradable mulch films. Because these materials are designed to degrade, the extent and rate of their degradation is often tested under controlled conditions in the laboratory. Researchers have also begun to evaluate their decomposition in the field, taking into consideration the numerous environmental and other factors that can affect degradation.

Results from the SCRI 1 project specifically inform this question. The study evaluated the difference in degradation of several BMFs under two cropping systems at three geographically distinct locations over a two-year period by measuring percentage of mulch area remaining after burial. The regions were in 1) the southeast with hot and humid summers (Lubbock, TX), 2) the high plains south with hot and dry summers (Knoxville, TN), and 3) the Pacific Northwest with cool, humid summers (Mount Vernon, WA). The team reported that geographical factors, both abiotic and biotic, played a significant role in the degradation of BMFs at the three locations (Li, Moore-Kucera and Miles, et al. 2014). The characteristics with the most pronounced differences between sites were: diurnal temperature range (with the widest range at Lubbock), maximum daily soil temperature and initial pH.

The authors noted that the composition and activity of soil microbial communities are strongly influenced by soil temperature, moisture, pH and inorganic N content, which can help explain differences in decomposition rates between sites. The starch-based BMF degradation rate was highest at Lubbock, which had warm soil and air temperatures, alkaline soil, and a high abundance of fungi. (Moisture was not considered a factor due to year-round irrigation.) The authors postulated that the higher diurnal temperature range at Lubbock was a contributing factor to the higher rates of degradation there, and noted that alkaline soil has also been associated with higher degradation rates. Conversely, they observed that the cool year-round temperatures, relatively moist conditions in winter fallow periods, and low soil diurnal temperature range in the Northwest may prevent or limit degradation of the mulch materials there.

Regarding cropping system, the high tunnel plots had higher inorganic N levels than open fields at each site, but this factor did not appear to influence degradation rate. Degradation of mulches as measured by percent mulch area remaining was not statistically different between the two cropping systems. However, results reported two years prior did note more rips, tears and holes, and greater visually observed deterioration for the starch- and cellulose-based BMFs in the open field plots as compared to the high tunnels at the three sites, likely due to higher winds, and greater solar radiation and rainfall in the open field plots (Miles, Wallace, et al. 2012).

Brodhagen et al. (2015) also discuss environmental factors affecting microbial degradation of BMFs. They note that the biological reactions involved in microbial decomposition, hydrolysis and oxidation are affected by temperature, as are abiotic weathering reaction rates contributing to BMF degradation in soil. Increased temperatures enhance catalytic enzymatic activity, which leads to increased microbial metabolic rates. Soil pH also affects degradation rates: neutral pH generally favors microbial activity, but extremely acidic or basic pH can also speed hydrolysis of ester linkages and glycocidic bonds in starch. Because hydrolysis and oxidation reactions are dependent on the availability of oxygen and water, soil moisture is also another key factor.

A limited number of studies have considered differences in the composition of native soil microbiota between different sites to assess their role as a variable in determining the decomposition of different types of BMFs (Moore-Kucera, Cox, et al. 2014; Li, Moore-Kucera and Miles, et al. 2014). Brodhagen et al. (2015) note that the native microorganisms of a site may not include those that are most efficient at degrading BMFs. Different types of ecosystems have different biodegradation pathways, even when degrading the same polymer (Fritz 2014).

As expected, degradation rates also differ based on the type of BMF material in combination with external conditions. For example, polylactic acid (PLA), a biological resin base for some BMFs, undergoes hydrolysis at a very slow rate at temperatures below 20-25 ºC, but very fast at temperatures above 60 ºC. PLA degrades quickly in compost (several weeks), but much slower at room temperature (several years) (César 2014). Brodhagen et al. (2015) reported on comparative rates of biodegradation of different BMF feedstocks (both biobased and hydro-carbon based) in soil. Of the biobased feedstocks, starch has a high biodegradation rate, cellulose moderately high, polyhydroxyalkanoates (PHAs) such as poly(3-hydroxybutyrate) (PHB) and poly(3-hydroxyvalerate) (PHV) a moderate rate, and PLA a low rate of biodegradation in the soil. Kasirajan and Ngouajio (2012) describe the characteristics of polymers that play a role in their degradation: chemical structure and molecular mobility, tacticity, crystallinity, molecular weight, type of functional groups and substituents present in the polymer's structure, as well as plasticizers and other additives.

The authors reporting on the SCRI 1 project in 2014 recommended small-scale, localized testing of BMFs to determine their suitability to a specific location and conditions (Li, Moore-Kucera and Miles, et al. 2014).

5. Are there metabolites of these mulches that do not fully decompose, and if so, is there an effect upon soil health or biological life?

It is currently unknown whether complete degradation of BMF is possible (Flury 2016). Metabolites of BMFs include carbon dioxide or methane, water and biomass. Intermediate molecules that appear in the degradation process may include ketones, alcohols, acids and more (César 2014). César (2014) notes that full bioassimilation is almost never complete, and that the degree of biodegradation which actually occurs in the field is difficult to determine experimentally. Incomplete biodegradation of BMFs may occur when growing conditions for the microorganisms responsible for biodegradation are not optimal, or when the film is difficult to cleave. This can result in metabolites other than CO_2, water and mineral salts accumulating in the soil, which have the potential to affect microbial activity and plant growth (Fritz 2014).

Biodegradability of a mulch film can be established by the standardized tests outlined by the ASTM; however, these test results do not provide information on the compatibility of the breakdown materials with the environment. Residuals of polyethylene plastic mulch left in the field could interfere with root development of subsequent crops, as buried pieces of plastic mulch decompose more slowly (Kasirajan and Ngouajio 2012). The environmental impacts of this have not been fully evaluated. As noted previously, plastic fragments in the soil that do not degrade may have the potential to adsorb persistent toxins, based on research on the impacts of plastic debris in aquatic and terrestrial ecosystems (Li, Moore-Kucera and Lee, et al. 2014).

The effect of BMF additives, processing aids and their metabolites which are released into the environment during BMF degradation have not been extensively addressed in the scientific literature. Some starch-based polyethylene films are reported to be formulated with 40% starch, as well as urea, ammonia, and various portions of low density polyethylene and poly(ethylene-co-acrylic acid). Starch itself can be used as an additive, and contains amylose and amylopectin (Kasirajan and Ngouajio 2012). Other additives can include plasticizers like dioctyladipate and epoxidized soybean oil, alcohols, polyoxyalkenes and surfactants (Brodhagen et al. 2015). Additives used to counteract the brittleness of PLA-starch blended polymers include plasticizers such as glycerol, formamide, sorbitol, urea or triethyl citrate (Lu, Xiao and Xu 2009; Kasirajan and Ngouajio 2012). Other additives have been reported as general nucleating agents, plasticizers, coloring agents, performance additives and lubricants. The environmental impact of such additives has been acknowledged as a potential concern (Corbin, et al. 2013).

One study did evaluate the toxicity of additives used in lactic acid-based polymers for plant growth and microbial inhibition in compost (Tuominen , et al. 2002). They found that polymers in which the additive 1,6-hexamethyldiisocyanate (HMDI) was used for chain linking lactic acid oligomers did cause toxicity as measured both in plant growth and microbial inhibition. When this additive was substituted with another linking agent, 1,4-butane diisocyante, the toxicity was not observed (Tuominen , et al. 2002). Additives in

BMF blends are typically included at low concentrations; thus their ecotoxicological effects may be difficult to detect based on the dilution factor when they are mixed into the soil during biodegradation (Kapanen, et al. 2008). Kapanen et al. (2008) recommended that the toxicity of biopolylmers be tested during laboratory scale biodegradation tests and after using high concentrations of the polymers in order to account for the dilution factor.

Table 1. General toxicity of select additives used in biodegradable mulch films.

Additive	**CAS number**	**Degradability and potential ecological effects**
Dioctyl adipate	103-23-1	Not acutely toxic; not a bioaccumulator. Biodegrades readily in the presence of oxygen; 83% in 28 days. Estimated half-life 2.6hr in clean air, 26hr in polluted air. Water insoluble; cannot move in soil and water.
Epoxidized soybean oil	8013-07-8	Unknown eco-toxicological concern. Readily biodegradable: 79% in 28 days (Modified Sturm Test). Chemical oxygen demand 2,240 mg/g. Low potential to bioaccumulate.
Formamide	75-12-7	Aerobic biodegradability 99% in 28 days. The products of degradation are less toxic than the product itself. Possibly hazardous short-term degradation products are not likely; however, long-term degradation products may arise.
Glycerol	56-81-5	FDA GRAS listed at 21 CFR 182.1320. Readily biodegrades in soil and water. Not expected to significantly bioaccumulate. Not expected to evaporate significantly from soil. Soil degradation 50 days in the field.

Sources: Arkema 2010, EMD Chemicals Inc. 2001, Environmental Working Group 2012, HI-Valley Chemical Inc. 2006, IUPAC 2015, Megaloid Laboratories 2012, Pesticide Action Network 2016, Spectrum 2012, US FDA 2013.

Breakdown of a BMF polymer could potentially result in the release of nutrient elements such as nitrogen, with potential implications as a fertilizer or cause of toxicity, as in the case of ammonium, though such a scenario is more likely to occur in composted mulches (Fritz 2014).

Research related to the risks and benefits of carbon emissions during microbial breakdown of biodegradable mulches has yet to be undertaken (Inglis and Miles 2012); however, increased mineralization of soil organic matter due to elevated temperature and moisture has been cited as a source of increased greenhouse gas emissions (Leirós, et al. 1999).

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