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Research Report

Agricultural plastic pollution reduces soil function even under best management practices

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Abstract

Soil plastic contamination is considered a threat to environmental health and food security. Plastic films—which are widely used as soil mulches—are the largest single source of agricultural plastic pollution. Growing evidence indicates that high concentrations of plastic negatively affect critical soil functions. However, the relationships between agricultural plastic accumulation and its biogeochemical consequences in regions with relatively low levels of soil plastic pollution remain poorly characterized. We sampled farms across the California Central Coast (a region of global agricultural importance with extensive plastic mulch-based production) to assess the degree and biogeochemical consequences of plastic pollution in fields subject to "best practice" plastic mulching application and removal practices over multiple years. All farms exhibited surface soil plastic contamination, macroplastic positively correlated with microplastic contamination levels, and macroplastic accumulation was negatively correlated with soil moisture, microbial activity, available phosphate, and soil carbon pool size. These effects occurred at less than 10% of the contamination levels reported to degrade field soils, but were relatively subtle, with no detectable relationship to microplastic concentration. Identifying declines in soil quality with low levels of macroplastic fragment accumulation suggests that we must improve best management plasticulture practices to limit the threat to soil health and agricultural productivity of unabated plastic accumulation.

Significance Statement

The U.N. considers soil plastic contamination an environmental health and food security threat. Plastic film "mulches" are the largest source of agricultural plastic pollution. We assessed the degree and consequences of plastic pollution in farms managed following "best plasticulture practices" across California's Central Coast—a region of global agricultural importance with extensive plastic mulch use. All fields exhibited plastic contamination. Macroplastic and microplastic contamination were positively correlated, and macroplastic accumulation negatively correlated with soil moisture, microbial activity, phosphate, and carbon pool size. Effects occurred at <10% of contamination levels previously reported to degrade soil function. Given the extraordinary growth of agricultural plastic film use, it is critical to characterize how soil function is—potentially irrevocably—affected by this novel threat.

Introduction

Plastic mulch films cover over 25 million acres of farmland globally, resulting in a direct annual flux of approximately 6.7 million tons of nonbiodegradable material into terrestrial systems (1, 2). Single-use plastic mulch is considered an essential tool for weed management, temperature, and moisture modulation, allowing for efficient, cost-effective crop production (3–5). Although a valuable technology, the rise of plastic-dependent agriculture, or "plasticulture" is of concern from both an environmental and human health perspective, with plastic films constituting the largest single source of field soil plastic pollution (1). Soil plastic contamination has been documented in both intensive and smallholder production farms (1, 6). These macroplastics (>5 mm) fragment into micro (<5 mm) and nano (<1 μm) particles through physiochemical exposure in the soil environment (3, 5, 7). Soils in contact with plastic fragments are expected to be negatively affected by their accumulation, with growing concern that it may threaten soil health and plant productivity (1, 8). However, the relationship between macroplastic and microplastic accumulation, and their impacts on the soil environment under standard agricultural field practices remain poorly understood.

Plastic accumulation within agricultural soils is likely widespread due to the extent of plasticulture and plastic that is embedded into various agricultural products (9–11). Polyethylene (PE) plastic is used in greenhouses, walk-in tunnels, irrigation tape, and in the field as mulch. Polyvinyl chloride (PVC) irrigation line is a rigid, nonflexible piping also commonly used in agricultural fields, while polymer coated fertilizers and biosolids mixed with

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plastic residues are directly applied to soils, inadvertently adding microplastics along with the target nutrients (9–12). Plastic mulch is the largest contributor to the agricultural soil plastic pollution burden, an externality that reflects its extensive application globally, short usable lifespan of ~6 months, and challenges inherent in its removal (8, 13). Plastic removal from fields is labor-intensive and its disposal is costly due to the adhesion of soil particles to the films. Thus, agricultural plastics are rarely completely removed from fields (Fig. 1), leaving plastic residues that remain in soil for decades to centuries and can leach additives, thus also potentially polluting water systems (14–16).

Plastic mulch residue accumulation in agricultural soils can negatively impact plant growth (e.g. reduced crop yield, plant height, and root mass) and soil properties (e.g. lower water infiltration rate, organic matter content, soil carbon (C) storage, and plant-available phosphorus), threatening long-term food security (5). Plastic can influence soil properties and function via direct biochemical and trophic impacts and indirectly through alteration in soil structure (17). As plastic debris accumulates in the soil system, it disintegrates into finer fractions and can be incorporated into macro and micro aggregates, disturbing soil aggregate stability (18) and altering bulk density, porosity, hydrophobicity, and water-holding capacity (19). These physical changes can alternately increase or reduce soil water loss by affecting the flow and retention of water within the soil pore space, an effect that is controlled by soil texture, plastic fragment composition, size, and concentration (15, 20, 21).

Because soil moisture is a key regulator of microbially mediated decomposition and plant growth, changes in soil water retention driven by plastic debris can feedback to affect these biological processes (13). Plastic particles can serve as a novel habitat for soil microorganisms (22, 23), while also widening the soil C:nutrient ratio as C-rich plastics accumulate, increasing microbial nutrient immobilization (14, 15, 24, 25). In addition to the physical impacts of plastic accumulation across soil food webs, plastic-derived leachates (e.g. phthalates, Bisphenol A, and other novel contaminants) may deleteriously affect soil organisms (26, 27). For example, earthworm microplastic ingestion increases their mortality rate while reducing their growth and reproductive success (28).

Attempts have been made to quantify plastic concentrations within soils and their relationship to plasticulture practices, yet the agroecological implications of this growing pollution burden remain largely unknown (1). Most plastic soil contamination studies have been conducted in mesocosms (17, 28), controlled field studies (7, 29), or under laboratory conditions (30, 31)—our understanding of the distribution of plastic debris in the agricultural system and its impact on soil biogeochemical properties under field conditions remains sparse (9, 10, 16, 23). While recent reports have demonstrated the accumulation of macro- or microplastics in agricultural soils, no studies have addressed the relationships between plastic accumulation and biogeochemical properties across fields (23, 31–34). Field studies reporting in situ detectable biological or edaphic plastic pollution impacts are typically observed at extremely high contamination levels—upwards of 545 kg ha^{-1}—reflecting poor management (i.e. plastic is tilled into the field) (8). Given the potential scale of plastic pollution in agricultural soils, it is critical to characterize both the extent and implications of this novel pollution burden in agricultural systems that experience "best management practices" with regards to plastic film application and removal.

To address this knowledge gap, we studied the relationships between plastic properties (e.g. chemical composition, size, and shape), plastic pollution level (e.g. contamination by mass, area, and particle concentration), and soil properties across the California Central Coast—a region of global agricultural significance with over 40,000 acres of plastic mulch-based production (35). We assessed the abundance of macroplastic and microplastic in the surface soils of strawberry fields that had chronic single-use plastic mulch application over multiple years, characterizing the consequences of this practice on the soil plastic pollution burden. To better understand the consequences of this externality on the soil environment, we tested the correlations between surface macroplastic and microplastic accumulation, plastic identity, and critical soil health parameters.

Materials and methods

Surface soil and plastic sampling

Macroplastic debris and surface soil samples were collected from 12 fields within 5 farms along the Central Coast California where the strawberry crop—which is the dominant user of plastic mulch in the region—had recently been terminated for the season (Fig. 2). Fields were sampled from March to August 2022 following the

Fig. 1. A photo of agricultural soil with incorporated macroplastic debris and release of microplastics following surface soil extraction.

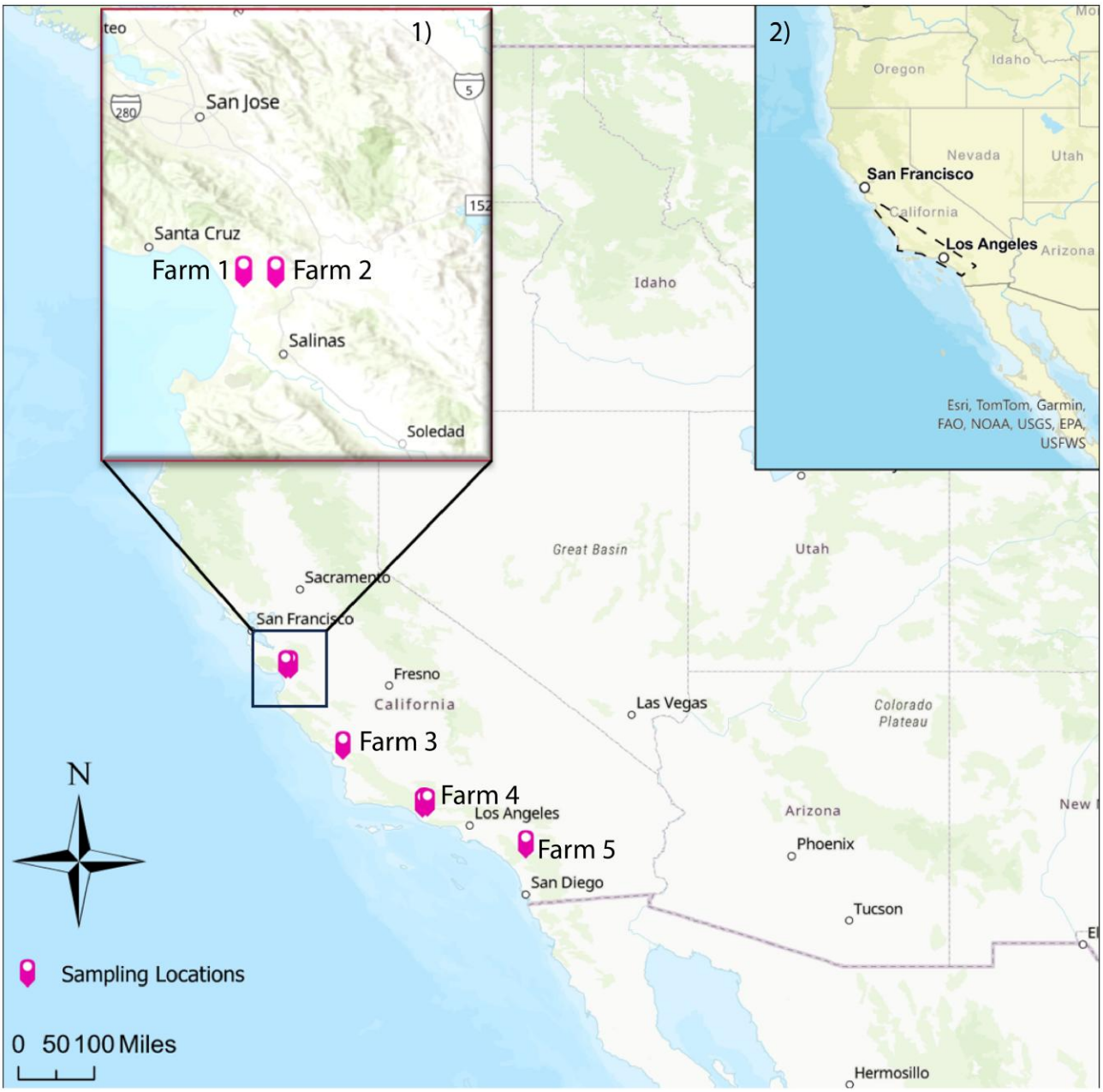

Fig. 2. A map highlighting the area in California where 12 fields within 5 farms (farm 1 [one field], farms 2 and 3 [two fields each], farm 4 [four fields], and farm 5 [three fields]) were sampled for soil and plastic contamination between March and August 2022. The distance between fields within a farm ranged from 0.04 miles (farm 2) to 5.8 miles (farm 5). Inset 1 represents a zoomed in map for farms 1 and 2 and inset 2 represents the Central Coast region sampled within California (encircled in the dashed line).

removal of agricultural mulch and drip tape from the fields, tilling, and leveling, but prior to the next crop planting. We sampled farms that used a "best practice" approach to plastic mulch removal—which entails actively collecting and removing all mulch rather than tilling it into the field, burning on site, or otherwise not attempting its complete removal—and used a transect method to estimate the contamination of macroplastics (>5 mm) and microplastics (200 μm–5 mm) on the soil surfaces to ~5 cm depth. We did not sample across depth because the fields had been tilled, rotating deeper soil to the surface.

A transect tape was placed along the longest length of the field and perpendicular transects were run at an interval of every 5–10 m, then a 1-m^2 quadrat was centered every 10 m along the perpendicular length of each transect. Four to five transects were sampled per field. All the visible macroplastic fragments were collected within each quadrat without further turning the soil and placed in labeled paper bags. Within each quadrat following macroplastic removal, we collected five surface soil scoops (~5 cm deep, one from each corner and one from the center) using a metallic shovel/soil knife and placed into a labeled mason jar with construction paper separating the plastic lined lid to reduce plastic contamination. Field samples were returned to the laboratory and stored at room temperature until processed. The samples were homogenized at the transect level for further processing.

Macroplastic analysis

Macroplastic samples were manually cleaned by removing all associated soil particles, then further analyzed for mass, count,

surface area, and identity in the laboratory. Macroplastic count and mass concentration were assessed per quadrat level (in square meter), averaged at the transect level, and scaled to per hectare. Macroplastic samples were photographed, and surface area was measured using ImageJ (36). Macroplastic area was measured in square meter per square meter of field area sampled at the quadrat level and reported as macroplastic area (in square meter) per hectare of field using the averaged values at the transect level. Macroplastic identity was confirmed using attenuated total reflectance-Fourier transform infrared spectroscopy. Macroplastic particles were placed on a cleaned sample stage using a tweezer and the spectra were obtained (4,000–400 cm^{-1} range) with a resolution of 4 cm^{-1} and a total of 32 scans. The obtained spectra were compared with the preexisting library using OMNIC software to determine the polymeric identity.

Microplastic extraction

The transect-level homogenized soils were extracted to assess microplastic contamination using a multiple-step wet oxidation and sieving procedure, followed by microscopy and μ-FTIR identification (37). Fifty grams of air-dried soil was weighed in a 500 mL glass beaker and 20 mL 30% H_2O_2 was added in portions to digest organic matter and break down any soil aggregates. Soils were then washed and wet sieved using 150 μm stainless steel mesh to remove fine soil particles followed by drying at 50 °C until a constant weight was reached. The dried soil extracts were density separated using a saturated $CaCl_2$ solution (density = 1.35 g cm^{-3}). Dried soil samples were thoroughly mixed with 100 mL of the saturated $CaCl_2$ solution using a glass rod and left undisturbed for 2 h or overnight (for samples with high concentrations of suspended particulate matter). Supernatant was carefully decanted on a 150 μm stainless steel mesh and suspended solid residue on the sieve was transferred to a glass beaker for Fenton's oxidation.

Density separation was repeated twice with the remaining soil samples to improve recovery, and solid residue on the sieve was collected for the oxidation. Beakers containing soil samples were rinsed thoroughly with DI water to transfer all the suspended solids to the sieve after the final density separation step. Twenty milliliters of Fenton's reagent (1:1 ratio of 0.05 M $FeSO_4$ and 30% H_2O_2) was gradually added to the beaker containing extracted solid residue to digest remaining natural organic matter. Digestion was performed at 50 °C in a water bath overnight followed by vacuum filtration on 5 μm stainless steel mesh. All the filtered samples were stored in glass Petri plates for microscopic sorting and polymer characterization. To check the recovery efficiency of the adopted extraction method, three soil samples were spiked using laboratory generated microplastic particles collected from large plastic debris ($n = 20$, 1–5 mm). Recovery efficiency was 86.7% for the method used in this study.

Microplastic characterization

To reduce the risk of misidentifying remaining lignocellulosic organic matter as plastic following the microplastic extraction procedure, we used a conservative method of visual sorting followed by polymeric identification using μ-FTIR (Nicolet iN10 Infrared Microscope, Thermo Scientific) to quantify microplastic contamination. Extracted microplastic particles were first sorted manually under a stereomicroscope (Leica EZ4 HD) at 8× and 35× magnification to reduce the plant debris load on the filter, and all the potential microplastic particles were subjected to polymeric characterization using μ-FTIR. Visually sorted particles were suspended in Milli-Q water and filtered on stainless steel mesh for imaging using a compound microscope equipped with an automated stage (Nikon eclipse LV100NPol) and images were used to analyze the size, shape, and color of the particles. The same filter containing the microplastic particles was subjected to an automated scanning under μ-FTIR and absorbance spectra were collected under reflectance mode within the range of 4,000–715 cm^{-1} using an imaging detector with low resolution.

Microplastic polymer identity was confirmed using OpenSpecy library (38). All microplastic particles were classified based on their size, shape, color, polymer type, and reported as particles per kilogram dry soil.

Quality control and quality assurance for microplastic extraction and characterization

Equipment and consumables containing plastic were avoided during field sampling and laboratory processing to minimize the chance of contamination. Glass jars and paper bags were used to collect and transport the soil samples to the laboratory. The microplastic extraction process was performed in a laminar flow hood. The work area was always cleaned using 70% ethanol, and glass containers were rinsed with Milli-Q water prior to use. Experimental blanks were run in parallel to sample processing to capture any contamination from the surroundings. Blank filters were also characterized using μ-FTIR—no significant procedural contamination was observed.

Soil biogeochemical and physical traits

Transect-level homogenized soil samples were analyzed for a suite of abiotic and biotic properties to assess whether plastic contamination correlated with key soil health indicators. Gravimetric moisture content was measured as a difference between fresh soil and oven-dried soil weight at 105 °C for 48 h. Soil texture was analyzed at the field level by homogenizing soils collected at the transect-level. Homogenized samples were sent to the Geospatial Laboratory for Soil Informatics at IOWA State University and analyzed using a laser diffractometer (39). All samples were analyzed in triplicates and the average of mean weighted particle size was used to calculate clay, silt, and sand percent. The soils were further classified using USDA texture classification.

We assessed the relationship between plastic accumulation in agricultural fields and soil particulate organic matter (POM) and mineral associated organic matter (MAOM) pools using a size fractionation/density separation method (40, 41). POM primarily consists of lightweight fragments that are relatively undecomposed, while MAOM is formed by organic material that has leached from plant material or been chemically transformed by the soil biota, but (unlike POM) are physically protected from decomposition via association with soil minerals (41). Air-dried soil samples (6 g) were suspended in 0.05% (w/v) sodium hexametaphosphate solution, and suspended particles were separated using a wet sieving method and defined as POM (53–2,000 μm) and MAOM (<53 μm) fraction of soil organic matter (SOM) based on size. Total %C of dried POM and MAOM fractions were estimated using an elemental analyzer and reported as g C per kg of dry soil.

To assess the relationship between soil biological activity and plastic contamination of agricultural fields, soil respiration rate and microbial biomass was estimated using a jar incubation procedure at room temperature (24 °C). Potential soil respiration was assessed using 6 g of fresh soil samples that were incubated in 8 oz mason jars fitted with an airtight headspace septum (Gray butyl, ALWSCI). Respiration was measured as CO_2 (μmol/mol) evolved over a 4-h period using a bench-top infrared gas analyzer

(LI-COR 850). Soil microbial biomass was estimated by substrate-induced respiration, where the addition of a labile C source (autolyzed yeast) was used to estimate the maximum potential respiration of the active microbial community present in the soil (42). A 10 mL of 12 g/L yeast extract was added to 6 g of fresh soil samples in 8 oz mason jars fitted with an airtight headspace septum. Jars were shaken at 240 rpm for 10 min before taking the first measurement, and CO_2 was measured at initiation (T0), after 2 h (T1), and 4 h (T2) of incubation (42).

Plant-available nutrients are a critical regulator of crop productivity (43). Total inorganic nitrogen (TIN), the sum of nitrate (NO_3^-) and ammonium (NH_4^+), was measured by extracting soils with a 2 M KCl solution, and shaking at 250 rpm for 2 h. The soil suspension was centrifuged at 2,000 rpm for 5 min followed by filtration using Whatman 1 filter paper. A colorimetric assay was performed to analyze the extractant using a plate reader (Tecan Infinite M Nano Plus). NO_3^- and NH_4^+ concentrations in soil extractants were determined using modified Berlethot (44) and Griess (45) assays, respectively. Plant-available phosphorous (P) was assessed using the Olsen-P extraction method. Na_2CO_3 (0.5 N, pH 8.5) solution was used to extract the inorganic orthophosphate (PO_4^{3-}) at the soil-to-solution ratio of 1:20. Extractants were analyzed by the colorimetric plate assay method (46).

Statistical analysis

The relationship between macroplastic and microplastic accumulation in soil was tested using a linear mixed effect model, with "field" nested within "farm" treated as a random effect. The influence of macroplastic (count per hectare, surface area per hectare, mass per hectare, and mass per surface area) and microplastic (count per kilogram soil) on soil properties was also tested with "field" nested within "farm" treated as a random effect. Because clay content strongly influences soil biogeochemical properties and can increase the retention of microplastics in the soil even after typical mulch removal practices (17, 47), average clay content at the field level was included as a covariate. Response variables were log transformed when assumptions of normality were not met and the transformation improved the residuals (gravimetric soil moisture, P content, POM, and MAOM). Response variables that had values which fell below detection (e.g. "0") were left untransformed (observed for TIN, soil respiration, microbial biomass, and microplastic count per kilogram soil). Predictor variables (macroplastic count per ha and macroplastic mass per surface area) were rescaled by log transformation to improve model fit. The "ggeffect" function was used to predict the response variable and associated 95% CI based on the "lmer" model to fit the obtained data points. Data analysis was completed using R (version 4.3.1) and RStudio (version 2023.09.0-463) using the packages "lme4" and "lmerTest" (48, 49). All plots were made using the ggplot2 package (50). Field and farm identity is anonymized for data presentation.

Results

Agricultural soil plastic contamination

All 12 fields sampled exhibited both macroplastic and microplastic contamination on the soil surface. PE mulch constituted more than 99% of the total macroplastic encountered both by count and mass concentration. Macroplastic contamination ranged from 36,970 ± 10,062 to 215,000 ± 79,540 particles per ha and 1.7 ± 1.2 to 25.3 ± 20.5 kg per ha across the 12 fields (Fig. 3a and b). Macroplastic fragments covered 42.5 ± 29.3 to 336.2 ± 157.3 m^2 area per ha (Fig. 3c) suggesting macroplastics incorporated into the soil surface alone cover 0.4–3.4% of field area following normal seasonal mulch removal.

Microplastic contamination was observed across all the studied sites, varying from 82 ± 68 to 340 ± 193 particles per kg of dry soil weight with an average concentration of 175 ± 116 particles per kg (Fig. 4a). Macroplastic and microplastic count concentrations positively correlated across all fields ($\beta = 112.22 \pm 30.09$, $t = 3.73$, $P = 0.001$, Fig. 4b).

Microplastics were further characterized based on their shape, thickness, flexibility, and color. Particles with flat and thin structures were categorized as films, and thick and rigid particles with irregular boundaries were categorized as fragments (51). Filaments were considered as thin elongated and flexible particles. Filaments were the most dominant fraction (63.9% of total microplastics), followed by films (32.2%), and fragments (3.8%) (Fig. S1a). Fields accumulated microplastic of size range 1–3 mm (43.8%), followed by <1 mm (33.6%), 3–5 mm (13.04%), and 9.5% of total extracted particles were found >5 mm size range (Fig. S1b). White/translucent microplastic was the most commonly observed color (51.4%), followed by black (19.8%), green (15.1%), and other colors (13.7%) (Fig. S1c).

Eight different polymers: polyolefins (PO), polyterephthalates (PET), polyester, polystyrene (polyphenylethylen, α-methylstyrene; PS), polyamides (polylactames; PA), polymethacrylates (PMA), polyurathanes (isocynates; PU), and polyhaloolefines (vinylhalides; PVH) were detected. PO, which is a main constituent of PE and polypropylene, was the most dominant polymer type found across the studied fields, accounting for 81.2% of identified polymers. PET (8.5%) was the second most observed polymer type followed by polyester (3.3%). PS, PMA, PU, and PVH (mainly PVC and PA) were also detected (Fig. S1d).

Plastic contamination influence on soil biogeochemical properties

The accumulation of macroplastic was negatively correlated with several surface soil biogeochemical traits, while no association between microplastic number concentration and soil properties was observed (Fig. 5 and Table S1). Soil moisture ($\beta = -0.28 \pm 0.1$, $t = -2.74$, $P = 0.008$) and soil respiration ($\beta = -0.15 \pm 0.05$, $t = -3.26$, $P = 0.002$) declined with increasing macroplastic count per hectare (Fig. 5a and b), whereas no effect was observed on microbial biomass. Plant-available PO_4^{3-} negatively correlated with macroplastic mass ($\beta = -0.01 \pm 0.004$, $t = -3.01$, $P = 0.004$, Fig. 5c) and mass per surface area ($\beta = -0.2 \pm 0.07$, $t = -2.88$, $P = 0.005$, Fig. 5d). A marginally significant negative correlation between macroplastic area and TIN was observed ($\beta = -0.01 \pm 0.006$, $t = -1.8$, $P = 0.08$); no other significant effects of plastic contamination on the TIN pool were detected. Surface soil POM ($\beta = -0.01 \pm 0.004$, $t = -3.06$, $P = 0.003$, Fig. 5e) and MAOM ($\beta = -0.003 \pm 0.001$, $t = -2.18$, $P = 0.03$, Fig. 5f) also exhibited an overall negative correlation with macroplastic mass concentration. Macroplastic area also negatively correlated with POM ($\beta = -0.001 \pm 0.0003$, $t = -2.48$, $P = 0.01$).

Discussion

The UN FAO states that plastics in soil are a threat to food security, health, and the environment (52). Given the potential scale of plastic pollution in agricultural soils, it is critical to characterize both the extent and implications of this novel pollution burden; however, there is a paucity of information on the relationships between agricultural plastic accumulation and its biogeochemical consequences in regions with lower levels of soil plastic pollution.

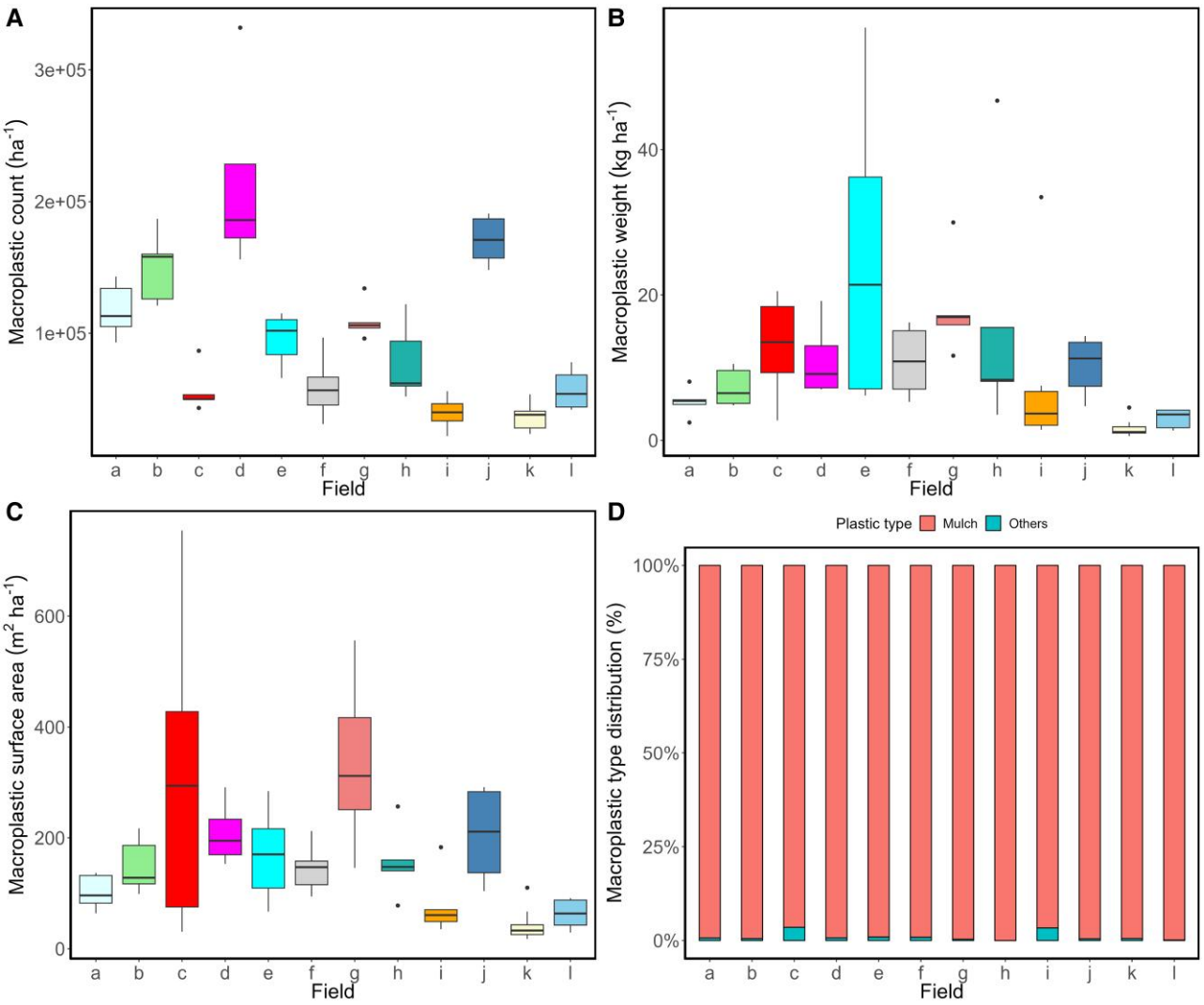

Fig. 3. Macroplastic abundance in agricultural soils by: a) count, b) mass concentration, c) area covered per hectare, and d) percent distribution by plastic type within the fields sampled. The lower and upper hinges of the boxplots correspond to the first and third quartiles and the median is represented by the line within the box.

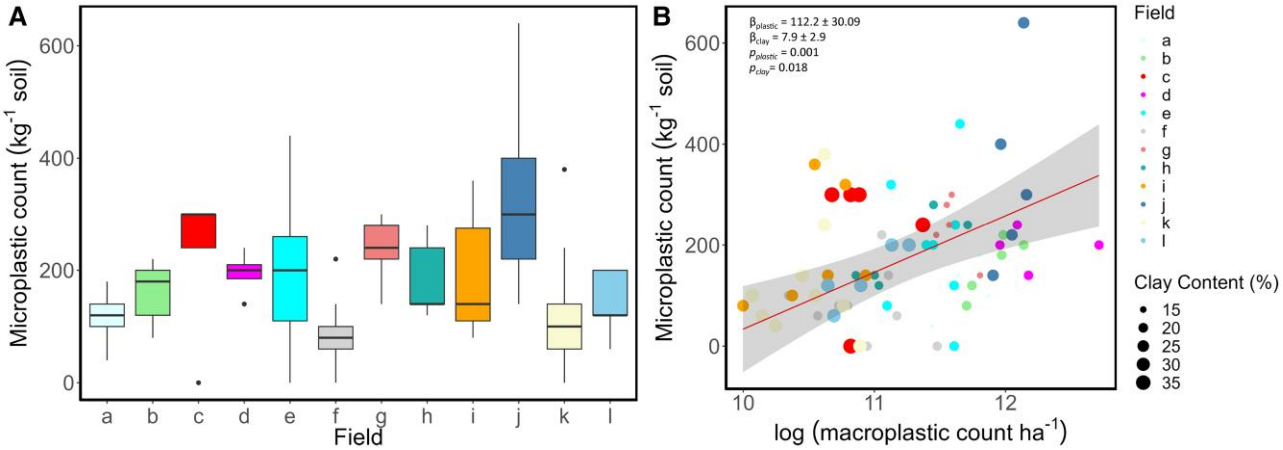

Fig. 4. a) Microplastic count concentration (the lower and upper hinges of the boxplot correspond to the first and third quartiles and the median is represented by the line within the box) and b) correlation between microplastic and macroplastic count across different fields (the coefficient representing slope value (β) with standard error and P-value for the influence of plastic and clay content are shown using Satterthwaite's method for the linear mixed effect). The fitted line and shaded area represents the predicted values and associated 95% CIs obtained from a linear mixed effect model fit using the ggeffect function in R.

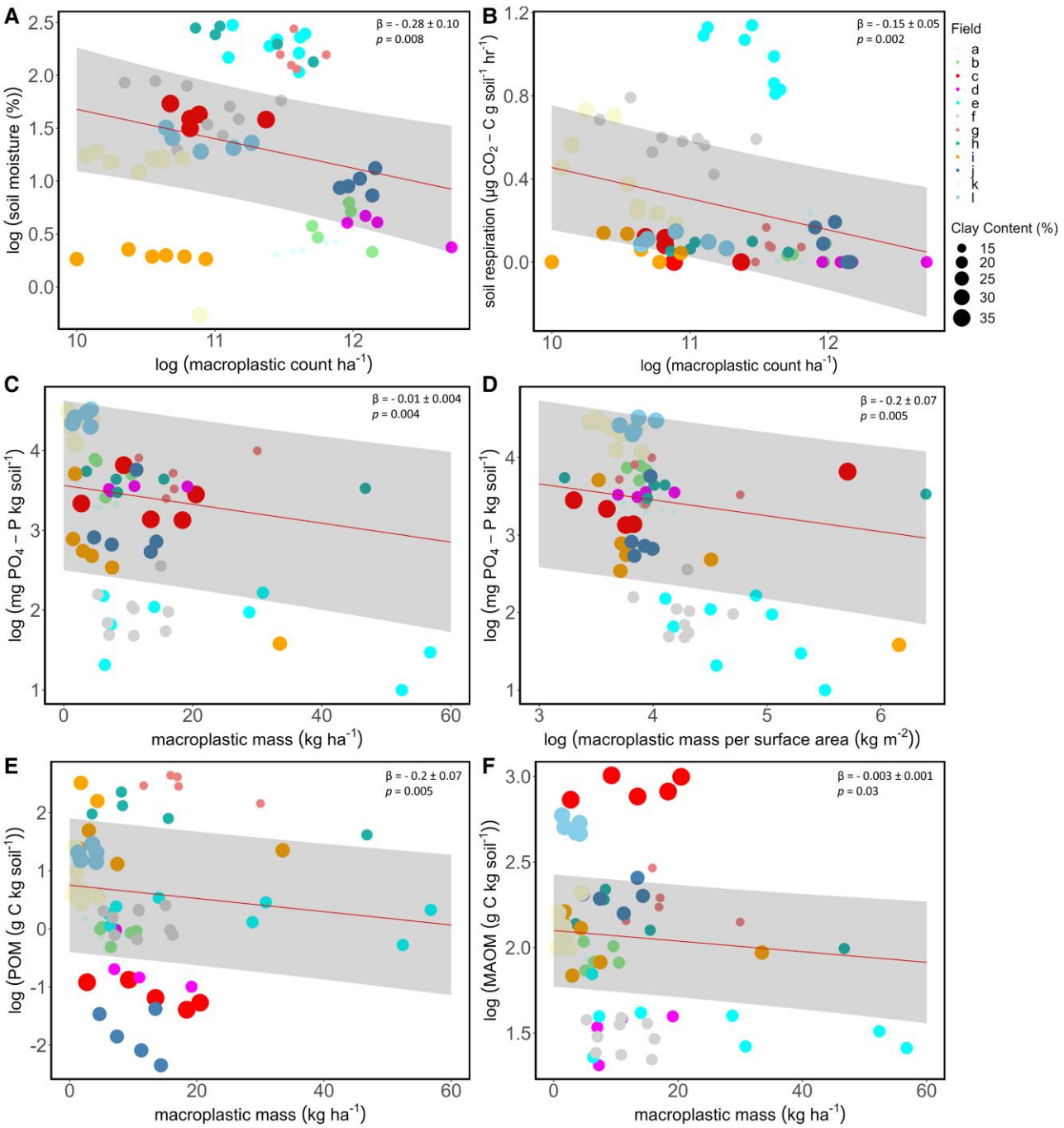

Fig. 5. Effect of macroplastic fragments on soil biogeochemical properties: a) soil moisture (%), b) soil respiration (µg CO_2-C g^{-1} dry soil h^{-1}), c, d) Olsen-P (mg PO_4-P kg^{-1} dry soil), e) POM (POM; g C kg^{-1} soil), and f) MAOM (MAOM; g C kg^{-1} soil). The slope (β) ± SE and *P*-value using Satterthwaite's method for the linear mixed effect of plastic contamination on each response variable is shown. The fitted line and shaded area represents the predicted values and associated 95% CIs obtained from linear mixed effect model fit using the ggeffect function in R.

All fields surveyed—which experienced "best practice" plastic mulching application and removal practices over multiple years—had marked plastic contamination in the surface soil. Macroplastics covered up to 3.4% of the soil surface, with a mass of up to 25 kg per ha. Studies from China—the world's largest user of agricultural plastic mulch—report plastic residues ranging from 0.2 to 545 kg per ha in cropland soils (5, 8), representing an extreme extent of soil plastic pollution not currently seen in other regions despite expanding plastic film use (10, 53). Reduced soil function in field studies has been observed at high plastic concentrations (>240 kg per ha) following repeated incomplete removal (or tillage into the soil) of plastic mulch films and in mesocosm studies (5, 8). We found that the accumulation of macroplastics negatively correlated with key soil characteristics associated with plant productivity and soil health at <10% of the contamination concentration previously associated with degraded soil properties under field conditions (8).

Accumulation of macroplastics can alter soil structure by affecting aggregate formation and soil water retention (20). Across our sample fields, macroplastic accumulation was negatively correlated with field soil moisture content, which may be driven by both the hydrophobicity of the plastic fragments and increased

desiccation cracking on the soil surface amplifying evaporative loss (13, 54). We observed an ∼2.6% decline in soil moisture with every 10% increase in macroplastic number concentration under nonirrigated field conditions. This response suggests that macroplastic accumulation can negatively affect this critical control on plant productivity and microbial decomposer activity (13), an effect which may become exacerbated under drought and heat stress conditions. These field-based findings support observations from a mesocosm study, where increasing plastic concentration and size were correlated with reduction in soil water content, especially in sandy soils with low baseline water availability (17).

Soil moisture reduction driven by plastic accumulation can directly affect microbially driven soil respiration and nutrient mineralization rates (55), while plastic debris can also serve as a novel microbial habitat (22, 23). We found that macroplastic concentration was negatively correlated with soil microbial respiration rate. Similar findings were reported in an incubation study under controlled conditions where the presence of eight different microplastics decreased soil respiration, but this effect was mediated by microplastic shape, size, concentration, and polymer type (56, 57). While macroplastic concentration (count per hectare) did not detectably influence plant-available inorganic N, soil PO_4^{3-} availability negatively correlated with macroplastic accumulation by mass per hectare and mass per unit surface area. Increasing drought stress can enhance the negative effects of drying on soil microbial activity and plant nutrient uptake, with soil extractable P being particularly sensitive to reduced soil moisture (58).

These findings lend support for field-level plastic contamination impacts as inferred by incubation studies that have reported negative relationships between plastic concentration and plant-available nutrients (59, 60). Notably, a mesocosm study that included plants, soil, and fertilization reported a decrease in inorganic N and P with increasing concentration of microplastic, whereas low density PE macroplastic contamination positively correlated with nutrient availability (13). These contrasting responses relative to our field observations may reflect differences in basal nutrient availability and the potential of plants to act as nutrient sinks (i.e. reducing soil extractable nutrients through their uptake) being impaired by the plastic contamination. At the observed contamination range, increasing levels of macroplastic contamination reduced plant-available PO_4^{3-} by ∼1% per unit increase in macroplastic mass concentration and by ∼0.2% for every 1% increase in macroplastic mass per unit surface area of soil. PO_4^{3-} is a key limiting nutrient for crop productivity (43). If macroplastic accumulation reduces agricultural soil PO_4^{-3}, this deficit may exacerbate the need for exogenous fertilizer application over time.

The accumulation of plastic pollution can contribute to the total soil organic C pool but also disrupt microbially mediated SOM cycling (25, 61). We found that macroplastic mass concentration in the surface soil was negatively correlated with both the POM and MAOM C pools. Thus, increasing macroplastic contamination may reduce the size of both the actively cycling (POM) and physically protected (MAOM) soil C pools. We did not detect any impacts of soil plastic contamination on microbial biomass; however, other studies have found plastic accumulation negatively affects soil microbial biomass (13, 31), aggregate formation and stability (18, 62). Thus, the observed reduction in soil MAOM and POM C pools with increasing plastic contamination may be driven by a decline in aggregate formation and detritus inputs due to reduced moisture and microbial activity associated with elevated plastic accumulation.

We did not detect any biogeochemical correlations with microplastic abundance at the concentrations observed in our field study. However, we found that field surface soil microplastic and macroplastic abundance positively correlated across the sample fields and that PO—which include PE plastics—was the dominant microplastic polymer. These findings suggest that the weathering of larger plastic film debris contributes to the generation of soil microplastics, and that more readily observed visible plastic fragments can be quantified and used to estimate microplastic contamination levels even in moderately polluted soils. Similar findings between micro and macroplastic mulch fragments were reported in Chinese agricultural studies (33, 63) and highlights the potential to use macroplastic pollution on the surface of fields as an indicator of microplastic contamination in agriculture soils.

We found that under best management practices, plastic derived from mulch films is accumulating in agricultural soils, that this accumulation can reduce agricultural soil functions even at relatively low concentrations, and that these deleterious effects increase with greater plastic contamination. However, these soil health impacts were relatively subtle at the observed contamination levels, with no detectable relationship to microplastic concentration. Terrestrial plastic pollution impacts are modulated by local edaphic conditions and management history, making it challenging to identify thresholds whereby plastic pollution seriously impairs soil function. Because plastic accumulation in agricultural soils positively correlates with the number of years that plastic mulching has been employed (64), our findings suggest that shifting traditional plasticulture practices to those that reduce plastic debris accumulation is essential to prevent the deleterious effects on soil health that are observed under high plastic contamination levels. Given the continued extraordinary growth of agricultural plastic film use globally (1), it is critical to characterize the mechanisms and thresholds by which soil function is—potentially irrevocably— affected by this novel threat under real-world field conditions.

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Supplementary Material

Supplementary material is available at *PNAS Nexus* online.

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Author Contributions

S.S. conceived the idea and designed the methodology, with support from E.T. E.T. and S.S. collected field samples and E.T. performed the laboratory analyses. E.T. and S.S. analyzed the data and S.S. led writing the manuscript. Both authors contributed to the drafts and gave final approval for submission.

Data Availability

All soil biogeochemical data, plastic data, and related code are available at: https://datadryad.org/stash/share/TGEaAP52mlnfO60jpAXRdVEPqB0cmk1ZPsj7IUNQXaU.

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