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Review

Benchmarking the Agronomic Performance of Biodegradable Mulches against Polyethylene Mulch Film: A Meta-Analysis

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Received: 9 September 2020; Accepted: 13 October 2020; Published: 21 October 2020

Abstract: Growers are interested in biodegradable alternatives to petroleum-based polyethylene mulch film (PEM). However, many growers cite limited knowledge about biodegradable mulch films (BDMs) as a significant barrier to adoption. Agronomic field tests of BDMs are often limited temporally or spatially, and the variability of performance results relative to PEM may be contributing to this perceived knowledge gap. Our objective was to use data available in the scientific literature to provide the first quantitative performance benchmark of BDMs against PEM. We extracted data from 66 articles for meta-analysis. Response ratios were calculated for comparison of BDMs relative to black PEM, and differences among categorical groups were determined using 95% bootstrap confidence intervals. Overall, BDMs reduced soil temperature by 4.5% ± 0.8% (±one standard error) compared to PEM, and temperatures were coolest beneath paper-based BDM. Starch-polyester BDM was less effective than PEM for weed control, but paper-based BDM reduced weed density and biomass by 85.7% ± 9.2%. Paper-based BDMs were particularly useful for controlling *Cyperus* spp. weeds. Despite differences in soil temperature and weed suppression, crop yields were not different between BDMs and PEM. Future research should focus on reducing costs, adding functional value, and increasing the biodegradability of BDMs.

Keywords: biomulch; mulching; sustainable agriculture; biobased products

1. Introduction

Agricultural mulches are characterized as a physical barrier between the soil and cultivated crop, and are most commonly used in specialty crop production, including small fruits and vegetables [1–3]. Potential agronomic benefits of mulch include weed suppression [4], soil moisture conservation [5], reduced soil erosion [6], increased soil temperature, crop protection from insects and pathogens, and increased crop yield and quality [7]. The most common mulch used in commercial agricultural systems is polyethylene plastic film [6]. First introduced in the mid-20th century, polyethylene mulch (PEM) film revolutionized commercial production of many vegetable crops [8]. Polyethylene mulch film is popular because of its low cost, availability, and its physical properties (e.g., flexible yet durable) that allow for easy mechanical application on a commercial scale [9,10]. However, there are increasing concerns about PEM because it is manufactured from non-renewable petroleum-based polymers, and may contribute to environmental contamination after use [10,11]. Polyethylene mulch must be removed from the field after use and the majority is buried in landfills or incinerated. Given the environmental limitations of PEM, considerable research and innovation efforts over the last four decades have been invested in the development and evaluation of biodegradable mulch (BDM) alternatives to PEM [7,12].

Biodegradable agricultural mulch products (typically defined by the inherent biodegradability of constituent polymers under ideal soil conditions, e.g., [13]) can be manufactured from biobased or synthetic polymers, and most often include a combination of both. However, prior to use on USDA certified organic farms, BDMs must satisfy additional requirements including: (1) 90% biodegradation, bioassimilation, or mineralization to microcrystalline cellulose by soil microbes in less than two years under typical field conditions [14]; (2) the BDM must be manufactured from 100% biobased materials (no petroleum-based feedstocks or synthetic polymers allowed); and (3) manufactured without the use of genetically engineered organisms (including plant feedstock and processing microorganisms) [3,9,15]. On-farm adoption of BDMs has been limited by premature deterioration of BDM during the growing season, unpredictably slow biodegradation rates in soil, and concerns about environmental fate of polymers [6,12]. An additional barrier to adoption is that BDMs are usually more costly to manufacture and more expensive for growers than PEM [16]. Despite these challenges, interest in and demand for BDM remains steady, due in part to the increasing public urgency of the global plastic pollution crisis [17].

Commonly proposed biodegradable or biobased alternatives to PEM have included paper-based BDM (including oil- and wax-coated paper; Figure 1) and BDM films and fabrics derived from biodegradable polyesters including (but not limited to) polyhydroxyalkanoates (PHA), polyhydroxybutyrate (PHB), polylactic acid (PLA), polybutylene adipate/terephthalate (PBAT) polylactides, and starch-polyester blends (e.g., Mater-Bi) [7,18]. Early research and development of BDMs is often focused on the polymer science, including physical and mechanical properties and biodegradability of prototype films, e.g., [15,19]. There has been considerably less research on the agronomic performance of BDM, and results of these field-based studies can vary depending on crop species and management, local conditions including soil and weather, and mulch properties, e.g., [20].

Figure 1. Winter squash (*Cucurbita pepo* L.) growing in a paper-based (**left**) versus polyethylene mulch (**right**).

Despite recent reviews on various aspects of BDM [7,9,21,22] and PEM [23], there have been no previous attempts to aggregate and systematically quantify agronomic performance of BDM relative to PEM (or bare soil) reported in the scientific literature. Nearly four decades since the introduction of agricultural BDM, a quantitative meta-analysis of agronomic performance will provide a useful benchmark for the industry. This benchmark will help to identify successes and shortcomings of BDM innovations to date, which can inform future research and development of PEM alternatives. Thus, our objective was to use data available in the scientific literature to estimate the effects of BDM type and properties on soil temperature, weed suppression, and crop yield relative to PEM and bare soil.

2. Materials and Methods

The agronomic benefits of BDM compared to PEM were estimated via systematic literature review and meta-analysis of data extracted from the literature. To begin, a literature search was conducted using Google Scholar with search terms including "biodegradable," "mulch," "crop," "polyethylene," and "yield" or "weed" or "soil moisture" or "soil temperature" in all fields. The search was limited to papers published between 1970 and 7 November 2019, which resulted in approximately 5380 papers. From these results we extracted data from original refereed research papers and excluded patents, citations, theses, dissertations, review papers, and case studies. Additional requirements for inclusion in the meta-analysis were that the article must: (i) include agronomic study of at least one BDM; (ii) include a black PEM control; (iii) include data for yield (of any cultivated crop), weeds, soil moisture, and/or soil temperature for at least one BDM in comparison to PEM; (v) be published in English or Portuguese; and (vi) have full text available on-line or through the University of Nebraska-Lincoln Library. Results of the Google Scholar search were sorted by relevance and considered for inclusion in the analysis until 30 consecutive search results were culled from consideration in the analysis for failing to meet one of the parameters described above. At which point, we determined the literature search to be exhaustive (if not all-inclusive). In total, we reviewed 380 search results and extracted data from 66 original research papers for meta-analysis.

Data Extraction and Analysis

Data were extracted from selected studies and coded by BDM type (i.e., material or polymer, color, and thickness; including bare soil controls), study year and location, crop species, growing environment (i.e., open field or protected), and number of site-years (i.e., spatial and temporal replications of study treatments). Similar mulch types were aggregated into testing groups to create sufficient replication for meta-analysis and these included: (1) starch-polyester films, (2) paper-based mulches (including those treated with oils), and an "other" category that included less common (often experimental) mulch products manufactured from biodegradable or biobased polymers (e.g., polybutylene adipate-co-terephthalate, polyhydroxyalkanoate, polylactic acid, and polypropylene carbonate). Polyethylene mulch was assumed to be black when not described by study authors, and paper-based BDM was assumed to brown unless otherwise noted. As with mulch type, crop species were grouped by family, function, or growth cycle to create sample groups with sufficient replication for meta-analysis (e.g., Solanaceae versus Cucurbitaceae families, vegetative versus fruiting type, and annual versus perennial crops). When necessary, data were extracted from graphs by approximation using the Web Plot Digitizer v. 3.8 (http://arohatgi.info/WebPlotDigitizer).

Response ratios for agronomic performance were determined for each treatment within the study as: (i) BDM yield/PEM yield, (ii) BDM weed abundance/PEM weed abundance, (iii) BDM soil temperature/PEM soil temperature, and (iv) BDM soil moisture/PEM soil moisture. Response ratios were calculated for every unique BDM treatment by site-year combination presented in a study and treated as independent observations within the meta-analysis. The natural log of response ratios were calculated to linearize the ratio and improve normality [24], and ratios were weighted by the number (n) of reps × sites contributing to a reported mean observation as [25]:

$$\text{weight} = (n_{\text{agronomic response}} \times n_{\text{control}})/(n_{\text{agronomic response}} + n_{\text{control}}) \quad (1)$$

Non-parametric bootstrap confidence intervals (95%) were calculated for mean agronomic response ratios of interest using a first-order normal approximation and 4999 iterations ("boot" package; R v. 3.6.2) [25]. Response ratios were calculated for comparison across different mulch types and colors, geographical regions, growing environments, and crop type. Mean response ratios were considered significant if its bootstrap confidence intervals did not overlap with zero. Differences between treatment groups were considered significant when confidence intervals between the two groups did not overlap. Confidence intervals and response ratios were back-transformed and reported as a percent increase or decrease relative to the PEM control in all figures. We opted for this categorical boot-strapping approach to meta-analysis (instead of a quantitative meta-regression approach) due to the relatively small sample size of our response groups and the significant variability among methods of individual studies included in the meta-analysis [26].

Possible publication bias was investigated by fitting data to a random effects model using the "metafor" package in R [27] and assessing how individual observations influenced effect sizes [28]. Because sampling variance was not available for all observations, we assigned a random standard deviation of between 10% and 20% of the mean response value [24]. The random effects model was first used to confirm significance of individual factors (e.g., yield) and tested effects (e.g., mulch type), and then to assess potential effects of non-independence [29]. Funnel plots were evaluated by regression analysis to identify any data asymmetry, and sensitivity analysis was conducted using the "influence" function in the "metafor" package to identify influential observations [27,30]. Data were symmetrical for all tested effects ($p > 0.05$). Values identified as influential were verified in the original citation, but overall there were between zero and only two influential observations per tested effect (Figures S1–S8).

3. Results and Discussion

There were no significant differences in response ratios observed across geographical regions, growing environments, or crop type ($p > 0.05$; data not shown); therefore, results presented were limited to the effects of mulch type and color on soil moisture and temperature, weed suppression, and crop yield. Mulch thickness varied by type (paper-based mulch > PEM > starch-polyester films) and was an inherent difference among mulch types captured by this analysis; but within mulch types, there was insufficient variability and inadequate reporting in the literature to assess the possible effects of BDM thickness on response ratios of interest.

3.1. Soil Moisture

We were able to extract soil moisture data from only 9 of the 66 studies in this meta-analysis (resulting in 18 observations), and bootstrapping analysis of this limited data did not reveal any differences among BDM, PEM, or bare soil (data not shown). Detecting soil moisture conservation benefits of mulches can be difficult given confounding influences of crop and weed growth, precipitation, and irrigation. Nonetheless, in all studies reviewed here, soil moisture beneath BDMs was equal to or greater than in PEM [31–40]).

3.2. Soil Temperature

Soil temperature beneath BDM and bare soil compared to PEM was analyzed across 146 observations from 35 studies. Overall, soil temperature beneath BDMs was reduced by 4.5% ± 0.8% (±one standard error) compared to PEM. Temperature beneath starch-polyester BDMs was 3.6% ± 1.5% less than beneath PEM (Figure 2). BDMs are often thinner and less durable than PEM, which may contribute to reduced soil warming benefits. Indeed, mean thickness of starch-polyester BDMs reviewed herein was 19.7 ± 0.8 μm (±one standard error) compared to 28.1 ± 1.4 μm for PEM. Thinner mulch may have a lower mass and reduced potential for thermal absorptivity, and is also more likely to deteriorate early. Early deterioration would reduce or eliminate soil warming associated with absorption of infrared radiation and transfer to the soil [5]. Thus, soil warming benefits of a BDM are often correlated with its durability or deterioration throughout the growing season; and BDMs that deteriorate prematurely will begin to mimic the soil temperature characteristics of bare soil.

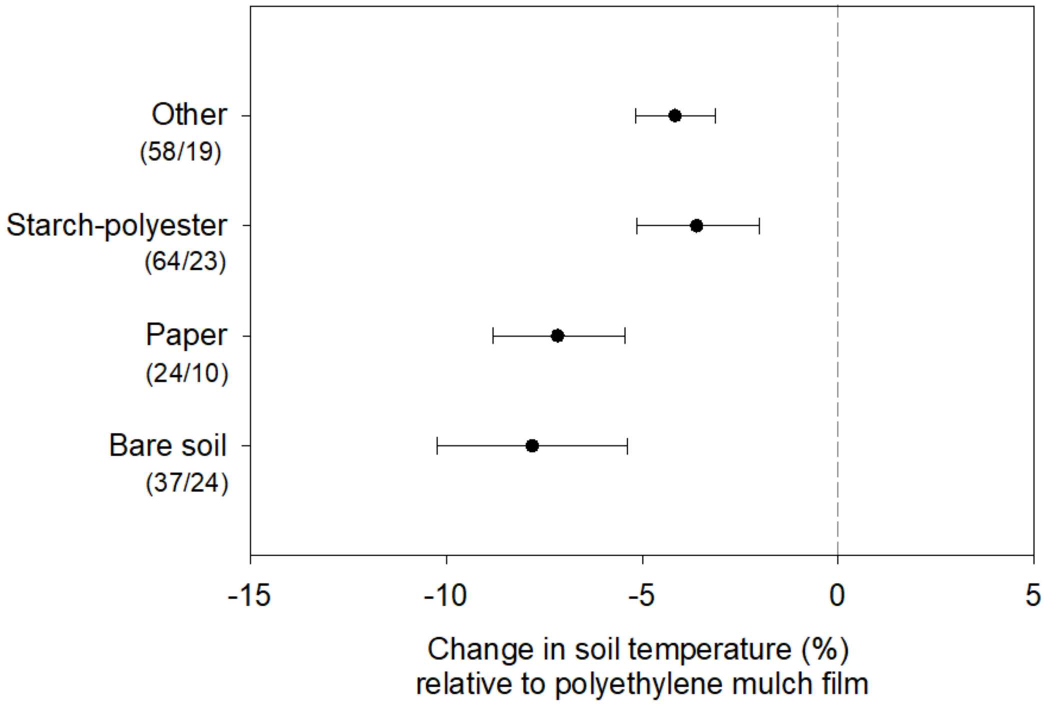

Figure 2. Mean change in soil temperature as influenced by bare soil and biodegradable mulch type (relative to polyethylene mulch film). Numbers below y-axis labels indicate the number of observations and studies (left/right, respectively) contributing to each mean. Error bars represent 95% confidence intervals determined via bootstrapping.

Moreno et al. tested the effects of a commercial black corn starch-polyester BDM on tomato in comparison with PEM and found that the BDM reduced soil temperature (27.8 °C) compared with PEM (31.8 °C) [41]. In contrast, Waterer observed no difference in soil temperatures between a corn starch-polyester BDM film and PEM during a three-year trial across a number of different vegetable crops in Canada [42]. Though soil temperatures were sometimes reduced by starch-polyester BDMs, this mulch type usually increased soil temperature compared to bare soil (Figure 2). Ghimire et al. found that starch-polyester BDM increased soil temperature by 0.7%–7.3% compared to bare soil in a pumpkin crop grown in Washington and Tennessee [20]. Effects of BDM films made from other polymers were similar to the starch-polyester films (4.3% ± 1.1% cooler than PEM), but not different from bare soil (Figure 2).

Paper BDMs reduced soil temperature by 7.2% ± 1.7% compared to PEM, and did not influence temperatures relative to bare soil (Figure 2). In some instances (e.g., light soil color or dry conditions), paper BDM can reduce soil temperature compared to bare soil. Zhang et al. reported a 26.7% reduction in soil temperature beneath a kraft paper BDM (14.3 °C) compared to bare soil (19.5 °C) [43]. Zhang et al. attributed this response to the combination of reduced heat transfer and wetter conditions in the paper BDM soil environment (resulting in a greater specific heat of soil beneath the mulch). Reduced soil temperature beneath BDMs can also be explained by the capacity for the BDM to conduct thermal energy, which is driven in part by the polymer composition and color of the BDM [8].

It is generally understood that dark-colored mulches will absorb, transmit, and reradiate solar energy and can increase soil temperature, whereas light-colored mulches will reflect more solar radiation resulting in reduced soil temperatures [44]. Results of this meta-analysis help to quantify the expected effects of BDM color on soil temperature, relative to black PEM (Figure 3). As expected, soil temperature was greater beneath black than white BDMs; however, it is interesting to note that black BDMs reduced soil temperature by 4.0% ± 0.9% compared to black PEMs. In the absence of a color difference, this result suggests the physical and chemical properties of PEM contribute to a greater capacity for soil warming than BDM polymers (e.g., greater thermal absorptivity and transmittance of PE due to greater mass and thickness of mulch) [8]. Brown BDM reduced soil temperature by 8.0% ± 1.7% compared to black PEM; however, nearly all brown BDMs were paper-based and the reduced soil temperature was more likely driven by the poor thermal absorptivity and transmittance of paper compared to polyethylene plastic. Reduced soil temperature beneath brown, typically paper-based, mulches can lead to reduced crop yield in cooler climates [20]. However, Moore and Wszelaki reported consistently cooler soil temperatures (10 cm depth) beneath a paper-based BDM compared to PEM in Tennessee, which actually helped to prevent root zone heat stress and transplant shock in mid-summer pepper production (*Capsicum annuum* L.) [45].

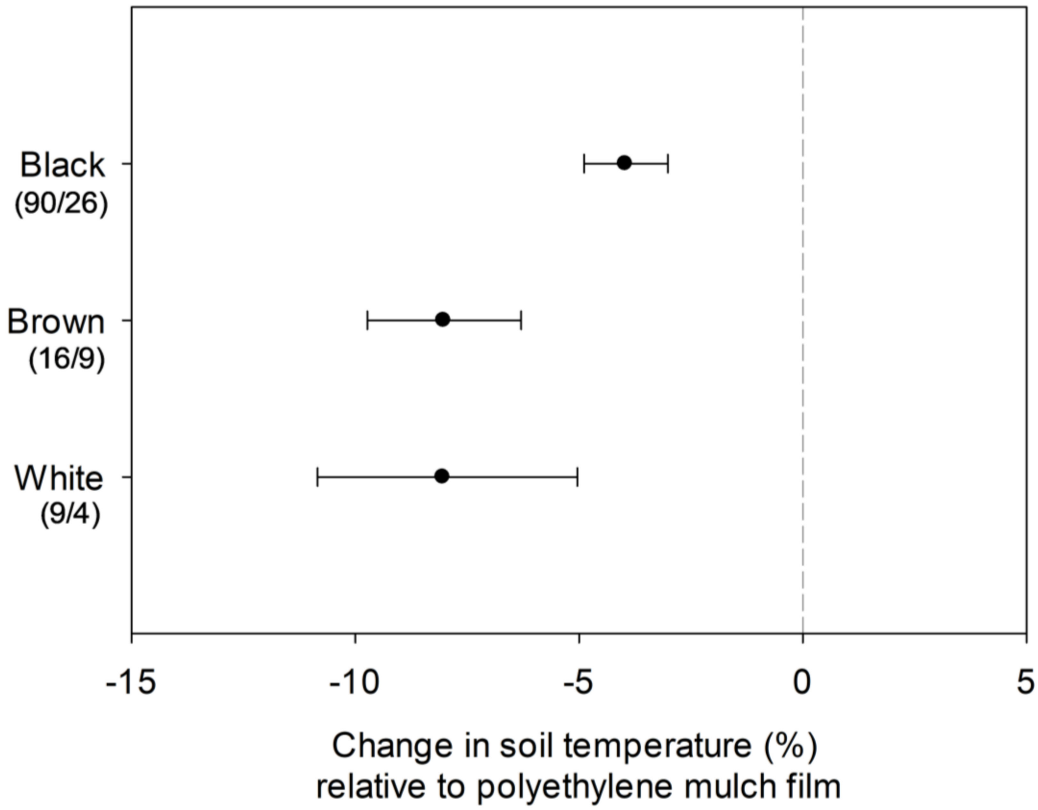

Figure 3. Mean change in soil temperature as influenced by biodegradable mulch color (relative to black polyethylene mulch film). Numbers below y-axis labels indicate the number of observations and studies (left/right, respectively) contributing to each mean. Error bars represent 95% confidence intervals determined via bootstrapping.

3.3. *Weed Suppression*

The sample size for BDM weed suppression was relatively small (only 15 of 66 studies reported weed suppression data resulting in 82 observations) and quite variable, which suggests future BDM research should prioritize collecting data on weed response. Variability of the weed suppression data (particularly in bare soil) also reflects differences in weed management (e.g., herbicides versus hand-weeding) and ambient weed populations among studies. Nonetheless, there were significant differences in weed suppression among BDM, PEM, and bare soil. Weed suppression is an essential agronomic function of any agricultural mulch; thus, viable BDM alternatives should provide weed suppression greater than or equal to that achieved by PEM [46]. Paper-based BDM reduced weed pressure by 88.0% ± 7.7% compared to PEM, whereas starch-polyester and other bio-based polymer BDM films were less effective than PEMs (Figure 4). Improved weed control efficacy of paper-based BDM compared to PEM and other BDM films is mostly commonly documented for sedge weeds (*Cyperus* spp.). Sedges are difficult to control with PEM and other films because the emerging leaves can pierce the film and continue to grow above the mulch barrier. Cirujeda et al. studied six BDMs (including starch-polyester and paper-based) in processing tomato (*Solanum lycopersicum* L.) and found that purple nutsedge (*Cyperus rotundus* L.) biomass was reduced by paper-based BDM compared to PEM and starch-polyester BDM [47]. Similarly, Anzalone et al. reported reduced biomass of purple nutsedge in a paper BDM (29.1 g m^{-2}) compared to PEM (48.3 g m^{-2}) and a starch-polyester BDM (102.9 g m^{-2}) [4]. Moreno et al. observed increased weed pressure in a starch-polyester BDM film compared to PEM due to the poor durability of the BDM, and this contributed to reduced tomato yields [41]. While paper-based BDMs can degrade quickly along edges buried in soil (especially in warm, humid climates), results of this meta-analysis and review suggest starch-polyester BDM films are susceptible to weed invasion from weed protrusion (especially sedges) and rips, tears, and holes from physical weathering [48].

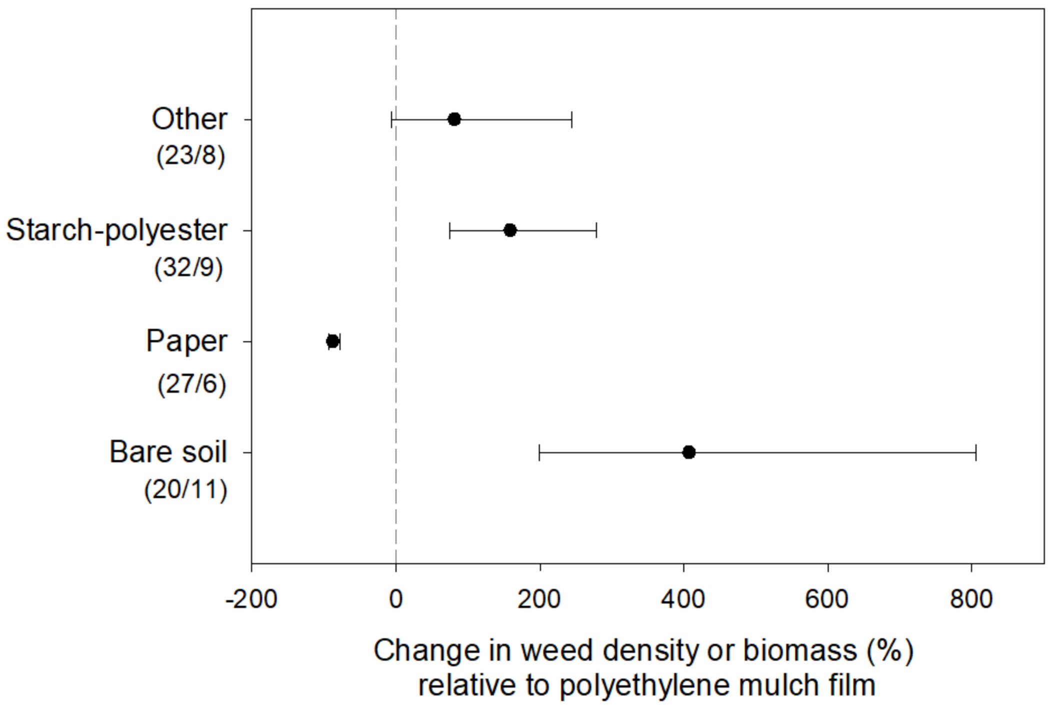

Figure 4. Mean change in weed density or biomass as influenced by bare soil and biodegradable mulch type (relative to polyethylene mulch film). Numbers below y-axis labels indicate the number of observations and studies (left/right, respectively) contributing to each mean. Error bars represent 95% confidence intervals determined via bootstrapping.

Color is an important mulch property for weed control because it will directly influence the quality and quantity of light transmittance through the mulch. We did not have enough replicate studies in this meta-analysis to explore the relationship between mulch color and weed suppression, but a brief review of the literature confirms the importance of mulch opaqueness. Ngouajio et al. compared black and white BDMs (from aliphatic-aromatic copolyester polymers) with PEM in tomato and found that only the black BDM achieved weed suppression comparable to PEM [49]. Results are similar for paper-based BDM. Jenni et al. (2002) found that a black paper-based BDM was more effective for weed suppression than a similar "pale" colored BDM [50].

We would expect weed competition in mulch-based cropping systems to be influenced by interacting factors of mulch type and color, crop species, weed species present, and local conditions, but there is currently not enough data in the literature to explore these relationships. This is important because some BDM products may be capable of matching PEM function in select situations, but not others. For example, Wortman et al. reported on a polylactic acid-based BDM fabric that provides excellent weed control and soil moisture conservation, but mulch properties contribute to cooler soil temperatures [18]. This type of BDM may have potential for use in warmer climates and on organic farms (given excellent weed suppressive properties), even if it is not as versatile as PEM.

3.4. Crop Yield

The agronomic benefits of mulch documented herein (i.e., increased soil temperature and weed suppression) are important and may help explain or predict changes in crop yield, but growers' willingness to adopt BDMs will ultimately be driven by effects on crop yield and profitability [12,51]). Thus, it is significant that results of this meta-analysis of crop yield (292 observations across 66 studies) suggest yields in BDMs are greater than those in bare soil and are not different from PEM yields (Figure 5). Yield of crops grown in paper-based BDM were trending lower (−7.3% ± 12.6%), but were not different from PEM or the other BDM types. Despite the negative trend, Cirujeda et al. observed increased tomato yield in paper-based BDM relative to PEM across multiple years and locations (which partially explains the greater variance in paper-based BDM) [47,52]. There were no significant effects of crop type, geographic region, growing environment, or mulch color on yield response relative to PEM or among BDMs (data not shown).

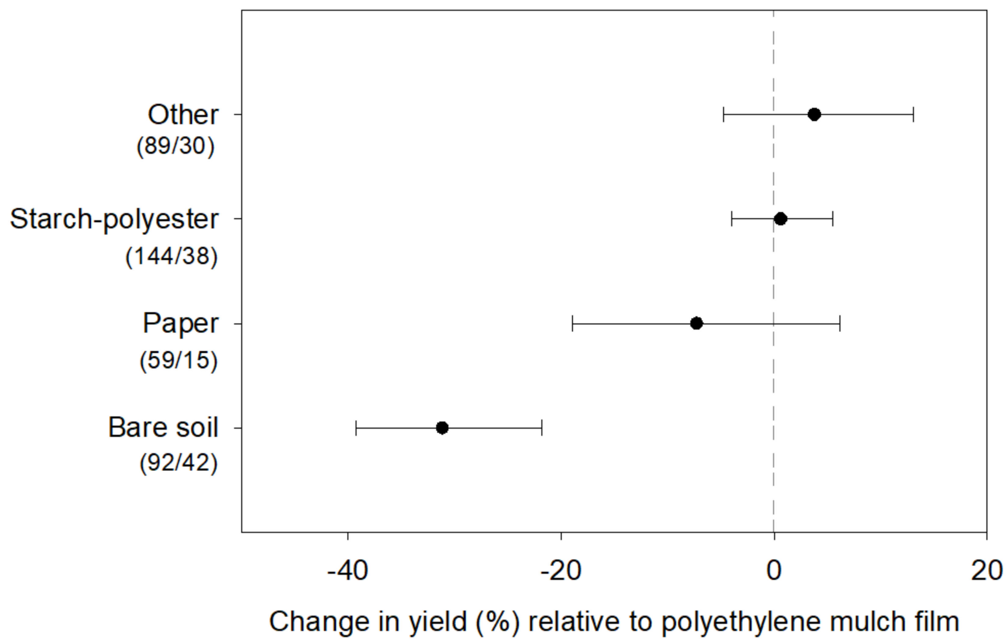

Figure 5. Mean change in crop yield as influenced by bare soil and biodegradable mulch type (relative to polyethylene mulch film). Numbers below y-axis labels indicate the number of observations and studies (left/right, respectively) contributing to each mean. Error bars represent 95% confidence intervals determined via bootstrapping.

Minuto et al. demonstrated comparable yield potential of a starch-polyester BDM compared to PEM in tomato, zucchini (*Cucurbita pepo* L.), and lettuce (*Lactuca sativa* L.) [53]. Similarly, Moreno and Moreno reported tomato yield and fruit quality in BDMs were not different from PEM [44]. Ghimire et al. tested four plastic BDMs (two starch-polyester) and a paper-based BDM in pie pumpkin (*Cucurbita pepo* L.) across two diverse environments and found that yield was similar to PEM in eight of ten cases (the two exceptions were in a cooler climate, suggesting soil warming benefits of PEM contributed to yield benefits) [20].

The most important conclusion from this meta-analysis is that, on average, yield of crops grown in BDM products of any type are not different from those grown in PEM. The relative yield performance of BDMs was somewhat unexpected given the reduced soil warming and weed suppression benefits compared to PEM. Paper-based BDM provided better weed suppression than PEM (particularly for *Cyperus* weed species), but soil temperatures were similar to bare soil due to the color and thermophysical properties of paper-based BDM. The lack of a clear relationship between soil warming, weed suppression, and crop yield in agricultural mulches suggests that some agronomic benefits of PEM are either redundant or counterproductive. For example, in warmer climates, the soil warming effect of black PEM can contribute to heat stress in the root zone and reduced yield [54]. Weed suppression measured in PEMs (relative to BDMs) may be redundant if the benefit occurs after the critical weed-free period in a given crop. In pepper (*Capsicum annuum* L.), the critical weed-free period is approximately 60 days (e.g., the first half of the growing season) [55], and any weed emergence and growth beneath the crop canopy in the second half of the growing season should have negligible effects on yield. Indeed, several studies have reported that BDM deterioration and subsequent weed invasion often occurs late in the growing season with limited effects on crop yields in that same season [5,18,48,56].

In the absence of a yield gap between BDM and PEM, future research and innovation should be focused toward reducing costs and increasing biodegradability of BDMs. Surveys by Goldberger et al. indicated that insufficient knowledge about BDMs, increased cost of BDMs, and their unpredictable degradation rates in soil were the primary barriers to grower adoption [12]. Results of this meta-analysis can address the first barrier and help to educate growers about the agronomic benefits of BDMs, but innovation in material engineering will be needed to address the other barriers. If reducing the cost of BDMs relative to PEM is not feasible (due to the low cost of petroleum, for example), there may be opportunities to add value to BDM products. Thompson et al. (2019) demonstrated the value of embedding raw soybean meal and alfalfa meal particles in a BDM matrix; these mulches degraded in soil faster than a similar BDM without embedded particles and could contribute plant available nutrients to crops in the same or subsequent growing seasons [15]. Growers want to reduce their plastic waste [12] and this meta-analysis suggests there are many agronomically viable alternatives to PEM, but additional work is needed to address remaining social, economic, and environmental barriers to adoption.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/10/10/1618/s1. File S1. Figure S1: Funnel plots (top) and difference in fits (DFFITS) values (bottom) for each observation contributing to the mean soil temperature response ratio for bare soil (left) and other (right) mulch types. Significant asymmetry in the funnel plot suggests possible publication bias and a red dot above a short dash line in the DFFITS plot identifies potentially influential observations. Figure S2: Funnel plots (top) and difference in fits (DFFITS) values (bottom) for each observation contributing to the mean soil temperature response ratio for paper (left) and starch (right) mulch types. Significant asymmetry in the funnel plot suggests possible publication bias and a red dot above a short dash line in the DFFITS plot identifies potentially influential observations. Figure S3: Funnel plots (top) and difference in fits (DFFITS) values (bottom) for each observation contributing to the mean soil temperature response ratio for black (left) and brown (right) mulch color. Significant asymmetry in the funnel plot suggests possible publication bias and a red dot above a short dash line in the DFFITS plot identifies potentially influential observations. Figure S4: Funnel plots (top) and difference in fits (DFFITS) values (bottom) for each observation contributing to the mean soil temperature response ratio for white mulch color. Significant asymmetry in the funnel plot suggests possible publication bias and a red dot above a short dash line in the DFFITS plot identifies potentially influential observations. Figure S5: Funnel plots (top) and difference in fits (DFFITS) values (bottom) for each observation contributing to the mean weed response ratio for bare soil (left) and other (right) mulch types. Significant asymmetry in the funnel plot suggests possible publication bias and a red dot above a short dash line in the DFFITS plot identifies potentially influential observations. Figure S6: Funnel plots (top) and difference in fits (DFFITS) values (bottom) for each observation contributing to the mean weed response ratio for paper (left) and starch (right) mulch types. Significant asymmetry in the funnel plot suggests possible publication bias and a red dot above a short dash line in the DFFITS plot identifies potentially influential observations. Figure S7: Funnel plots (top) and difference in fits (DFFITS) values (bottom) for each observation contributing to the mean yield response ratio for bare soil (left) and other (right) mulch types. Significant asymmetry in the funnel plot suggests possible publication bias and a red dot above a short dash line in the DFFITS plot identifies potentially influential observations. Figure S8: Funnel plots (top) and difference in fits (DFFITS) values (bottom) for each observation contributing to the mean yield response ratio for paper (left) and starch (right) mulch types. Significant asymmetry in the funnel plot suggests possible publication bias and a red dot above a short dash line in the DFFITS plot identifies potentially influential observations.

Author Contributions: Conceptualization, M.B.D.T. and S.E.W.; methodology, S.E.W.; investigation, M.B.D.T.; writing—original draft, M.B.D.T.; writing—review and editing, S.E.W.; funding acquisition, M.B.D.T. and S.E.W.; resources, S.E.W. All authors have read and agreed to the published version of the manuscript.

Funding: This project is based on research that was partially supported by the Nebraska Agricultural Experiment Station with funding from the Hatch Act (accession 1014303) through the USDA National Institute of Food and Agriculture (NIFA) and the Fulbright Scholar Program.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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