National Organic Standards Board (NOSB) – Questions about Soil-Biodegradable Plastic Mulches in Organic Production

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This document summarizes responses to questions and concerns regarding the use of soil-biodegradable plastic mulch films (referred to as "BDMs") in certified organic agriculture in the United States. Questions were provided by members of the NOSB and responses are followed by a list of select refereed journal publications. The content provided in this document represents the current understanding of these materials' performance based on the authors' collective expertise and experience with these materials through field and laboratory experiments.

Effect on Soil, Ecology, and Ecosystem Functions

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

   Summary. Research to date on how soil chemical, physical, and biological properties are impacted from continuous application of BDMs has shown there are few consistent effects that can be attributed to BDM application and soil incorporation. A two-year study led by Sintim et al. (2019) looked at 19 soil health variables in pie pumpkin production systems in Knoxville, TN and Mount Vernon, WA. Soil properties, health indicators, and functions were affected more by site and time than by mulch treatment from 2015-2017. Soil microbial community structure and function were also more impacted by site and time of sampling (i.e., season) (Bandopadyay et al., 2020). Extracellular enzyme rate assays similarly showed site and season more strongly influenced microbial activity than the mulch treatments. Together, these results show soil microbial community structure and function were similar among plots treated with polyethylene (PE) and BDMs in both locations following two consecutive years of use (note that PE was not soil-incorporated in any of these studies). Research results show that BDMs degrade more quickly at higher soil temperatures, but different proprietary blends (e.g., feedstocks, production processes, etc.) can be affected differently by temperature, and can thus be optimized for different climates (Anunciado et al., 2021; English, 2019). After four consecutive years of BDM application (a continuation of the 2 year study aforementioned), Sintim et al. (2021) also found no detrimental effects of BDM on soil health compared with conventional PE mulch in both Knoxville, TN and Mount Vernon, WA. Mola et al. (2021) assessed the effect of soil solarization on soil quality using BDM and PE mulch under greenhouse conditions and found that the BDMs avoided a high ammonia concentration in the soil due to lower soil water content and slightly lower temperature than PE mulch, which was attributed to optimal conditions for growth of nitrifying bacteria under BDMs. Longer-term field studies would enable a better assessment of how soil health is impacted by BDM usage, but results to date show

BDMs have similar effects as PE mulch on soil health and soil biology, and that geographic location and season are stronger determinants of the measured variables than BDM application and incorporation.

Literature addressing impacts of BDMs on soil health, including biology, can be found in the following published scientific articles.

- Anunciado, M.B., D.G. Hayes, A.F. Astner, L.C. Wadsworth., C.D. Cowan-Banker, J.E. Liquet y Gonzalez, and J.M. DeBruyn. 2021. Effect of environmental weathering on biodegradation of biodegradable plastic mulch films under ambient soil and composting conditions. J. Polym. Environ. 29:2916-2931. doi 10.1007/s10924-021-02088-4.
- Bailes, G., M. Lind, A. Ely, M. Powell, J. Moore-Kucera, C.A. Miles, D. Inglis, and M. Brodhagen. 2013. Isolation of native soil microorganisms with potential for breaking down biodegradable plastic films used in agriculture. J. Vis. Exp. 75: e50373.
- Bandopadhyay, S., L. Martin-Closas, A. M. Pelacho, and J. DeBruyn. 2018. Biodegradable plastic mulch films: Impact on soil microbial communities and ecosystem functions. Front. in Microbiol. 9:819.
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compostable plastics in three contrasting agricultural settings. Applied. Microbiol. Biotechnol. 98(14): 6467-6485.
- Saglam, M., H.Y. Sintim, A.I. Bary, C.A. Miles, S. Ghimire, D.A. Inglis, M. Flury. 2017. Modeling the effect of biodegradable paper and plastic mulch on soil moisture dynamics. Agri. Water Manage. 193: 240-250.
- Schaeffer, S.M., M. Flury, H.Y. Sintim, S. Bandopadhyay, S. Ghimire, A.I. Bary, and J.M. DeBruyn. 2015. Soil physical characteristics and biological indicators of soil quality under different biodegradable mulches. AGU Annual Meeting Abstracts, San Francisco, December 14-15.
- Sintim, H.Y., and M. Flury. 2017. Is biodegradable plastic mulch the solution to agriculture's plastic problem? Enviro. Sci. Technol. 51(3):1068-1069.
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2. What is the cumulative effect of the continued use of 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?

<u>Summary</u>. Please see the response above, which addresses research on how BDMs impact soil health. Generally, soil health comprises chemical (e.g. soil nutrient balance), physical (tilth), and biological measurements. These are addressed above. The longest study we are aware of that evaluated effects of BDM on soil health is the four-year study by Sintim et al. (2021), and no negative effects of BDMs on soil health were observed in this study. Additionally, during this study, there was not a significant effect on soil microbial communities and their activities (Liquet y Gonzalez, 2019), or on the overall accumulation of soil organic matter (English, 2019). We are unable to provide results for a longer time frame, as they are not available in the literature.

<u>Literature:</u>

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- Liquet y Gonzalez, J. E. 2019. Effects of long-term use and incorporation of biodegradable plastic mulch films on soil microbial community structure and activity. MS Thesis, University of Tennessee, Knoxville, TN.
- Sintim, H. Y., S. Bandopadhyay, M.E. English, A. I. Bary, J. E. Liquet y Gonzalez, J. M. DeBruyn, S. M. Schaeffer, C.A. Miles, and M. Flury. 2021. Four years of continuous use of biodegradable plastic mulch: Effects on soil and groundwater quality. Geoderma 381:114665. doi.org/10.1016/j.geoderma.2020.114665.

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

   <u>Summary</u>. This is an important question with few published studies to date with PE mulch and no studies published regarding BDM. Overall, studies that have looked at 2-4 years of BDM application have shown crop yields and performance are comparable to PE mulch and generally higher than non-mulched treatments (see publications below). This suggests immediate degradation products are not negatively impacting crop growth and development. For non-BDM studies, Taylor et al. (2020) show polystyrene plastic (not a BDM) micro- and nano-particles accumulate on the surface of Arabidopsis and wheat root cap cells, but there was no evidence of uptake, and plastic particles were not found internally within the root. In contrast, Li (2020) reported uptake of submicrometre plastic (polystyrene and polymethylmethacrylate; both non-BDMs) in wheat and lettuce roots grown in hydroponic cultures and in sand matrices or a sandy soil after treatment with wastewater. These plastic particles entered via naturally-formed cracks at lateral root emergence sites and were found to move into the shoots via transpirational pull. There is a rapidly growing body of literature reporting effects of micro- and nano- (non-BDM) plastics on soil fauna (Bootes et al., 2019; Helmberger et al., 2020) generally concluding that particles of this size can have effects on growth, reproduction, stress and immune responses, locomotion and gut microflora (Buks et al., 2020; Chen et al., 2020; Helmberger et al., 2020; Hodson et al., 2017; Huerta Lwanga et al., 2016 and 2017; Kim et al., 2019; Lei et al., 2018; Maaß et al., 2017; Prendergast-Miller et al., 2019; Rillig et al., 2012 and 2017; Rodríguez-Seijo et al., 2017 and 2018; Sun et al., 2018; Yi et al., 2020; Zhu et al., 2018a, 2018b, and 2018c).

   Ingestion of various sizes (0.1, 1.0, and 5 μm) and types of non-BDM microplastics by the model nematode *Caenorhabditis elegans* showed that 1.0 μm microplastic particles caused the highest lethality and damage, regardless of composition, concluding that toxicity of micro-plastics is more dependent on size than composition (Lei et al., 2018). Indeed, high concentrations and small particle sizes of microplastics appear to be the greatest contributors to toxicological effects across a range of soil microfauna (Buks et al., 2020). Presumably, BDMs would be a lower threat from a toxicological standpoint because they are degrading in soils and there would be less-to-no accumulation of micro-plastics depending on how frequently BDMs are applied. Thus, microplastics would be produced during the degradation process, but their residence time would be reduced, lessening the potential risks. However, we have no data to support or refute this hypothesis at this time and it's an important area of research. In other studies, earthworms have been shown to drag BDM pieces into the soil, but no negative effects on earthworms have been observed (Zhang et al., 2018). Effects of microplastics (non-BDM) on soil microbes has been mixed, with some studies reporting altered composition and activities, and others no effect (Fei et al., 2020; Huang et al., 2019; Liang et al., 2019; Wiedner and Polifka, 2020; Yan et al., 2020; Zhang et al., 2019).

Studies on uptake of BDM degradation products into plants have not been done to our knowledge and we are also not aware of published literature that investigates impacts on livestock that graze upon fields previously mulched with BDMs.

Literature:

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4. Do breakdown byproducts influence the community ecology and ecosystem function of soils, plants, and the livestock that graze on crops grown in these soils?

   Please see our responses to Qs 1-3.

5. As fragments degrade, do they pose a problem to terrestrial and aquatic wildlife? How will BDMs behave in marine environments? What are the environmental fates of micro- and nano-plastic fragments resulting from biodegradable mulch film degradation, and what hazards do they present to organisms that they interact with on the way to that fate?

Summary. To date, research has not shown that BDMs pose problems to terrestrial and aquatic wildlife. According to standards (EN 17033, which is the first international standard directly pertaining to BDMs), BDMs will achieve ≥90% biodegradation within two years in the laboratory under aerobic conditions in natural topsoil from an agricultural field or forest at temperatures between 20 to 28°C, using a standardized test to measure CO_2 evolution. The rationale for the 90% biodegradation limit, and not 100%, is because a portion of carbon in BDM plastics is incorporated into microbial biomass and therefore will not be broken down to CO_2. In addition, there is limited precision to measure CO_2 evolution in lab tests assessing biodegradability below a ±10% error. However, field tests have shown that degradation under real agricultural settings for some BDM products, including commonly available commercial products, may take longer than 2 years (Griffin-LaHue et al., 2022; Sintim et al., 2020). This result is expected due to fluctuations of temperature and moisture under field conditions; therefore, a measure of time that accounts for temperature (e.g., cumulative degree days) may be a useful benchmark for comparing biodegradability in the lab and field. The EN 17033 standard lists requirements for ecotoxicity in soil systems (i.e., toxic effects on plants, invertebrates, microorganisms), but it does not include ecotoxicity requirements in aquatic or marine environments. See our response to Q9 for more information on ecotoxicity.

The environmental fate and risk of micro- and nano-plastic fragments resulting from BDMs has received limited study due to a lack of robust analytical methodologies to detect and quantify fragments. However, methodologies are being developed by Dr. Schaeffer's lab (Univ. TN–Knoxville) and are being applied to current and future research projects (English, 2019; see Q15 for more detail). To date, impacts on soil microbial community structure and function are more strongly influenced by geographic location and season then by mulch application and degradation.

Literature:

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6. Are there any studies that track the impact on livestock or wildlife (terrestrial, avian and aquatic) that might be attracted to consume pieces of the biodegradable plastic before it has completely degraded in 2 years or secondary metabolites that remain in the soil and are taken up by crops?

   Summary. The only study we are aware of is with earthworms, which have been shown to drag BDMs into their burrows, and are also able to ingest small BDM fragments (Zhang et al., 2018). In a short duration study, no toxic effects on earthworms was observed (Zhang et al., 2018), although others have reported toxic effects of polystyrene plastic beads (polystyrene is not a BDM; Huerta Lwanga et al., 2016). We are not aware of any studies on mammalian livestock nor avian and aquatic organisms with BDMs. We asked colleagues in livestock/animal science and they also echoed that they are not aware of any studies on the effects of BDMs on vertebrates that could consume BDMs.

   Literature:

   - Huerta Lwanga, E., Gertsen, H., Gooren, H., Peters, P., Salanki, T., van der Ploeg, M., Besseling, E., Koelmans, A. A. and Geissen, V. (2016). Microplastics in the terrestrial ecosystem: Implications for Lumbricus terrestris (Oligochaeta, Lumbricidae). Environ. Sci. Technol. 50, 2685-2691.
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Biodegradability of BDMs

7. Are there metabolites or breakdown products of these mulches that do not fully decompose? If so, is there an effect upon soil health or biological life? Do any of these mulches fully decompose?

   Summary. We are not aware of any metabolites or breakdown products of BDMs' polymeric constituents that have a deleterious effect on soil health (including soil biology; please see the responses above). It's also important to note that some commercially available BDMs are composed of a blend of synthetic and biobased polyesters, including starches. However, BDMs also contain inorganic constituents (e.g., colorants, fillers, and plasticizers) that may be released during biodegradation. These components may not decompose. However, the EN 17033 standard also regulates heavy metals content and prohibits the presence of substances of very high concern (SVHC) in order to reduce the environmental impact of BDMs.
   BDMs that are 100% biobased are not commercially available and are "cost prohibitive". The highest percentage of biobased content is 60% at the time of this writing (available in Italy). It is important to note that **biobased content does not correlate with degradation**

(a common misconception). Furthermore, degradation rates can vary under diverse soil and environmental conditions with soil temperature, moisture, and soil microbial composition having the biggest influence on degradation, along with physicochemical changes of the BDMs resulting from environmental weathering during the cropping season (Anunciado et al., 2021; Calmon et al.,1999; English, 2019; Sintim et al., 2019). Tillage practices have also been anecdotally reported to influence degradation rates due to its impact on fragment size and surface area available to soil microorganisms. However, for a BDM to be considered biodegradable, it should at a minimum meet compostability and soil biodegradation standards. ASTM D6400, the standard for compostability, evaluates for biodegradability using the ASTM D5338 laboratory test method, while EN17033 is the standard for testing under aerobic conditions (the latter of which is discussed in our response to Q5 above). Visual assessments of macroscopic BDM fragments (≥2.36 mm) show that after 4 years of annual BDM application from 2015 to 2018 in northwest Washington, mulch recovery from soil in spring 2019 ranged from 23 to 64% of the amount applied (area basis), indicating there was no accumulation of mulch fragments in the soil even after repeated applications (Ghimire et al., 2020). Recovery further decreased to 4-16% (mass basis) 2 years after the final mulch incorporation in fall 2020 (Griffin-LaHue et al., 2022). Only paper BDMs (e.g. Weed Guard Plus) show 100% biodegradation within the timespan of this study, but the conclusion from the study was that BDMs are degrading and do not accumulate in soil after repeated use.

Literature:

- Anunciado, M.B., D.G. Hayes, A.F. Astner, L.C. Wadsworth., C.D. Cowan-Banker, J.E. Liquet y Gonzalez, and J.M. DeBruyn. 2021. Effect of environmental weathering on biodegradation of biodegradable plastic mulch films under ambient soil and composting conditions. J. Polym. Environ. 29:2916-2931. doi 10.1007/s10924-021-02088-4.
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- Ghimire, S., M. Flury, E. Scheenstra, and C.A Miles. 2020. Sampling and degradation of biodegradable plastic and paper mulches in field after tillage incorporation. Sci. Total. Environ. 703:1-7.
- Griffin-LaHue, D., S. Ghimire, Y. Yu, E.J. Scheenstra, C.A. Miles, and M. Flury. 2022. In-field degradation of soil-biodegradable plastic mulch films in a Mediterranean climate. Sci. Total. Environ. 806:150238. https://doi.org/10.1016/j.scitotenv.2021.150238.
- Sintim, H.Y., A.I. Bary, D.G. Hayes, M.E. English, M. Sean, C.A. Miles, and M. Flury. 2019. Release of micro- and nanoparticles from biodegradable plastic during in situ composting. Sci. Total Environ. 675, 686–693.
- Sintim, H.Y., A. Bary, D. Hayes, L. Wadsworth, M.B. Anunciado, M. English, S. Bandopadhyay, S. Schaeffer, J. DeBruyn, C.A. Miles, J. Reganold, and M. Flury. 2020. In situ degradation of biodegradable plastic mulch films in compost and agricultural soils. Sci. Total Environ. 727: 138668.

8. Do the residues of these films accumulate after repeated use?

Summary. After BDMs are tilled into the soil, the mulch fragments continue to degrade into smaller fragments over time until they are metabolized by soil microorganisms and the carbon in BDMs becomes CO_2 or microbial biomass. Based on field studies, plastic BDMs take several years to completely degrade, while paper mulch has been found to degrade within one year (Griffin-LaHue et al., 2022; Ghimire et al., 2020). Research shows that there is no substantial buildup of BDM macroplastics in soil. However, as the film residue reaches a size at or below 2.36 mm it becomes difficult to measure through standard soil assessment methods that depend on visual observation for quantification (Ghimire et al., 2020). This indicates that significant quantities of BDM macroplastics will not accumulate in soil after repeated use. Retrieval of micro- and nano-particles from soil is challenging methodologically (Wang et al., 2018) and published literature on accumulation of BDM micro- and nano-particles is limited. Minor additives, such as carbon black, can be released from the mulch as it degrades. Carbon black is nondegradable and can accumulate in soil (Sintim et al., 2019). The quantity of each additive used to produce commercially available mulches are often unknown as this is proprietary information of mulch manufacturers. It is possible for these residues to accumulate in soil after the repeated application of BDMs, but there is no published literature documenting this. Further sampling methods are necessary to evaluate for the potential accumulation of micro-and nano-particles to determine the full extent of BDM biodegradability in soil. Recent published work modeled degradation of BDMs in the Mediterranean climate of western Washington and predicted that 90% degradation will take ~21 to 58 months, depending on the mulch product used (Griffin-LaHue et al., 2022). Furthermore, this study showed modeling using thermal time rather than calendar time led to better agreement between in-field and laboratory degradation rates, and degree day accumulation is slower in the field than laboratory assays due to cooler temperatures and fluctuations. Visible recovery of mulch fragments after 4 years of continuous application and 2 years undisturbed was 4–16% of total mulch mass incorporated, indicating the mulches were still deteriorating albeit at a slower rate than in the laboratory standard test, which was attributed to environmental factors (see Q10). However, we’d like to point out the potential for non-biodegradable PE mulch residues to accumulate (even with field removal, as fragments often remain) is greater as these materials are not engineered to biodegrade and can have deleterious effects on soil health (Lozano et al., 2020; Zhang et al. 2020).

Literature:

- Ghimire, S., M. Flury, E. Scheenstra, and C.A. Miles. 2020. Sampling and degradation of biodegradable plastic and paper mulches in field after tillage incorporation. Sci. Total. Environ. 703:1-7.
- Griffin-LaHue, D., S. Ghimire, Y. Yu, E.J. Scheenstra, C.A. Miles, and M. Flury. 2022. In-field degradation of soil-biodegradable plastic mulch films in a Mediterranean climate. Sci. Total. Environ. 806:150238 https://doi.org/10.1016/j.scitotenv.2021.150238.
- Lozano, Y.M., T. Lehnert, L.T. Linck, A. Lehmann, and M.C. Rillig. C. 2020. Microplastic shape, concentration and polymer type affect soil properties and plant biomass, p. 245-258. In: D. He and Y. Luo (eds.). Microplastics in Terrestrial

Environments, Emerging Contaminants and Major Challenges. Springer, Nature, Switzerland.
- Zhang, D., E.L. Ng, W. Hu, H. Wang, P. Galaviz, H. Yang, W. Sun, C. Li, X. Ma, B. Fu, and P. Zhao. 2020. Plastic pollution in croplands threatens long-term food security. Global Change Biology 26(6):3356-3367.
- Wang, Z., S.E. Taylor, P. Sharma, and M. Flury. 2018. Poor extraction efficiencies of polystyrene nano- and microplastics from biosolids and soil. PLoS ONE, 13, e0208009, doi.org/10.1371/journal.pone.0208009.

9. Is there information on the toxicity or effect of all secondary metabolite residues as the product breaks down?

Summary. BDMs should meet standards before being considered and labeled as "biodegradable". One important international standard is EN 17033, which contains requirements for ecotoxicity (i.e., toxic effects on plants, invertebrates, microorganisms) among other factors (Hayes and Flury, 2018; please see our response to Q5 for additional details). Therefore, for a BDM that meets this important standard, ecotoxicity is being tested for and controlled. As reviewed by Bandopadhyay et al. (2018), no ecotoxic effects have been observed in tests with the widely used starch-copolyester blend, Mater-Bi® (Novamont, Novara, Italy) (Sforzini et al., 2016). Furthermore, nitrification potential (ISO 14238:2012) (Ardisson et al., 2014) and reproduction of white worm (*Enchytraeus albidus*; ISO/CD 16387) and *Vibrio fischeri* (a marine, bioluminescent bacteria, ISO 11348 flash test) (Kapanen et al., 2008) have not been adversely affected when exposed to Mater-Bi®. Other common feedstocks for BDMS [Ecoflex®; BASF, polyhydroxybutyrate (PHB), and polyhydroxyalkanoate (PLA)] likewise showed no visual phytotoxicity (ISO 11269-2) (Rychter et al., 2006, 2010).

Literature:
- Ardisson, G. B., M. Tosin, M. Barbale, and F. Degli-Innocenti. 2014. Biodegradation of plastics in soil and effects on nitrification activity. A laboratory approach. Front. Microbiol. 5:710. doi: 10.3389/fmicb.2014.00710.
- Bandopadhyay, S., L. Martin-Closas, A.M. Pelacho, and J. DeBruyn. 2018. Biodegradable plastic mulch films: Impact on soil microbial communities and ecosystem functions. Front. in Microbiol. 9:819.
- Hayes, D.G and M. Flury. 2018. Summary and assessment of EN 17033:2018, a new standard for biodegradable plastic mulch films. Report No. EXT-2018-01. Available online at < https://ag.tennessee.edu/biodegradablemulch/Pages/factsheets.aspx>.
- Kapanen, A., E. Schettini, G. Vox, and M. Itävaara. 2008. Performance and environmental impact of biodegradable films in agriculture: a field study on protected cultivation. J. Polym. Environ. 16, 109–122. doi: 10.1007/s10924-008-0091-x.
- Rychter, P., R. Biczak, B. Herman, A. Smylla, P. Kurcok, G. Adamus, et al. 2006. Environmental degradation of polyester blends containing atactic poly(3-hydroxybutyrate). Biodegradation in soil and ecotoxicological impact. Biomacromolecules 7, 3125–3131. doi: 10.1021/bm060708r.

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- Sforzini, S., L. Oliveri, S. Chinaglia, and A. Viarengo. 2016. Application of biotests for the determination of soil ecotoxicity after exposure to biodegradable plastics. Front. Environ. Sci. 4:68. doi: 10.3389/fenvs.2016.00068.

10. 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)?

    <ins>Summary.</ins> Degradation is influenced by soil moisture, temperature, oxygen, microbial activity, mulch chemical structure and formulation, and farming practices (e.g., tillage, cover cropping, compost additions, etc.). Dry soil conditions and cold temperatures will slow down degradation of BDMs (Sintim et al., 2020). Conversely, higher temperatures result in faster degradation, with different constituents of BDMs degrading at different rates (Anunciado et al. 2020; English, 2019). In general, greater soil microbial activity promotes degradation in aerobic conditions at temperatures where the mulch material approaches its glass transition temperature (Anunciado et al, 2021; Hayes et al., 2017). At the glass transition temperature, the supramolecular structure of polymeric material is opened up, allowing for greater access to soil moisture and microorganisms to enable the degradation process. It is important to remember that the degree of biobased content <ins>does not</ins> reflect a material reaching a glass transition phase at lower temperatures nor enhanced degradability. Because it is not possible for scientists to test degradation under all these field conditions and their combinations, we recommend growers and certifiers test weathered BDMs in their unique field setting using the mesh bag test methodology (Madrid et al., 2020). This mesh bag test will provide an indication of the biodegradability under certain farming practices and environments. It is also worthy of mention that the climactic conditions of the cropping season affects the physicochemical properties of BDMs, with warmer and moister climates imposing a greater change that results in an enhancement of biodegradability under ambient soil and composting conditions (Anunciado et al, 2021)

    Recent published work highlighted the role of environment on in-field degradation. Griffin-LauHue et al. (2022) modeled degradation of BDMs in the Mediterranean climate of western Washington and predicted that 90% degradation will take ~21 to 58 months, depending on the mulch product used. Furthermore, this study showed modeling using thermal time led to better agreement between in-field and laboratory degradation rates, and degree day accumulation is slower in the field than laboratory assays. Visible recovery of mulch fragments after 4 years of continuous application and 2 years undisturbed was 4–16% of total mulch mass incorporated, indicating the mulches were still deteriorating albeit at a slower rate than the laboratory standard test, which was attributed to environmental factors including soil temperature, moisture, biological communities, and mulch fragment size. One important aspect of this study was that it highlighted the importance of verifying laboratory-based standards and associated tests with in-field data.

Literature:

- Anunciado, M.B., D.G. Hayes, L.C. Wadsworth, M.E. English, S.M. Schaeffer, H.Y. Sintim, and M. Flury.2020. Impact of agricultural weathering on physicochemical properties of biodegradable plastic mulch films: Comparison of two diverse climates over four successive years. Journal of Polymers and the Environment https://doi.org/10.1007/s10924-020-01853-1.
- Anunciado, M.B., D.G. Hayes, A.F. Astner, L.C. Wadsworth., C.D. Cowan-Banker, J.E. Liquet y Gonzalez, and J.M. DeBruyn. 2021. Effect of environmental weathering on biodegradation of biodegradable plastic mulch films under ambient soil and composting conditions. J. Polym. Environ. 29:2916-2931. doi 10.1007/s10924-021-02088-4.
- English, M. 2019. The role of biodegradable plastic mulches in soil organic carbon cycling. Biosystems Engineering and Soil Science. University of Tennessee, Knoxville, p. 112.
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- Griffin-LaHue, D., S. Ghimire, Y. Yu, E.J. Scheenstra, C.A. Miles, and M. Flury. 2022. In-field degradation of soil-biodegradable plastic mulch films in a Mediterranean climate. Sci. Total. Environ. 806:150238. https://doi.org/10.1016/j.scitotenv.2021.150238.
- Madrid, B., H. Zhang, C.A. Miles, M. Flury, H.Y. Sintim, S. Ghimire, and L. DeVetter. 2020. Assessing degradation of soil-biodegradable plastic mulches. Small Fruit Horticulture Research and Extension. Washington State University, Mount Vernon. 20 August 2020. https://s3.wp.wsu.edu/uploads/sites/2181/2020/08/BDM-Mesh-Bag-Factsheet.pdf.
- Sintim, H.Y., A. Bary, D. Hayes, L. Wadsworth, M. Anunciado, M. English, S. Bandopadhyay, S. Schaeffer, J. DeBruyn, C.A. Miles, J. Reganold, and M. Flury. 2020. In situ degradation of biodegradable plastic mulch films in compost and agricultural soils. Sci. Total Environ. 727: 138668.

11. How rapidly do these mulches fully decompose, to what extent does cropping system, soil type, and climate mediate decomposition rates, and does the percentage of the polymers in the mulch film affect the decomposition rate?

    Summary. The degradation rate can vary widely and cannot be specified due to the numerous factors that can influence degradation (such as soil moisture, temperature, oxygen, microbial activity, mulch chemical structure and formulation, and farming practices; please see our response to Q 10). Likewise, the specific impact of individual factors on degradation cannot readily be isolated or quantified. The composition of BDMs, including the polymeric components and their relative amounts, as well as minor components such as colorants, fillers, and plasticizers, can impact degradation, either directly due to their inherent degradability, or indirectly due to how they impact film manufacturing or through changes of mulch properties during agricultural weathering.

We have found that, among the mulches that differed only in color and underwent identical agricultural weathering conditions, a black-colored film was slightly more compostable than a white-on-black and clear version of the BDM (Anunciado et al, 2021).

Literature:

- Anunciado, M.B., D.G. Hayes, A.F. Astner, L.C. Wadsworth., C.D. Cowan-Banker, J.E. Liquet y Gonzalez, and J.M. DeBruyn. 2021. Effect of environmental weathering on biodegradation of biodegradable plastic mulch films under ambient soil and composting conditions. J. Polym. Environ. 29:2916-2931. doi 10.1007/s10924-021-02088-4.

12. Is the biodegradability of the mulch film the main issue, or should a future annotation include other issues?

    Summary. In our opinion, a future annotation should address the use of genetically modified bacteria and yeast (i.e., GMOs) that are used for the fermentation of feedstocks to make biobased polymers, which are used to make BDMs – is this use of GMOs in the processing step acceptable or not? Requiring the use of non-GMO processing technology would make BDMs more costly and likely would be an economic barrier for use. Also, address the rate of biodegradation under field conditions as our data show more than 2 years are needed in the different climates and soil systems that we evaluated. Additionally, a primary issue that should be addressed is the requirement for BDMs to be 100% biobased, as biobased content is not a prerequisite for a BDM to be biodegradable. Biobased content of 20-50% is more feasible at the manufacturing level.

13. Should a future annotation try to include consideration that different soils and climates might not be able to meet the biodegradability standard set in the annotation, and how would certifiers be able to verify the use of the material met the biodegradability standard?

    Summary. The relevant standards, EN 17033 (for BDMs and tested in agricultural or forest soils) and ASTM D6400 (compostability standard), do not include any specifications for biodegradability in different soil types or climates. Both standards specify "inherent" biodegradability as assessed using standardized laboratory tests. Fulfillment of these standards and their inherent biodegradability requirements ensures that the BDMs will biodegrade under the environments specified in each standard. However, as pointed out in our responses to Qs 10 and 11, the biodegradation process in a field environment can vary widely in soil or compost due to differences in environmental conditions and farming practices. To verify that BDMs are compliant with the specific requirements of the standards EN 17033 and ASTM D6400, BDM manufacturers could provide documentation that compliance was met to OMRI or other third-party certifiers. In this way, the burden of documentation does not fall on individual growers, and every grower is not being asked to obtain this documentation.

    Also of note: it is not possible to test all commercially available BDM products within the diversity of field and soil environments encountered in agriculture. Individual grower practices, such as tillage and cover cropping, may influence degradation within and among farms, complicating assessments and creating generalizable recommendations or considerations. BDM manufacturers are well aware of how environmental variations can impact performance and they adjust mulch thickness for different environments, generally making films thicker for warmer climates where degradation occurs more rapidly. Given this complexity, another recommendation could be that a grower and/or certifier perform their own assessments of degradation by burying pieces of field-weathered BDM in mesh bags in the field. We have developed a Factsheet that describes how a grower or certifier can measure visual degradation of biodegradable mulches in their fields and suggest this tool could be used to assess whether a material meets biodegradation standards (Madrid et al. 2020).

The recent paper by Griffin-LaHue et al. (2022) also underscores the importance of verifying lab-based biodegradation standards with in-field data.

This Factsheet is available for free online at: https://s3.wp.wsu.edu/uploads/sites/2181/2020/09/BDM-Mesh-Bag-Factsheet.pdf.

A video also accompanies the Fact Sheet: https://s3.wp.wsu.edu/uploads/sites/2181/2020/09/BDMs-Mesh-bag-video.mp4

Literature:

- Griffin-LaHue, D., S. Ghimire, Y. Yu, E.J. Scheenstra, C.A. Miles, and M. Flury. 2022. In-field degradation of soil-biodegradable plastic mulch films in a Mediterranean climate. Sci. Total. Environ. 806:150238 https://doi.org/10.1016/j.scitotenv.2021.150238.
- Madrid, B., H. Zhang, C.A. Miles, M. Flury, H.Y. Sintim, S. Ghimire, and L. DeVetter. 2020. Assessing degradation of soil-biodegradable plastic mulches. Small Fruit Horticulture Research and Extension. Washington State University, Mount Vernon. 20 August 2020. Available online at < https://smallfruits.wsu.edu/plastic-mulches/application-management/>.

14. Are the testing protocols in place to insure decomposition standards?

Summary. There are standardized testing protocols, operated under controlled laboratory conditions, referred to by the standards to ensure BDMs entering the marketplace will meet performance specifications both above and below the soil. However, the standards do not take into account the variability in performance that can be strongly affected by environmental conditions or farming practices (see Griffin-LaHue et al., 2022). Please see Table 1 below for a list of different BDM standards. Our aforementioned factsheet was designed as a tool to evaluate whether BDMs meet the decomposition standards under various field and soil conditions, and to explain the underlying goals and purposes of standards

Table 1. BDM Standards (Dentzman and Hayes, 2019; Hayes and Flury, 2018)

Standard Organization	**Standard Name**	**Comments**

European Committee for Standardization (CEN)	**EN 17033** (2018) Plastics– Biodegradable Mulch Films for Use in Agriculture and Horticulture – Requirements and Test Methods	First international standard directly pertaining to biodegradable mulches by an international organization
Association Francaise de Normalisation (AFNOR)	**NFU 52-001 (2005)** Biodegradable Mulches for Use in Agriculture and Horticulture - Mulching Products - Requirements and Test Methods	French standard pertaining to biodegradable mulches. This standard has been substituted by EN 17033.
Ente Nazionale Italiano di Unificazione (UNI)	**UNI 11495** (2013) Biodegradable Thermoplastic Materials for Use in Agriculture and Horticulture - Mulching Films - Requirements and Test Methods	Italian standard pertaining to biodegradable mulches. This standard has been substituted by EN 17033.
ASTM, International	**ASTM D6400** (2012) Standard Specification for Labeling of Plastics Designed to be Aerobically Composted in Municipal or Industrial Facilities	Pertains directly to biodegradation under industrial composting conditions, and is often misrepresented[1]
TUV Austria (Vincotte formerly)[2]	**OK Biodegradable SOIL** (label)	Certifies that plastic materials will biodegrade fully and will not promote ecotoxicity in the soil
[1] ISO (International Organization for Standardization) has equivalent standards		
[2] TUV Austria is not a standards organization but is a certification body authorized by European Bioplastics, an association representing the interest of the European bioplastics industry.		

Literature:

- Dentzman, K. and D. Hayes. 2019. The role of standards for use of biodegradable plastic mulches: truths and myths. Report No. EXT-2019-01. Accessed 3 Sept. 2020. <https://ag.tennessee.edu/biodegradablemulch/Documents/Standards%20Factsheet%20Formatted%20revised%2015Jan2019.pdf >.
- Griffin-LaHue, D., S. Ghimire, Y. Yu, E.J. Scheenstra, C.A. Miles, and M. Flury. 2022. In-field degradation of soil-biodegradable plastic mulch films in a Mediterranean climate. Sci. Total. Environ. 806:150238 https://doi.org/10.1016/j.scitotenv.2021.150238.
- Hayes, D.G and M. Flury. 2018. Summary and assessment of EN 17033:2018, a new standard for biodegradable plastic mulch films. Report No. EXT-2018-01. Available online at < https://ag.tennessee.edu/biodegradablemulch/Pages/factsheets.aspx>.

Microplastics

15. What is the availability and status of methods to measure microplastics that might derive from incompletely biodegraded mulch (i.e., plastic particles, not metabolic products)?

Summary. Protocols and approaches are being developed by us and by other research groups worldwide to develop a robust methodology to isolate and characterize micro-plastics, and perhaps in the future, nano-plastics, in soil (English, 2019). Characterization methodologies (e.g., size and size distribution, shape/geometry, chemical composition, and the presence of adhered microorganisms) are readily available and are being refined by several groups worldwide. Our group has developed a methodology to prepare micro- and nano-plastics from mulch films that would represent those residing in agricultural soils, and we are using the nano-plastics to study their agglomeration behavior with soil particulates (Astner et al., 2020 and 2021).

Literature:

- Astner, A.F., D.G. Hayes, H.M. O'Neill, B.R. Evans, S.V. Pingali, V.S. Urban, and T. M. Young. 2019. Novel methodology to form micro- and nano-plastics from agricultural plastic materials and their dimensional, thermal, and chemical characterization, Science of the Total Environment. 685:1097-1106 (doi 10.1016/j.scitotenv.2019.06.241).
- A.F. Astner, D.G. Hayes, S.V. Pingali, H. M. O'Neill, K.C. Littrell, B.R. Evans, and V.S. Urban. 2020. Effects of soil particulates and convective transport on dispersion and aggregation of nanoplastics via small-angle neutron scattering (SANS) and Ultra SANS (USANS). PLOS ONE 15(7):e0235893.
- English, ME. 2019. The role of biodegradable plastic mulches in soil organic carbon cycling. Biosystems Engineering and Soil Science. University of Tennessee, Knoxville, p. 112.

16. Are there studies looking at whether PE film, even removed at the end of the season, contributes to microplastics in soil?

Summary. We are not aware of specific literature that shows how incomplete PE mulch removal at the end of the season contributes to micro-plastic pollution in soils. However, it is important to note that it is often not possible to completely remove PE mulch from the soil after use. It is estimated that 5-10% of residual PE mulch is left in the field, where it negatively impacts soil structure, water quality, and crop growth, and can enter water systems, thereby disrupting the agricultural ecosystem and overall environment (Miles et al., 2017). Particularly, in China where PE mulches are thinner than in the USA, incomplete removal of PE film after crop harvest has led to accumulation of PE fragments in soil (Liu et al., 2014; Zhang et al. 2019; Qi et al. 2018; de Souza Machado et al. 2018). As a consequence, many years of PE mulch use have led to serious pollution with PE plastic fragments and negative impacts on soil health and crop yields (Liu et al., 2014).

Literature:

- de Souza Machado, A.A., W. Kloas, C. Zarfl, S. Hempel, and M.C. Rillig. 2018. Microplastics as an emerging threat to terrestrial ecosystems. Global Change Biology 24: 1405-1416. doi: 10.1111/gcb.14020.
- Liu, E.K., W.Q. He, and C.R. Yan. .2014. White revolution to white pollution—Agricultural plastic film mulch in China. Environ. Res. Lett. 9, doi: 10.1088/1748–9326/9/9/091001.

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- Zhang, M., Y. Zhao, X. Qin, W. Jia, L. Chai, M. Huang, and Y. Huang. 2019. Microplastics from mulching film is a distinct habitat for bacteria in farmland soil. Science of the Total Environment 688: 470-478. doi: https://doi.org/10.1016/j.scitotenv.2019.06.108.

Composting BDMs

17. If BDM is composted on an organic farm, can the compost be used on that farm? (I assume that since it is not organic currently, that it could not be used on an organic field).

    Summary. If BDMs are not approved for organic production, then we agree that the interpretation would be that a compost containing BDM should not be applied to organic land. We have found that BDMs, particularly after agricultural weathering, are readily compostable using a standardized laboratory test (Anunciado et al., 2021). However, a consideration is that as BDMs degrade, they become weak, friable, and start to fragment. In this condition, removal from a field and to a composting environment would be difficult, labor intensive, and complete removal would be practically impossible. If a grower does want to compost BDMs on-farm as a means of end-of-life management, the probability of successfully composting is high given these materials must meet compostability standards (ASTM D6400) and based on our experience at Washington State University where we composted BDMs in piles representative of on-farm situations (data not published). BDMs are likely not a good compost feedstock in municipal settings if the goal is producing large amounts of compost as BDMs account for a large initial volume but eventually degrade into very little useful product for the composter. Composting may be considered, however, as a management strategy for disposing of BDM, and the residual compost is a byproduct that can be land applied.

    Literature:

- Anunciado, M.B., D.G. Hayes, A.F. Astner, L.C. Wadsworth., C.D. Cowan-Banker, J.E. Liquet y Gonzalez, and J.M. DeBruyn. 2021. Effect of environmental weathering on biodegradation of biodegradable plastic mulch films under ambient soil and composting conditions. J. Polym. Environ. 29:2916-2931. doi 10.1007/s10924-021-02088-4.

Additional Considerations

18. What is your opinion on mulch films that could be engineered to include macro or micronutrients or pesticides that would then make the mulch film provide more benefits than just a mulch?

Summary. Multifunctional films that have pesticides or other agrichemicals embedded within them for crop benefits and are affordable to farmers are worthy of research. We are not aware of any published research that addresses these questions.

19. Is the risk/benefit of keeping plastic mulches out of landfills part of the Organic Food Production Act criteria the NOSB should consider when reviewing this material?

    Summary. This is a philosophical question regarding the function of the NOSB and Organic program and thus we feel it is not appropriate for us to comment.