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Use of biodegradable plastic film mulch over three years of organic horticultural production promotes yield but does not affect soil organic matter content

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KEYWORDS

Net ecosystem exchange, organic horticulture, soil bacterial community, soil carbon balance, sustainable plasticulture

HIGHLIGHTS

- Biodegradable plastic film mulch (PFM) increased vegetable yield by up to 46%.
- Biodegradable PFM did not significantly affect soil organic matter content over 3 years.
- Biodegradable PFM had minimal effects on the soil bacterial community.

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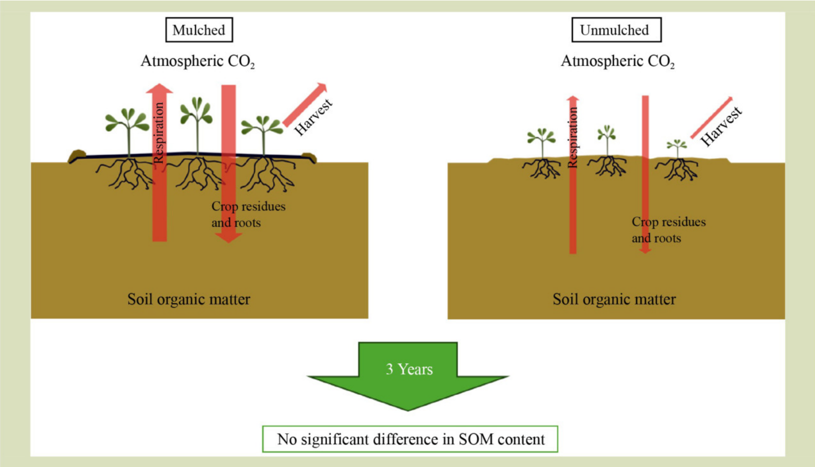
GRAPHICAL ABSTRACT



ABSTRACT

Soil organic matter (SOM) is an important store of carbon and is vital to maintaining soil health. Growing crops generally causes a reduction in SOM. However, organic farming systems often adopt practices that partially mitigate this loss. Biodegradable plastic film mulch (PFM) can increase yields by improving soil hydrothermal conditions, increasing nitrogen use efficiency and suppressing weeds. It can also speed up SOM breakdown and induce changes to the soil microbiome. Further, the increased return of C from rhizodeposition and crop residues from PFM-grown crops can compensate for SOM breakdown, although outcomes vary substantially with agronomic and environmental conditions. To address these uncertainties, a plot-scale field experiment was conducted on an organic farm with a 3-year vegetable rotation measuring SOM content from treatments with and without biodegradable PFM, inputs of poultry manure or green waste compost, and with or without an overwinter green manure. Biodegradable PFM caused a significant increase in yield in all the crops grown (43%–46%) and the overwinter green manures (18%), resulting in more organic matter incorporated into the soil. Despite this, there was no significant difference in the SOM content between the biodegradable PFM- and non-PFM-mulched plots over the 3 years, nor was there any significant change in soil bacterial diversity. In contrast, the large difference in the mass of green waste compost and poultry manure addition resulted in a 15% increase in SOM after 3 years. Biodegradable PFM did not affect alpha (Shannon) or beta diversity of soil bacterial community.

1 Introduction

Soil contains more carbon than the atmosphere and aboveground biomass combined, so its fate is critical to the greenhouse effect[1]. Agricultural activity can affect soil C dynamics in many ways, including cultivation, fertilization, and crop choice[2]. Maximizing soil C storage therefore represents an important part of tackling climate change[3]. Organic farming is founded on the idea of the importance of healthy, living soil to a sustainable, productive agricultural system and was early in valuing the organic component of soil[4]. As a result, it adopts many practices which can be beneficial to soil C storage, such as the addition of organic matter in the form of composts and manures, the use of green manures and leys, diverse rotations and mixed farming which have been found to enhance soil C[5]. However, restrictions on mineral fertilizers (particularly nitrogen) restrict yield, meaning environmental impacts that can be better on an area basis may not prove so on a yield-scaled basis[6]. A reliance on mechanical cultivation rather than herbicides for weed control changes environmental impacts but does not necessarily improve overall performance[7]. These factors can be even more significant for intensive horticultural crops with high fertility demand[8] and low weed tolerance[9].

Plastic film mulch (PFM) can mitigate these problems as it effectively controls weeds, increases yields and increases mineral N availability to crops by increasing the mineralization of soil organic matter (SOM) and reducing losses through the major N loss pathways, viz. nitrate leaching and ammonia volatilization[10–12]. However, concerns have been raised about the environmental footprint of PFM. First, plastics are potentially environmentally undesirable, and their persistence in the wider environment is a problem[13]. This can potentially be addressed by the use of biodegradable plastics. Biodegradable PFMs offer similar agronomic advantages to conventional low-density polyethylene-based PFM[14] and potentially mitigate problems with the disposal of plastics and their long-term buildup in agricultural soils[15,16]. Another concern is that the soil conditions promoted by PFM lead to the faster breakdown of SOM and, therefore, the long-term depletion of soil C stocks and net release of CO_2, which could also have implications for soil quality[17,18].

The factors influencing the soil C balance are complex. Although the breakdown of SOM under PFM can be faster[19,20], greater plant growth can compensate for this by the return of organic matter from crop residues, root turnover and root exudates[21,22]. Biodegradable PFMs are not expected to have a substantially different impact on SOM levels as the direct C input is relatively low, and the effect on net primary production (the net C gain by plants from photosynthesis minus respiration) and soil respiration is similar to that of conventional PFM. However, long-term experiments are needed to confirm this[23].

Biodegradable PFMs can affect soil organisms in two ways: first, their effects when in use as a mulch influence the soil microclimate, and second, when they are incorporated into the soil by the physical impact of film fragments, the chemical effects of any PFM additives and breakdown products both as potential phytotoxins and nutrients[24]. The use of biodegradable PFM has been found to lead to increased bacterial abundance and diversity and to benefit groups associated with degradation of polymers and N cycling[25].

Although much research has been published in recent years, much of which refutes the hypothesis that PFM results in losses in SOM[26], it has focused on a limited number of commodity crops such as maize, wheat or potatoes in specific regions such as northeastern China and the North American plains, and in conventional farming systems. There has been little research undertaken on horticultural crops in temperate maritime areas or in organic farming systems. We hypothesized that biodegradable PFM would increase crop yield and accelerate the breakdown of SOM, leading to a decrease in SOM in the medium-term (3 years) and would increase soil microbial diversity. To test these hypotheses, we conducted an experiment on an organic vegetable farm in Wales, UK, with a horticultural rotation of three crops with a biodegradable PFM and an unmulched control. We also examined the interactions of biodegradable PFM with different organic inputs and management practices to assess if these could mitigate SOM losses and improve soil C dynamics. Hence, we included two sources of organic inputs, green waste compost and poultry manure, and two different overwinter treatments, green manure and mulching with a woven polypropylene ground cover material.

2 Materials and methods

2.1 Site

The experimental field site was located at Top Meadow, Bancffosfelen, Carmarthenshire, UK (51°47′ N, 4°12′ E; 135 masl). The soil at this site is classified as a free-draining, silty clay loam textured Eutric Cambisol developed on a carboniferous sandstone and shale parent material. The main soil chemical and physical properties are summarized in Table S1. The methods used to determine these are described in the Supplementary Information, Section 1. The mean annual rainfall (1991–2020) was 1346 mm, and the annual mean air temperature was 10.5 °C (Met Office, 2024). The land is sheltered by tall hedges and slopes gently to the south. The site was a commercial organic vegetable farm and the treatments applied in the experiment had all been used on the site in the preceding 10 years.

2.2 Experimental design

A randomized block design was used, and treatments were: mulch treatment, biodegradable PFM or no mulch; fertilizer treatment, green waste compost or poultry manure; overwinter treatment, covering with a woven plastic mulch or sown with a green manure of rye and vetch. The mulch film used was biodegradable PFM, Gro-clean Bio-Mulch (Gromax Industries Ltd., Hadleigh, Suffolk). The fertilizers were examples of fertility amendments commonly used in organic horticulture with different C:N ratios. They were (1) pelleted organic fertilizer based on sterilized poultry manure (Greenvale Farms limited, Middleton Tyas, North Yorkshire, UK), which was spread at 100 $g\cdot m^{-2}$, i.e. the rate recommended by the manufacturer, and (2) municipal green waste and food waste compost (Cwm Environmental Ltd., Nantycaws, Carmarthenshire, UK) which was spread at 2.5 $kg\cdot m^{-2}$ which is a typical rate for compost in organic horticulture[27]. The nutrient content of these and quantities added are given in Table S2. The overwintering green manure used was a mixture of 70% cereal rye (*Secale cereale* cv. Elago) and 30% early common vetch (*Vicia sativa* cv. Early English) (Cotswold Seeds, Moreton-in-the-Marsh, Gloucestershire, UK) sown at 50 $g\cdot m^{-2}$; the woven plastic mulch was Mypex (Don and Low Ltd., Forfar, Angus, UK). The four beds, 1.2 m wide, were created, running east to west across the slope. These were divided into four blocks 4.8 m wide and split into eight first-level plots (over two adjacent beds within each block) containing the overwinter treatments of green manure or a woven polypropylene mulch fabric. These were divided into two second-level plots (1 bed), each containing the mulch treatments: biodegradable PFM or no mulch. The second-level plots were further divided into two subplots, which received either poultry manure or green waste compost. There were, therefore, four replicates. The plot layout is shown in Fig. S1.

The experiment was conducted between spring 2021 and spring 2024, using crops and treatments typically grown in commercial organic horticulture in the UK[28]. The crops grown were leeks, sweetcorn and lettuce in 2021, 2022 and 2023, respectively. In 2023, after the lettuce harvest, a quick-growing green manure of mustard was sown for the remainder of the summer on the plots that were allocated to have overwinter green manures. Full details of the crops are given in Table S3. After harvest, all trimmings and residues were returned to the plots they came from and incorporated into the top 5 cm of soil with the economic portion of the crop removed. The overwinter green manure was also incorporated into the top 5 cm of soil, except the postharvest mustard green manure in 2023 was removed. The total C added to the soil by amendments and crop returns is given in Table S4.

2.3 Crop and green manure measurements

At harvest, three plants were harvested from a row in each plot and weighed. Then these were processed to produce an economic product that met the marketable standard. Hence, the trimmed leek pseudostem with 15 cm of green leaf, sweetcorn cobs or whole lettuce with damaged or senescent outer leaves removed made up the marketable product for the three crops. These prepared crops were then weighed to obtain the economic yield. Similarly, three 20 cm × 20 cm quadrants of green manures were sampled. The dry matter yield of the whole plant (marketable produce and trimmings) was determined by oven drying (80 °C, 8 h) to constant weight. The dried samples were ground using a Retsch stainless steel ball mill and then analyzed for total C and N using an Elementar EL VarioCube CN analyzer (Elementar Ltd, Stockport, UK).

2.4 Tea bag index

The tea bag method was used to estimate early decay rate k and stabilization factor S[29,30]. In each growing season, three pairs of green (Lipton Green Sencha) or red (Lipton Rooibos and Hibiscus) tea bags (Unilever Ltd., London, UK) were buried at a soil depth of 5 cm, spaced 20 cm apart, in each plot. These were recovered at the end of the growing season for each year. The burial periods were 113, 118 and 68 days in 2021, 2022 and 2023, respectively. Tea bag index (TBI) decay rate k and stabilization factor S were calculated using the method of Kueskamp et al.[29] and Duddigan et al[30].

2.5 Soil measurements

Before and after each crop in April and September, soil samples were taken to determine changes in SOM content. These samples were taken before the incorporation of crop residues or green manures. Five soil cores were taken from each subplot at depths of 0–10, 10–20 and 20–30 cm. The cores were combined and passed through a 2-mm sieve to remove stones and oven-dried (105 °C, 12 h). The SOM content was measured by loss-on-ignition (LOI) by weighing before and after combustion in a muffle furnace (450 °C, 16 h). Soil C and N content was determined using a TruSpec CN analyzer (Leco Corp., St Joseph, MI, USA).

2.6 Soil bacterial community analysis

In August 2022, soil samples were taken for soil microbiome analysis. Five samples were taken from the top 10 cm of each plot and immediately placed on dry ice until they could be freeze-dried in the laboratory and stored at −80 °C. These samples were placed into a MoBio PowerMag Soil DNA Isolation Bead Plate. DNA was extracted following MoBio instructions on a KingFisher robot. Bacterial 16S rRNA genes were PCR-amplified with dual-barcoded primers targeting the V4 region (515F 5′-GTGCCAGCMGCCGCGGTAA-3′, and 806R 5′-GGACTACHVGGGTWTCTAAT-3′)[31]. Amplicons were sequenced with an Illumina MiSeq using the 300-bp paired-end kit (v. 3). Sequences were denoised, taxonomically classified using Silva (v. 138) as the reference database, and clustered into 97%-similarity operational taxonomic units (OTUs) with the “mothur” software package (v. 1.48.0)[32]. The potential for contamination was addressed by co-sequencing DNA amplified from specimens and template-free controls (negative control) and extraction kit reagents processed the same way as the specimens. A positive control from S00Z1 samples, consisting of cloned SUP05 DNA, was also included. OTUs were considered putative contaminants (and removed) if their mean abundance in controls reached or exceeded 25% of their mean abundance in specimens.

Alpha diversity was estimated with the Shannon index on raw OTU abundance tables after filtering out contaminants. The significance of diversity differences was tested with ANOVA. To estimate beta diversity across samples, we excluded OTUs with a count of less than 3 in at least 5% of the samples and then computed Bray-Curtis indices. We visualized beta diversity, emphasizing differences across samples, using principal coordinate analysis ordination. Variations in community structure were assessed with permutational multivariate analyses of variance, with the treatment group as the primary fixed factor, and 999 permutations were used for significance testing. The relative abundance of operational taxonomic units was analyzed for each taxonomic rank, and the significance of differences between treatments was assessed by ANOVA. The results were considered significant if $p < 0.05$ with a Bonferroni correction applied for the number of tests conducted.

2.7 Statistical analysis

Data were analyzed in R[33]. Mixed effects modeling was carried out using the R package “lme4”[34]. The best-fit model was determined by a comparison of models using the experimental variables (mulch and density or fertility) as fixed effects and the block and bed and where relevant date as random effects in random intercept models. Comparisons of log-likelihood were used to determine which models were best, using ANOVA to determine the significance of the differences where necessary. A summary of coefficients and significance levels was extracted with the R package “lmeTest”[35]. Results are assumed to be significant where $p < 0.05$.

3 Results

3.1 Crop yield

Biodegradable PFM consistently increased crop yield in each growing season and each crop. The effects of fertility and overwinter treatments were smaller and less consistent. In 2021, PFM-mulched leeks produced 46% more dry matter yield than unmulched ($p < 0.001$) and poultry manure fertilization produced 19% more yield than green waste compost ($p = 0.022$) (Fig. 1). In 2022, mulched sweetcorn produced 43% more total dry matter yield (whole plant: cobs, stems and leaves) than unmulched ($p = 0.002$); with poultry manure, they produced 25% lower yield than green waste compost in unmulched plots, but the significance was low ($p = 0.056$), but 49% more in mulched plots ($p = 0.011$). The overwinter treatment had no significant effect (Fig. 2). In 2023, mulched lettuces produced 45% more dry matter yield than unmulched ($p < 0.001$), poultry manure produced a 21% lower yield than green waste compost ($p = 0.004$) and overwinter green manure in the previous winters produced a 16% greater yield than over winter mulching with woven polypropylene mulch. However, there was no interaction between the treatments (Fig. 3). The economic yields followed the same patterns with only minor differences (Table S5). C:N ratios of crop biomass were decreased by preceding overwinter green manure and in the second year by mulch (Table S6). Biodegradable PFM also increased the yields of overwinter green manures by an average of 18% and the post-harvest catch crop of mustard by 42% in 2023 (Fig. S2).

3.2 Tea bag index

Biodegradable PFM did not significantly affect the TBI rate of decay (k). However, it caused a significant reduction in the stabilization constant (S) in both the first and second year ($p < 0.001$ in both) but not in the third year (Fig. 4, Table S7). The fertility amendment had no effect on either measure. Preceding overwinter green manure resulted in a significantly lower k in the second year but not the third year and had no significant effect on S.

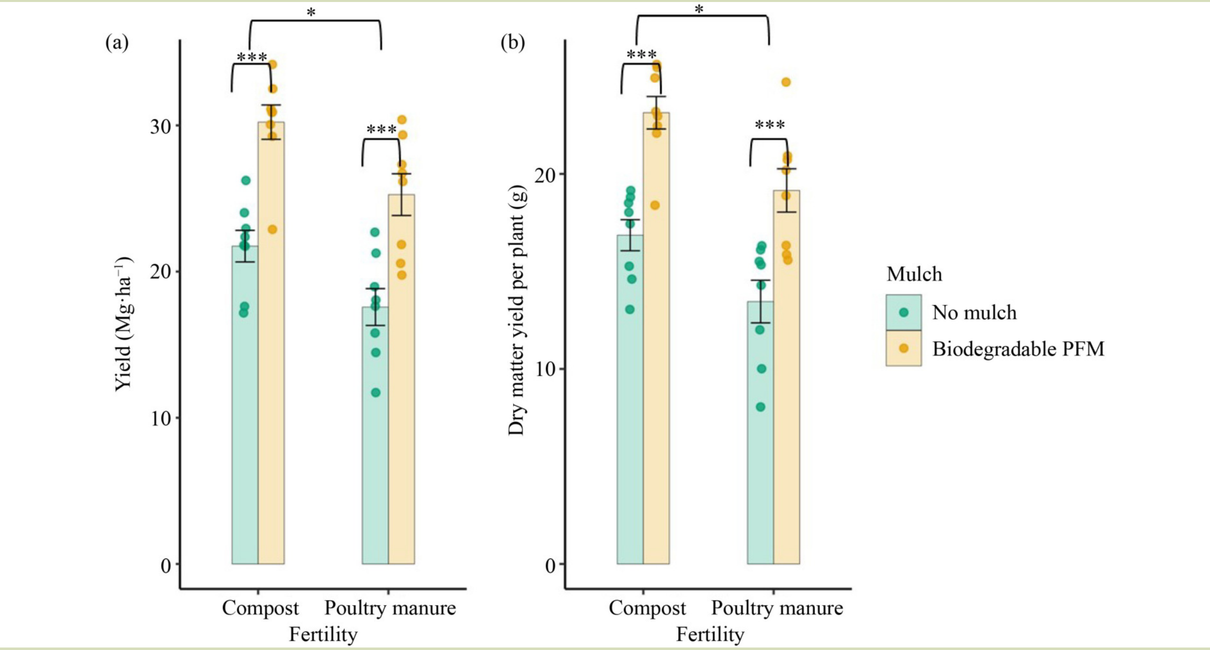


Fig. 1 Yield of leeks in first year of the experiment (2021) as (a) mass of trimmed marketable product, and (b) total dried aboveground biomass per plant in plots with or without biodegradable PFM and amended with green waste compost or poultry manure. The bars represent means ± SEM, and dots represent individual data points ($n = 8$). Significance of effect of main factors *** $p < 0.001$, ** $p < 0.005$, * $p < 0.05$.

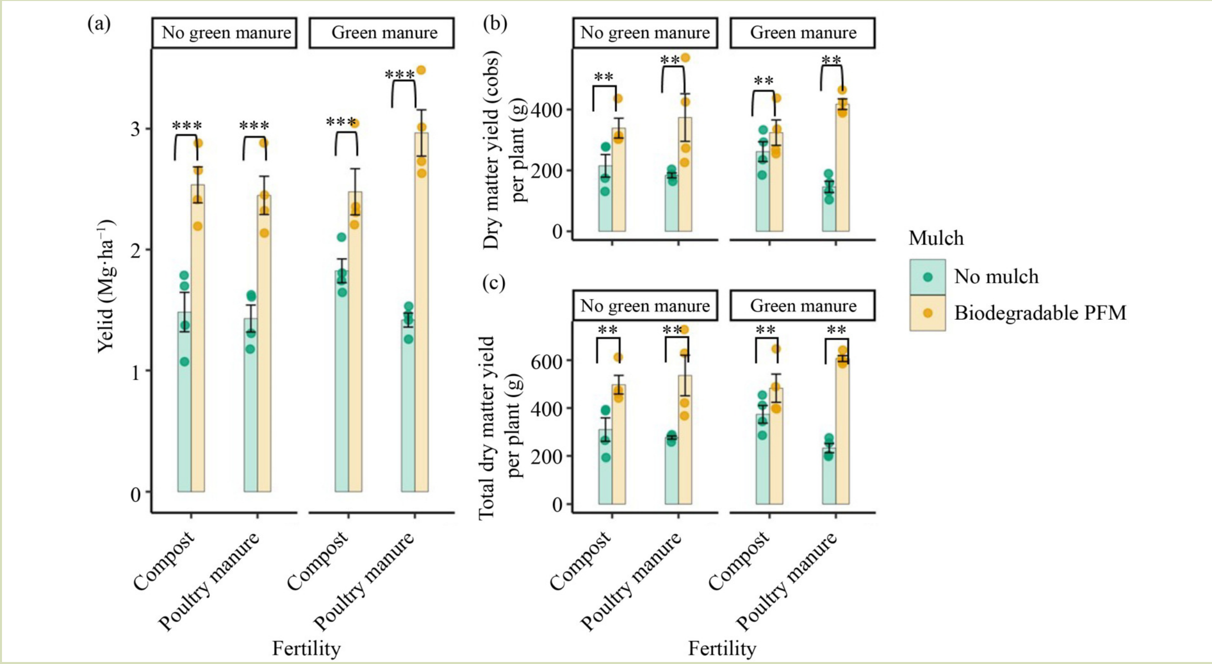


Fig. 2 Yield of sweetcorn in second year of the experiment (2022) as (a) marketable product (fresh cobs), (b) dry mass of cobs per plant, and (c) dried mass of residual aboveground biomass per plant in plots with or without biodegradable PFM, amended with green waste compost or poultry manure, and following overwinter mulching with a woven polypropylene mulch or overwinter green manure of cereal rye and vetch. The bars represent means ± SEM, and dots represent individual data points (n = 4). Significance of effect of main factors *** $p < 0.001$, ** $p < 0.005$, * $p < 0.05$; interaction effects not shown.

3.3 Soil organic matter content

SOM content measured by LOI was higher in the spring than in autumn and decreased with soil depth. Over the 3 years of the experiment, the average LOI in the top 10 cm of soil increased by 0.82 ± 0.35% from 12.6% to 13.4%. At the 10–20 cm depth and 20–30 cm depth, measurements were not taken in the final year, but the differences over 2 years were smaller than those for the top 10 cm. Biodegradable PFM had no significant effect on SOM at any point in the 3 years of the experiment. However, the green waste compost amendment resulted in significantly higher SOM content than poultry manure; this increased to a 9% and 15% difference in the top 10 cm of soil in the final autumn (2023) and spring (2024), respectively ($p < 0.001$ in both cases). There was also a 7% difference at 10–20 cm depth in the final autumn ($p < 0.005$), but the difference was not significant below this depth (samples were only collected for the top 10 cm in spring 2024). SOM content in the final year of the experiment is given in Table S8. In the top 10 cm, this significantly increased SOM content by 1.5% over 3 years in green waste compost fertilized plots, but there was no significant change in the poultry manure fertilized plots. Changes in SOM over the course of the experiment are shown in Fig. 5, Figs. S3 and S4. The overwinter treatment only significantly affected the top 10 cm in the final spring, where green manure significantly increased the SOM in the poultry manure-amended plots ($p < 0.05$).

3.4 Soil bacterial community

Neither alpha (Shannon) nor beta diversity were significantly different between the treatments. The most abundant OTUs were associated with the phyla: Acidobacteriota (28.4%), Proteobacteria (25.5%), Verrucomicrobiota (13.8%), Actinobacteriota (5.5%), Bacteroidota (5.2%) and Firmicutes (5.0%) (Fig. 6). The abundances of OTUs associated with different genera in the various treatments are shown in Figs. S5, S6 and S7. Biodegradable PFM resulted in a lower relative abundance of OTUs of the phylum Nitrospirota and the genus *Nitrospira* but a higher relative abundance of the genus *Pseudolabrys*, both the phylum Bacteroidota and the class

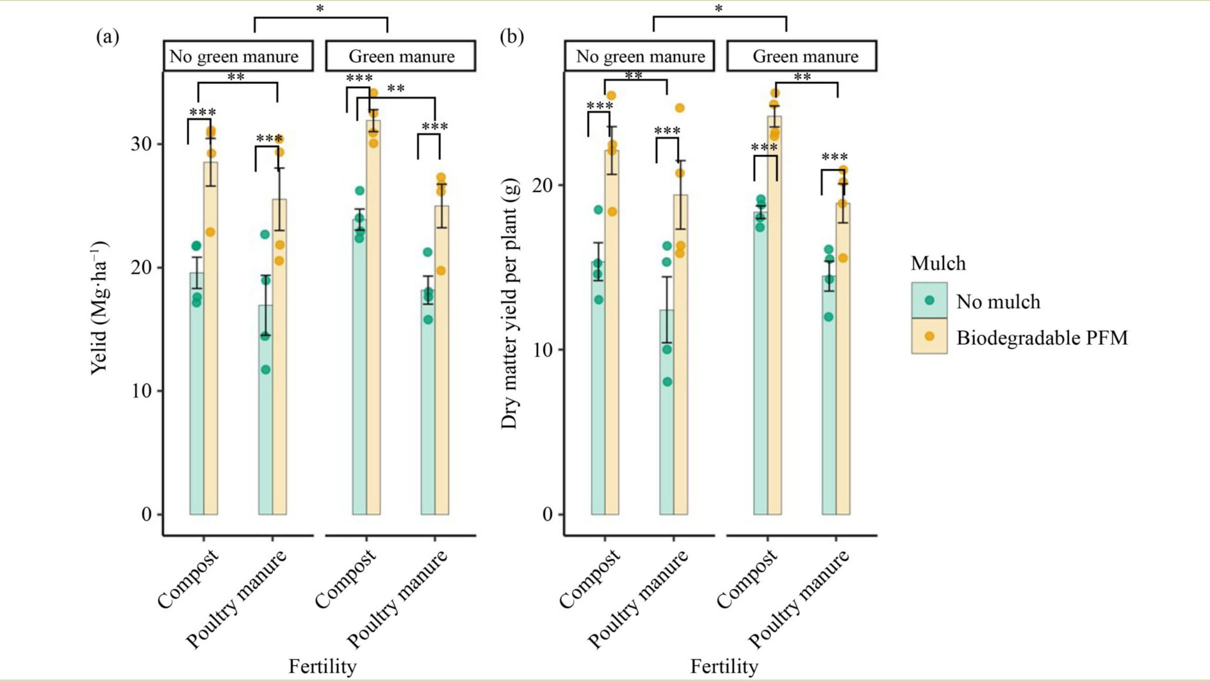


Fig. 3 Yield of lettuces in third year of the experiment (2023) as (a) marketable product per hectare, and (b) dried weight of total aboveground biomass per plant in plots with or without biodegradable PFM, amended with green waste compost or poultry manure, and following overwinter mulching with a woven polypropylene mulch or overwinter green manure of cereal rye and vetch. The bars represent means ± SEM, and dots represent individual data points ($n = 4$). Significance of effect of main factors *** $p < 0.001$, ** $p < 0.005$, * $p < 0.05$.

Bacteroidia, increased in relative abundance due to green waste compost v poultry manure and overwinter green manure.

4 Discussion

4.1 Crop yield

Biodegradable PFM consistently increased the yield of all the crops evaluated here. This is in common agreement with previous studied using these crops and others under different climatic conditions[36–39]. This increase in biomass is likely to result from more favorable soil hydrothermal conditions and better nutrient availability and uptake[40,41]. Conversely, the effect of organic matter inputs varied: in the first year, poultry manure increased yield relative to compost; in the third year, this had reversed; in the second year, there were contrasting effects with poultry manure, leading to higher yields in mulched and lower yield in unmulched plots than compost. Although this is insufficient evidence to conclude that there is a trend, the results are consistent with a cumulative effect of compost and the effects of increased SOM. Poultry manure has more immediately available N, but greater quantities of total N were added with compost. Overwinter green manure also increased yield in the final year, possibly because it provided additional fertility from a readily mineralizable source. The differences in the effect of biodegradable PFM in the second year may have been due to PFM retaining the quickly released mineral N from the poultry manure by reducing N volatilization or leaching[42].

4.2 Bacterial community

Some studies show that PFM significantly impacts bacterial diversity[43,44]. However, this is not always the case; differences were only found in soil bacterial community structure on one occasion over 2 years of seasonal testing in 1 of 2 sites in the USA between several biodegradable PFMs and unmulched soils despite significant differences caused by location and season and differences in extracellular enzyme activity caused by PFM[45]. Biodegradable PFM was not found to cause

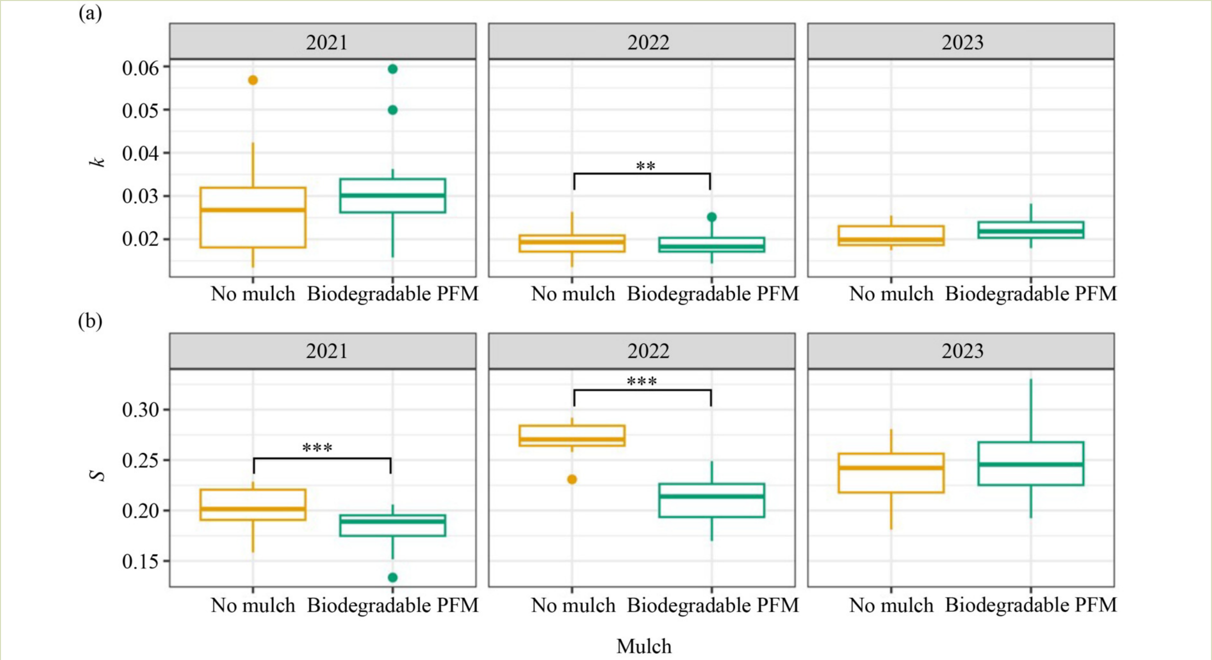


Fig. 4 Tea bag index early-stage decomposition rate constant *k* (a) and stabilization constant *S* (b) during the growing period on the 3 years of the experiment, with or without biodegradable PFM. The center line is the median value; the lower and upper hinges are the first and third quantile; and the whiskers represent 1.5 times the interquartile range (n = 16). Significance of effect of main factors *** $p < 0.001$, ** $p < 0.005$, * $p < 0.05$.

differences in soil bacterial community composition in two experiments growing maize. In one soil, samples were taken at the end of the growing period[46] and, in the other, soil temperature was not significantly different between mulched and unmulched soils[47]. Although we did not measure soil temperature during the season when the soil samples were taken for bacterial analysis, temperature differences between mulched and unmulched soils are known to decline as maturing crop canopy provides increasing shade. In future experiments, sampling earlier in the growing period may reveal differences. Another reason for the lack of difference could be the high SOM content (12.5%–13%); studies have found biodegradable PFMs have a greater effect on bacterial communities than polyethene mulches because they provide a source of C[48,49] which could be redundant in these conditions. It has also been observed that healthy, diverse soil microbial communities are less vulnerable to perturbations[50] and that the effects of biodegradable on soil bacterial communities are more profound in soils with poor fertility and health[51]. Another study under similar temperate field conditions found the addition of biodegradable microplastics at rates representative of normal agronomic use had no impact on soil bacterial community composition[52]. It could also be relevant that before the commencement of the experiment, the site had been used for commercial vegetable production in a system that made extensive use of biodegradable PFM. While the area had been under a fertility building ley without mulch for the previous 2 years, and there were no visible remnants of PFM from that time, it cannot be excluded that some remained in the soil.

The few significant differences in abundances of individual phyla and genera are minor and may not be important due to healthy, diverse populations providing redundancy of function[53]. Bacteria in the genus *Nitrospira* are known to contribute in several ways to the N cycle. They are principally known for nitrite oxidation, but some are also capable of ammonium oxidation, the production of ammonia from urea and complete nitrification (comammox)[54,55]. In contrast to our study, these have been found to be more abundant in biodegradable PFM-covered soils[25,56]. However, another experiment found that biodegradable PFM significantly

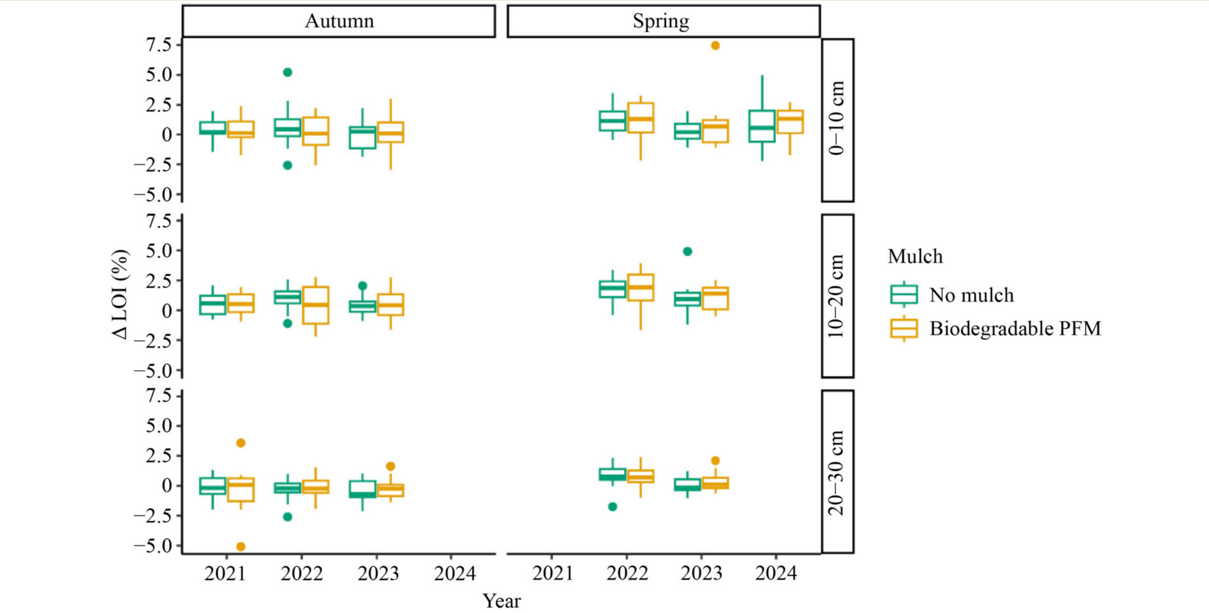


Fig. 5 Changes in SOM (LOI) over 3 years of vegetable production with and without biodegradable PFM. The center line is the median value; the lower and upper hinges are the first and third quantile; and the whiskers represent 1.5 times the interquartile range (*n* = 16).

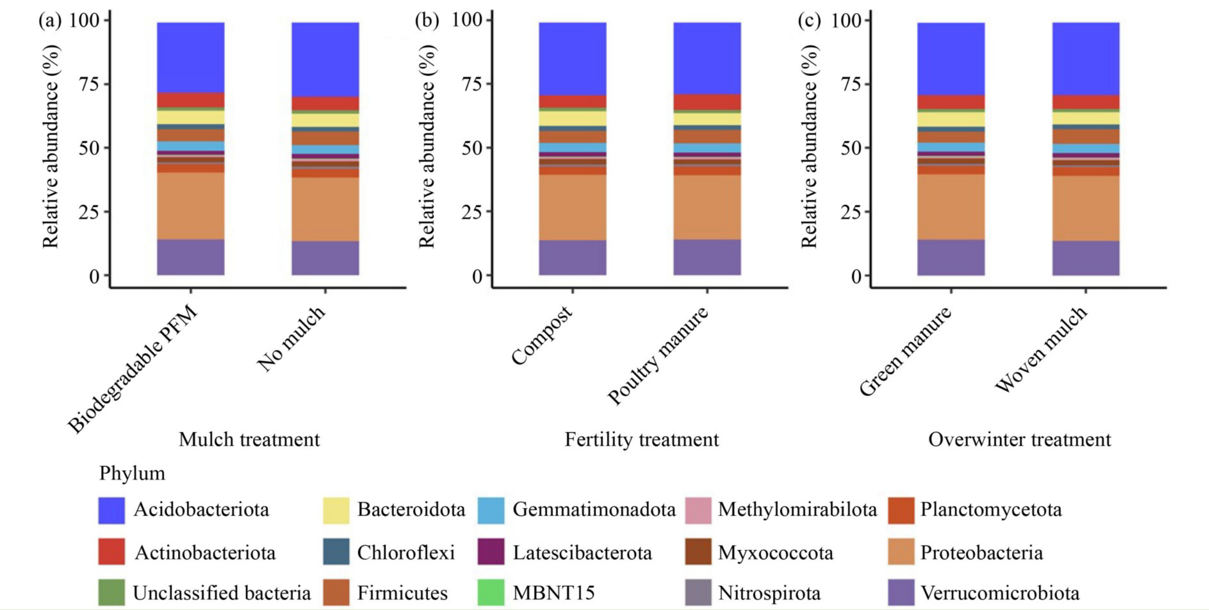


Fig. 6 Relative abundance of OTUs by bacterial phylum in soil from plots with and without biodegradable PFM amended with (a) green waste compost or poultry manure and (b) following an overwinter green manure of rye and vetch or (c) with overwinter mulching or with a woven mulch.

reduced the abundance of bacterial genes associated with nitrification, anammox and other N-cycle processes while increasing bacterial diversity, potentially due to stochastic changes[57]. In two of the three experiments conducted on this site, soil NH_4^+ concentration was higher in mulched than unmulched soils. Although some of this may be due to reduced ammonia volatilization, this indicates a possible inhibition of nitrification[58]. However, in the final year of this experiment, the opposite was the case, and in all cases, nitrate was the dominant form of mineral N and significantly higher in mulched soil. Similarly, the genus *Pseudolabrys* was significantly more abundant in our mulched soils. In contrast, the opposite was found in soils with < 0.5% biodegradable microplastics added[59], perhaps illustrating the difference between laboratory experiments using high concentrations of PFM mixed with soil, and field experiments with PFM used according to usual practice. The increased abundance of copiotrophic, organic matter-decomposing bacteria in the phylum Bacteriota with compost additions has been found by other researchers and it is abundant in compost[60]. Future experiments should also examine changes in the fungal and mesofaunal communities.

4.3 Soil organic matter dynamics

Biodegradable PFM incorporated into the soil post-harvest provided a minimal external C input. However, net primary production from the PFM plots was significantly increased, so crop residue returns were substantially higher. Although in the final year crop, whole lettuce heads were removed and no residues returned. Although no measurements were made of inputs from roots, root biomass increases similarly to aboveground biomass[61,62] and higher root exudates (which can account for 50% of C cycling in cropped agroecosystems) are correlated with higher root biomass[63]. However, the green waste compost provided the greatest organic C contribution, exceeding poultry manure by 395 $g\cdot m^{-2}$ per year. Biodegradable PFM resulted in ~50% increase in C inputs over the 3 years mainly from the extra sweetcorn stover produced in this treatment. Green manure applications (limited to only 2 of the 3 experimental years) contributed approximately 25% of the annual organic C input compared to the compost. Studies have shown that the return of crop residues combined with roots can be sufficient to maintain or increase SOM in PFM-mulched soils over many years[21].

Green manure only affected the manure-amended plots after the third winter. As SOM was measured before the incorporation of the green manure in the spring and at the end of the growing season, it can be concluded that the relatively low (between 20 and 35) C:N ratio green material green material was largely decomposed during the summer. Only roots would have been included in the sample, and some may have been removed by sieving. Another study has also reported that green manures such as barley or hairy vetch led to net soil C losses, as did PFM, and that a positive interaction between the two treatments further elevated loss[64]. However, we found no evidence for this.

We detected no significant effects of biodegradable PFM on SOM as measured by LOI. However, this could be because the time needed to detect a change in soil C content varies with the magnitude of the change to the C input and the power of the sampling regime to detect changes[65]. Our experiment was unlikely to detect significant differences in 3 years unless the differences in C inputs between the treatments were large[65]. Mulching only caused a difference in this magnitude when sweetcorn was grown in the second year. The addition of compost caused twice the C input over the 3 years as PFM did and impacted SOM within the time frame of our experiment. An alternative method would be to calculate the difference in inputs (net primary production and inputs) and outputs (respiration, removals and other losses) of C to calculate net ecosystem exchange[66]. However, as discussed earlier, this would require a reliable means of measuring CO_2 fluxes.

Changes in soil C content are caused by the difference between these inputs and soil C losses through soil microbial respiration. Higher respiration under PFM is likely, given findings on the lack of change to SOM despite the higher C inputs. However, the TBI indicates a faster breakdown of SOM in the first year, but this was not observed in the second or third year. The lack of major difference in soil bacterial community reinforces the conclusion that the effect of PFM on soil respiration was weak or inconsistent. In other experiments on the same site, we found similarly mixed results[42,58]. Although changes in soil hydrothermal conditions are likely to be the major factor in these changes, it has been reported that fragments of biodegradable PFM in soil can cause a small increase in litter decay[67]. However, the rate of decay of unincorporated plant material may be a poor guide to the effects on other SOM fractions[68].

The result that biodegradable PFM did not lead to a significant difference in SOM content despite some evidence of faster soil metabolic processes was important. It is likely that greater soil C losses from increased soil respiration during the growing season were balanced by returns of organic matter in the form of crop residues, roots, root exudates and greater returns of green manures, and any changes that happened were too small to detect. Importantly, we only determined gross changes in SOM measured by LOI. We do not know which fractions of SOM were affected. An increase in the input of more labile could mask a loss of the more recalcitrant fractions that would have a detrimental impact over a longer time frame. It is also possible that the lack of effect of biodegradable PFM on SOM content despite higher inputs was caused by differences in the C:N ratio of the added material. The addition of fresh crop residues and green manure foliage could have been highly degradable. The C:N ratios were < 35 (except for sweetcorn at < 57), and this added C could have been lost quickly.

In the first 2 years, the TBI stabilization constant *S* indicates that biodegradable PFM promoted the greater breakdown of the more stable SOM. Some researchers have found a decrease in the more stable SOM pools (18). Thus, it could be that the greater input of fresh material is masking a loss of more stable SOM. If this is so, a decline could become apparent over a longer period. In contrast, some researchers have found greater formation of stable soil-associated C is promoted by PFM mulching[69,70]. Our experiment did not examine these factors.

Although many studies have found that PFM does result in the depletion of soil C[18,64,71], this is not always the case[72]. If 5% or more of maize crop residues are returned, the net effect on soil C stocks is not significant or positive on most sites[26]. Soil C losses from respiration can be significantly lower than the increases in biomass production[73]. The use of PFM with organic or mineral fertilizer has been shown to increase the positive effect of additional N on soil C sequestration by decreasing losses through leaching and increasing crop growth[21,74].

Without longer-term measurements or analysis of the forms of organic C present in the soil, measured effects, or lack of effects, on LOI need to be treated with caution as total SOM can be affected by the buildup of more labile forms such as particulate organic matter that do not represent long-term C sequestration and could mask changes in more stable fractions[75]. C sequestration in cultivated soil can be increased by the addition of organic matter, but this has a long-term limit[76]. If management changes are reversed, it is likely to return to its original levels eventually[77]. The stability of the SOM will determine the durability of such changes.

5 Conclusions

Our experiment detected no significant negative effect of biodegradable PFM on SOM content or soil microbial biodiversity, indicating that the concerns of PFMs reducing SOM content[17] may not apply in all contexts. Additional experiments may be needed to verify changes in soil C in the long-term, and further testing at different points in the season and with other crops is required to confirm that soil bacterial communities are not significantly impacted. The use of biodegradable PFM significantly increased crop yields with no detrimental effect on SOM, which is a promising result. Given the positive impacts of green waste compost on SOM and crop yields, and the yield benefits of overwinter green manure, integrating these practices with biodegradable PFM offers a promising strategy for long-term agronomic and environmental outcomes.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2025608 contains supplementary materials (Figs. S1–S7; Tables S1–S8).

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Compliance with ethics guidelines

Martin Samphire, Davey L. Jones, and David R. Chadwick declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

Author contributions

Martin Samphire conceived and designed the study with advice from Davey L. Jones and David R. Chadwick, conducted the experiment, data collection, and analysis, and wrote the first draft. Davey L. Jones and David R. Chadwick advised and commented on the content, edited, and made corrections. All authors contributed to the article and approved the submitted version.

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