Journal of Hazardous Materials 477 (2024) 135318

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Tracing macroplastics redistribution and fragmentation by tillage translocation

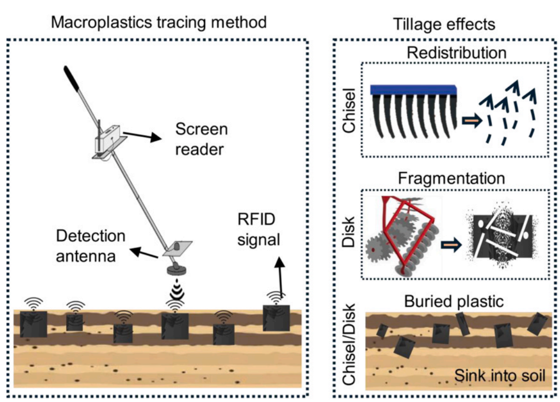
Ahsan Maqbool [a,b,*,1], Gema Guzmán [c], Peter Fiener [d], Florian Wilken [d], María-Auxiliadora Soriano [e], José A. Gómez [a]

[a] Institute for Sustainable Agriculture, CSIC, Cordoba 14004, Spain
[b] Doctorate Program "Ingeniería Agraria, Alimentaria, de los Recursos Naturales y del Desarrollo Rural Sostenible" University of Córdoba, 14014 Córdoba, Spain
[c] IFAPA-Camino de Purchil, Granada 18004, Spain
[d] Institute of Geography, Augsburg University, Augsburg, Germany
[e] Department of Agronomy (DAUCO), University of Córdoba, 14014 Córdoba, Spain

HIGHLIGHTS

- Macroplastics displacement was comparable with bulk soil displacement.
- A profound impact of tillage implement was found on macroplastics distribution.
- Tillage process drove the abundance of microplastics.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Comparative study
Fate and transport
Plastic debris
Radio frequency identification (RFID)
Tracers

ABSTRACT

Soil is polluted with plastic waste from macro to submicron level. Our understanding of macroplastics (> 5 mm) occurrence and behavior has remained comparatively elusive, mainly due to a lack of a tracing mechanism. This study set up a methodology to trace macroplastic displacement, which combined magnetic iron oxide-tagged soil and macroplastic pieces tagged by an adhesive passive radiofrequency identification transponder. By utilizing these techniques, a field study was carried out to analyze the effect of tillage implement and plastic sizes on plastic displacement, to understand the fate of macroplastics in arable land. Results indicated that the displacement of macroplastics did not depend upon plastic sizes but did depend upon the tillage implement used. The mean macroplastics displacement per tillage pass was 0.36 ± 0.25 m with non-inversion chisel tillage and

Abbreviations: LDPE, low-density polyethylene; PDF, probability density function; RFID, Passive radio frequency identification transponder; UV, Ultraviolet radiation.

* Corresponding author at: Institute for Sustainable Agriculture, CSIC, Cordoba 14004, Spain.
E-mail address: amaqbool@ias.csic.es (A. Maqbool).
[1] ORCID: 0000-0002-5968-3390

https://doi.org/10.1016/j.jhazmat.2024.135318
Received 31 March 2024; Received in revised form 23 July 2024; Accepted 24 July 2024
Available online 25 July 2024

0.15 ± 0.13 m with inversion disk tillage, which was similar to bulk soil displacement. However, only inversion disk tillage caused fragmentation (41 %) of macroplastics and generated microplastics (< 5 mm). In contrast, both tillage implements drove to similar burial of surface macroplastics into the tilled layer (74 % on average). These results highlight that tillage is a major process for macroplastics fate in arable soils, being one of the first studies to investigate it.

1. Introduction

Earth faces increasing pollution with macroplastic pieces (> 5 mm), which are the primary source of microplastics (< 5 mm) and nanoplastics (< 5 μm) particles. Moreover, these macroplastics can release hazardous substances during weathering processes, harming ecosystems' health [1]. Most studies on plastics in terrestrial ecosystems have focused on microplastics and nanoplastics distribution [2] and transport [3], their impacts on soil biota and key soil functions [4], and phytotoxicity [5]. However, few studies have investigated the effect of macroplastics on soil physical properties compared to microplastics [6]. Even analytical methods have also focused on micro(nano)plastic tracing and detecting in soil [7–10]. Although analytical techniques for measuring macroplastics in the environment are not complicated due to their detectability with the naked eye, accurate macroplastic quantification remains challenging in terrestrial ecosystems. Individual macroplastic pieces may be covered by soil and cannot be detected from remote and proximal sensors [11–13]. Despite their abundance in soil and their high potential for fragmentation and redistribution by anthropogenic and environmental processes, macroplastics remain an elusive and understudied domain in soil compared to microplastics and nanoplastics.

Sources of macroplastics are attributed to littering and intentionally used plastic in terrestrial environments. Littering of macroplastics (packaging, bottles, cigarette butts, and others) is found in roadside ditches in New York State [14]; it was estimated that 13 kg ha^{-1} yr^{-1} of polyethylene terephthalate are added alongside roads in Switzerland [15], measuring 73.5 to 1484 million plastic pieces per kg (3.60 to 72.67 % dry w/w) in soil contaminated with marine litter in Norway [16], from 22 to 167 tons yr^{-1} of urban wastewater discharged into the Greater Paris catchment [17], or macroplastics deposition in riverbanks due to flooding (e.g., on the Meuse River plain) [18]. Intentionally used plastic in agriculture (plasticulture) ranges from mulch films to silage foils. Conventional plastics have useful applications in arable systems, including mulch films, low and high tunnels, shading and safety nets, irrigation pipes and drip tapes, pots and nursery trays, sacks and storage bins, silage foils, and many others. Biodegradable plastic products for farm systems are developing, but their development and use are neither complete nor global. Only plastic greenhouses and mulch films cover 27.4 Mha (2–3 %) of global arable land [19], twice England's size. Compost and sewage sludge application are direct pathways of macroplastics accumulation in agricultural soils [20–22]. Secondary macroplastics from intentionally used plastics in farmlands accumulates in large quantities during the year of their consumption in the soil environment, thus 206 to 9247 pieces of plastic ha^{-1} have been reported in Germany [20,23], 0.5 to 5.5 kg $plot^{-1}$ (50 × 30 m) in Tanzania [24], 16 pieces kg^{-1} of soil in Turkey [25], 431 pieces ha^{-1} (6 kg ha^{-1}) in Hungary, or 50 to 260 kg ha^{-1} in China [24]. Likewise, on-farm agricultural plastic waste bothers farmers due to off-site plastic waste management stations [26]. As consequences, soil macroplastics affected the inhabitation of specific soil microbial communities [27], the risk of N leaching [28] or soil water flow [29], water uptake by plants and nutrient availability [28,30], and plant biomass production and crop yield [28,31]. This could pose a serious risk to the sustainability of fertile land, food security, and soil ecosystem functioning across all land uses. Thus, understanding the fate of macroplastics in soil due to tillage operations could help us identify the most affected domains for sustainable plastic use, soil management, and tillage practices.

Tracing soil studies can help define critical parameters for integrating arable land to evaluate macroplastics fragmentation and redistribution in the tillage process. The physiochemical and mechanical processes might be driving factors in understanding the fragmentation and distribution of macroplastics in the soil environment. Environmental fragmentation and degradation of plastic are triggered by exposure to UV light that fragments it into progressively smaller pieces known as microplastics and nanoplastics [1]. Due to chain scission, UV aging oxidizes polymer, inducing cross-linking by creating cracks and voids on the polyethylene film surfaces [32]. Environmental UV-aged macroplastics (high-density polyethylene, polypropylene, and extruded polystyrene) in salt marsh habitats turns into fragments [33]. Likewise, UV-aging of macroplastics followed by mechanical abrasion leads macroplastics fragment to the submicron level [34]. Tillage operations are usually applied after crop harvesting and partial collection of the utilized plastic. Meanwhile, residual macroplastics remain in the soil exposed to UV light for several months and degrade to a certain level. Soil tillage might have a high potential for macroplastics fragmentation and subsurface burial during the process, as reported for crop residue fragmentation and incorporation [35], soil carbonation distribution [36], and pesticide leaching [37]. Macroplastics degradation requires a robust UV-light-dependent photo-degradation process [38]. The potential burial of macroplastics by the tillage process could restrict their degradability, stopping physicochemical degradation by obstructing or ending UV light exposure or affecting the bioturbation processes. However, macroplastics fate during the tillage process remains elusive, and the reason might be the lack of a tracing technique to evaluate displacement. Macroplastics could behave differently than soil particles during translocation by tillage due to the contrasting characteristics of the plastic: it has a lighter weight and a different shape and interaction of surface forces (e.g., friction) compared to soil minerals, coarse fractions, and organic matter. Hence, tracing the redistribution of macroplastics and appraising their fragmentation with a robust approach during the soil tillage process is critical for studying macroplastics fate in the soil environment.

Comparative tracing of macroplastics and soil particles could further facilitate understanding the tillage operation impact on macroplastics' fate, including macroplastics redistribution in tillage layer depth. For tracing soil, magnetic iron oxide tagging represents non-selective transport relative to soil particles. Thereby, magnetic iron oxide revealed soil particles concentration and deposition zones at relatively high resolution in the till layer [39–42]. For tracing macroplastics, a passive radio frequency identification (RFID) transponder could be a feasible approach to understanding macroplastics behavior's underlying mechanisms and processes on land surfaces and dynamic environments. RFIDs offer fast-tracing of individual pieces with non-destructive monitoring, are produced commercially, and existing standard communication protocols with unique identification numbers, and ease of data collection manually or remotely without technical expertise [43,44]. Low-density polyethylene (LDPE) mulch film is the most widely used plastic on arable land worldwide [19,45]. Furthermore, it is very fragile and hard to remove without fragmentation. Therefore, LDPE mulch films are a substantial- or the highest input of plastic to soils.

In this study, horizontal and vertical redistribution of LPDE macroplastics and their fragmentation due to tillage operations, performed with different tillage implements, were measured and analysed, using untagged and RFID-tagged macroplastics. To compare macroplastics redistribution with previous studies focusing on soil redistribution, this was also measured using a magnetic iron oxide tracer, with all measurements carried out in a flat agricultural field (0° slope) to avoid any slope-related movement during the tillage operations. We will test the following hypotheses: (1) the redistribution of macroplastics due to tillage is different from the redistribution of bulk soil, (2) the horizontal and vertical redistribution of plastic by tillage will depend on the size of the macroplastic pieces, and (3) type of tillage implement will affect plastic redistribution and fragmentation.

2. Materials and methods

2.1. Experimental site and tillage and macroplastics treatments

The experiment was conducted at the Institute for Sustainable Agriculture (IAS-CSIC) experimental farm in Cordoba (Andalusia, southern Spain). Annual averages of maximum, minimum, and mean daily temperatures recorded during an 23 years (2001–2023) at the Córdoba agroclimatic station [46], located about 600 m from the experimental plot, were 25.1, 11.2, and 17.8 °C, respectively. Mean annual precipitation was 573 mm, and the annual average of daily solar radiation was 17.9 MJ m^{-2}. During the experimental period (July 10 to 14, 2023), daily averages of maximum, minimum, mean temperature, humidity, and radiation were 42.1 °C, 20.4 °C, 31.96 °C, 28.2 %, and 29.2 MJ m^{-2}, respectively, with no precipitation. A flat agricultural field (0° slope) was selected to avoid slope-related plastic movement during tillage operations. The topsoil had a loam texture with negligible stone content. The site has no existing history of any type of plastic input, including macroplastics.

Experimental design consisted of a set of experimental plots, which allowed controlled conditions with standardization and consistency in replicates and detailed and accurate measurements. Eight plots of 5 × 2 m (length and width; Fig. 1) were established after plowing the experimental field to homogenize the soil and remove any existing vegetation (weeds, crop residues). The eight experimental plots had a similar topsoil (0–0.15 m) bulk density of around 1200 kg m^{-3} and a low topsoil gravimetric moisture of around 4.15 % due to drought conditions (Table S1). Tillage treatments were applied in a set of three consecutive tillage passes, keeping tillage direction, tillage speed (4.5 km h^{-1}), and tillage depth (15 cm) constant. For a set of four experimental plots (P1, P2, P7, and P8) inversion disk tillage was used, while for the other set of four plots (P3, P4, P5, and P6) non-inversion chisel tillage (Fig. 1 and S1). Tillage treatments were performed from July 10 to 14, 2023. Prior to the tillage treatments, untagged macroplastics and RFID-tagged macroplastics of different sizes were located within the experimental plots (Fig. 1, S2, and S3), which were traced after the set of three tillage passes with the two different implement types. Magnetic iron oxide was used as a tracer to determine soil displacement due to tillage treatments. Thus, each tillage implement treatment had four replicates, two with untagged macroplastics and two with RFID-tagged macroplastics. Meanwhile, magnetic iron oxide soil tagging had two replicates for each tillage implement treatment.

2.2. Determining macroplastics displacement: untagged macroplastics

Pristine low-density polyethylene (LDPE) mulch film with a thickness of 25 µm was cut into pieces of three sizes: 2 × 2 cm, 4 × 4 cm, and

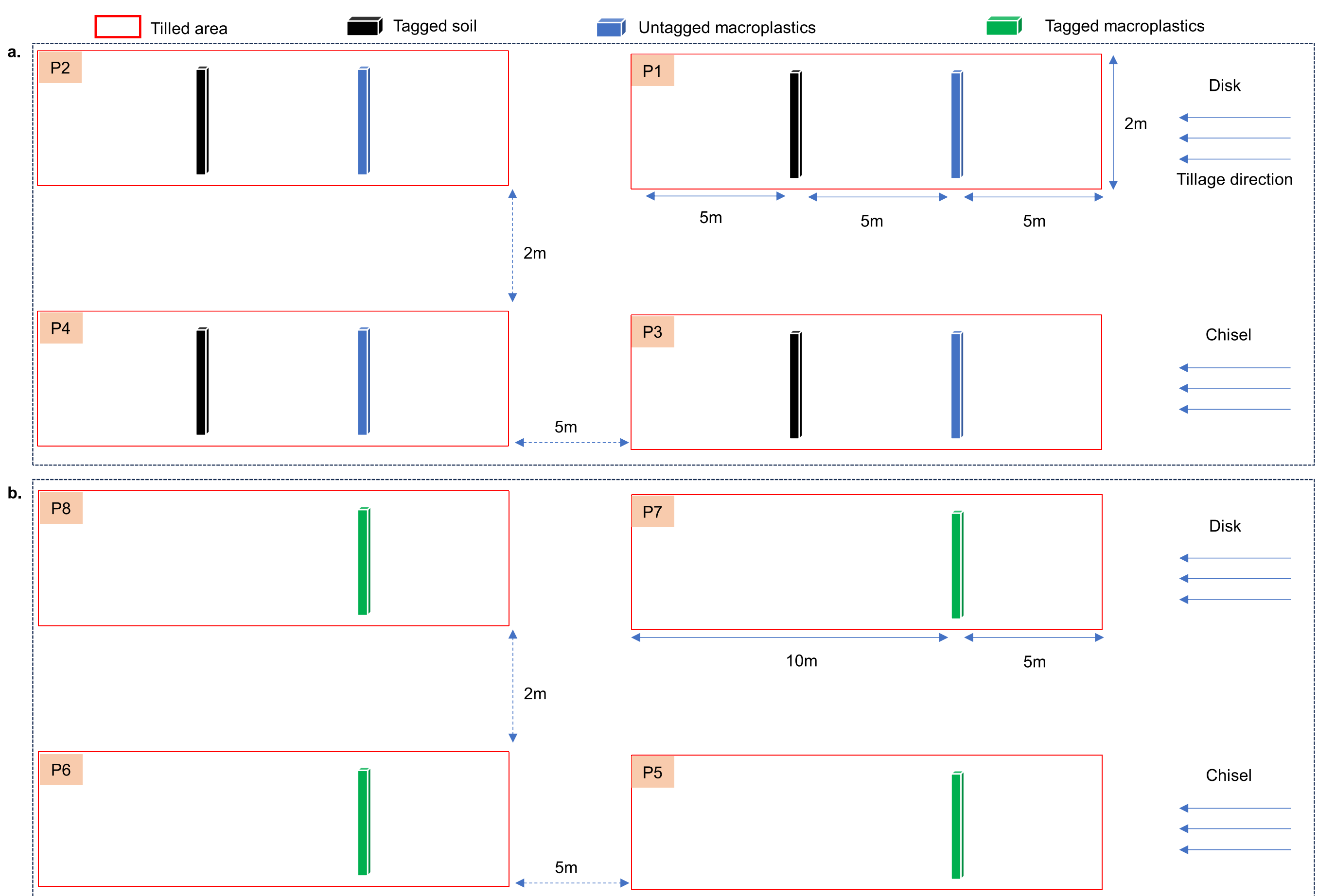


Fig. 1. Schematic of (a) experimental layout of the untagged macroplastic and magnetic tagged soil trench in the disk plow plot (P1 and P2) and chisel plow plot (P3 and P4). (b) Experimental layout of the RFID-tagged macroplastic trench in the chisel plow plot (P5 and P6) and disk plow plot (P7 and P8). Dimensions are not according to scale.

8 × 8 cm (hereinafter referred to as small, medium, and large macroplastic sizes, respectively). Individual macroplastic pieces were marked with numbers to differentiate their recovery based on their original depth. The three sizes of untagged macroplastics were placed at 8-cm soil depth and on top of the soil (hereafter referred to as subsurface and surface, respectively; Figure S2). In total, 120 pieces of macroplastic (20 of each size at each soil depth) were placed in each trench (8 cm × 25 cm × 160 cm; depth, length, and width, respectively) made in the experimental plots P1, P2, P3 and P4 (Fig. 1a). After the three tillage passes, macroplastics were recovered in two steps: i) hand-picking of visible macroplastic on the soil surface, considered as surface macroplastic pieces, and ii) a 25 × 25 cm grid was drawn for subsurface recovery of macroplastics up to 3 m from the trench and towards the tillage direction, sieving then the soil with a mesh size of 5 mm, considered as subsurface macroplastic pieces. However, the fragmented pieces in both steps are considered regardless of recovery depth. The location of the recovered macroplastics during the sieving step was assigned to the center of the grid where it was recovered. The displacement distance to the trenches (in the tillage direction and perpendicular to the trench) was measured after three consecutive tillage passes for both steps. Afterward, measured displacement was used to calculate the average macroplastics displacement per tillage pass.

2.3. Determining macroplastics displacement: RFID-tagged macroplastics

RFID transponders of 125 kHz frequency of two characteristics were used (model 1 and model 2, acquired to rfidspecialist.eu, Slovenia). RFID transponders (1) flat and stick-able with a diameter of 38 cm and thickness of 0.84 mm (hereafter referred to as RFID stickers), and (2) flat and non-stick RFID chips with a diameter of 25 cm and thickness of 1 mm (here referred to as non-stick RFID; Figure S3). The RFID stickers were pasted on the macroplastic pieces. Each trench (one in each plot P5, P6, P7, and P8; Fig. 1b) had 102 RFID transponders, i.e., macroplastics (4 × 4 cm, n = 16, and 8 × 8 cm, n = 19) RFID-tagged and RFID chips (n = 16), 51 placed on the surface and 51 in the subsurface (Fig. 1b and S3). RFID chips and RFID stickers are made from polyvinyl chloride (PVC) material. Individual RFID-tagged macroplastic pieces were marked with numbers for differentiating their recovery based on their original depth. RFIDs were recovered using an RFID detection antenna (Rolling Stone, TECTUS, Germany) to detect transponders up to 0.20 m soil depth (Figure S4). Likewise, non-stick RFID chips had a maximum detection depth of 0.1 m due to their smaller size. Therefore, the soil layer was removed after detecting the RFIDs at a depth of 0 to 10 cm and up to 3 m from the trench in the tillage direction and scanned again with the RFID detection antenna. Individual displacement of RFID-tagged macroplastics and RFID chips was measured with a measuring tape once they were detected, after the set of three tillage passes, as for the untagged macroplastics. Afterward, measured displacement was used to calculate the average macroplastics displacement per tillage pass. Meanwhile, fragmented pieces of macroplastics were collected on soil surface.

2.4. Determining bulk soil displacement

Magnetic iron oxide was used as a tracer to determine soil movement during tillage operations. Four trenches of 15 cm × 15 cm × 120 cm (depth, length, and width, respectively) were dug, one in each plot P1, P2, P3, and P4 (Fig. 1a). Soil was collected from each trench and air-dried after removing any coarse fragments of plant material. Through serial dilutions, 152 kg of soil was mixed with magnetic iron oxide (Fe_3O_4) to increase its magnetic susceptibility compared to the background soil concentration by two orders of magnitude, from 3.1×10^{-7} to 1.4×10^{-5}, following the protocols developed by Guzmán et al. [40]. The soil mixture was then applied back to the same trenches where it had been collected (Fig. 1a and S5). The volumetric soil magnetic susceptibility of P1, P2, P3, and P4 plots was measured from the magnetic trench up to 5 m in the direction of tillage on a 0.2 × 0.5 m (X, Y) grid using an MS2D field probe in conjunction with an MS2 sensor (Bartington Instruments, UK), before and after the set of three tillage passes. In addition, 30 soil samples were taken from the plowed layer (0–0.15 m) within each of the four plots, at 15 locations, before and after the tillage passes. Each of these soil samples was subdivided into six subsamples to measure the accuracy and reliability of the laboratory magnetic susceptibility measurement by the MS2B dual-frequency sensor. After a set of 10 readings, the sensor was recalibrated. Afterward, laboratory measurements were converted to mass magnetic susceptibility, evaluated, and used to calibrate the volumetric magnetic susceptibility of the field probe. It allowed us to convert a tracer's volumetric to mass magnetic susceptibility. Additional details about magnetic tracers as a proxy to simulate soil and sediment transport and this methodology can be found at [47,48]. Mass magnetic susceptibilities of the two plots per each tillage implement were combined to calculate soil displacement. Soil movement was considered as the measured distance between the trench and the threshold point of mass magnetic susceptibility. The threshold point is an area of mass magnetic susceptibility that becomes constant without any variability. Afterward, the mean displacement of soil per tillage pass was calculated from the mass displacement of the magnetic tracer (g kg^{-1} soil) using weightage by multiplying the mass concentration of the magnetic tracer. The flowchart of soil displacement calculation is presented step by step in Figure S6.

2.5. Data analysis

The mean displacement of macroplastics per tillage pass was calculated from the direct displacement measurements. The Gaussian kernel function was used to derive the probability density function (PDF) without any smoothness factor, to compare the displacement of soil and macroplastics. Soil redistribution rate was calculated using the model proposed by Govers et al. [49] as $Q = D\rho_b \vec{d}$; where Q is the soil redistribution rate for a single tillage pass (kg m^{-1} tillage-$pass^{-1}$), D is the tillage depth (m), ρ_b is the bulk density (kg m^{-3}) and $\vec{d}$ is the mean displacement of soil (m). One-way ANOVA was conducted (after normality was checked) to assess whether there were differences in the measured data (e.g., macroplastics recovery) between the different levels of the comparison groups (e.g., macroplastic sizes, RFID-tagged and untagged macroplastics, and tillage implements). When ANOVA yielded significant differences ($p < 0.05$), the Bonferroni post-hoc test was conducted to check for response differences among different levels of corresponding group. All data analyses were performed in STATA®17.0 (StataCorp, USA). Experimental raw data of macroplastics are presented in a supplementary file.

3. Results

3.1. Macroplastics redistribution

Significant macroplastics redistribution occurred after a set of three tillage passes, with a notable preferential burial of macroplastic pieces in the subsurface layer. Recovery of macroplastic was high for both untagged and RFID-tagged macroplastics, with mean total recovery rates of 90 % and 93 %, respectively, including all macroplastic sizes and depth of recovery (Table 1). Macroplastic pieces didn't reflect any systematic relationship between their sizes and recovery rates. Likewise, for both tillage implements (chisel and disk), the recovery rate of the macroplastic pieces was very high and similar (94 ± 4 % and 89 ± 3 %, respectively). Only 17 ± 10 % of macroplastics were recovered on the soil surface. Macroplastic pieces burial has been found at the subsurface, accounting for an average of 74 ± 9 % of the total recovery of macroplastic pieces (for a total average of 91 ± 4 %), although, compared to

Table 1
Recovery rates (%) of different sizes of untagged and RFID-tagged macroplastic pieces, according to the tillage implement used.

			Macroplastic pieces per original depth (#)			Translocation and recovery of macroplastic after three tillage passes				
						Total pieces recovery (%)		Recovery relative to original depth (%)		
Tillage implement	Tracer	Macroplastic size	Surface (0.0 m)	Subsurface (0.08 m)	Recovered fragmented macroplastic (#)	Surface (0.0 m)	Subsurface (0.01-0.15 m)	Surface to surface	Subsurface to subsurface	surface to subsurface
		Small	40	40	0	9	85	1	77	16
		Medium	40	40	0	21	73	6	56	31
Chisel	Untagged	Large	40	40	0	30	56	12	32	42
		Small	40	40	15	9	80	1	68	20
Inversion		Medium	40	40	35	5	86	1	75	15
Disk	Untagged	Large	40	40	44	5	78	0	62	20
		Small	32	32	0	27	66	10	49	33
	RFID-	Medium	32	32	0	25	73	5	53	40
Chisel	tagged	Large	38	38	0	34	64	10	37	51
		Small	32	32	2	13	77	2	65	23
Inversion	RFID-	Medium	32	32	29	14	77	3	67	20
Disk	tagged	Large	38	38	58	17	76	3	56	34

the original depth, 29 ± 12 % of the macroplastic pieces were transferred from surface to subsurface (Table 1). Meanwhile, only a few (5 %) of the macroplastic pieces translocated from surface to surface compared to subsurface to subsurface (58 %). Subsurface burial of macroplastic pieces was similar for both tillage implements, although slightly higher for inversion disk tillage plots (79 %) compared to non-inversion chisel tillage plots (70 %). A macroplastic pieces exchange occurred during plowing, with a mean of 31 % based on the differences between the total recovery and translocation rates relative to the original depth (Table 1). The apparent burial of macroplastic pieces with non-inversion chisel tillage and inversion disk tillage indicated soil as a sink of macroplastics.

All the macroplastic pieces showed a significant horizontal displacement (relative to their original location) after the set of three tillage passes, up to 2.55 m for the non-inversion chisel tillage and 1.00 m for the inversion disk tillage, in terms of 95-percentiles. Macroplastic pieces recovery at each soil depth (surface and subsurface) for their original placement depth showed no significant difference regardless of RFID-tagged or untagged macroplastic, neither for different macroplastic sizes, nor for the tillage implement used ($p > 0.05$, Table 2). Therefore, surface and subsurface data from RFID-tagged and untagged macroplastic pieces were combined for each macroplastic size and tillage implement to determine macroplastics displacement. Change in macroplastic size did not significantly influence macroplastics displacement for untagged and RFID-tagged macroplastic ($p > 0.05$, Table 3), regardless of the tillage implement used. However, the type of tillage implement used significantly influenced the displacement of macroplastic pieces of all sizes ($p < 0.001$, Table 3), untagged or RFID-tagged. RFID-tagging of macroplastics did not modify the mean macroplastics displacement compared to untagged macroplastic (Table 4). Moreover, the shape characteristics of the probability density function (PDF) curves for the displacement of untagged and RFID-tagged macroplastics for each tillage implement used, for each macroplastic size, showed a comparable pattern (Fig. 2). The mean displacement of macroplastic pieces per tillage pass in the non-inversion chisel tillage plots (0.36 ± 0.25 m; 95-percentile 0.85 m) was 140 % greater ($p < 0.001$) compared to inversion disk tillage plots (0.15 ± 0.13 m; 95-percentile 0.33 m). Large macroplastic pieces showed the lowest mean displacement per tillage pass (0.33 ± 0.24 m, 95-percentile 0.80 m, for chisel, and 0.14 ± 0.13 m, 95-percentile 0.33 m, for disk), while medium macroplastic pieces showed the highest mean displacement per tillage pass (0.38 ± 0.24 m, 95-percentile 0.87 m, for chisel, and 0.17 ± 0.16 m, 95-percentile 0.41 m, for disk). However, the different sizes of macroplastic did not significantly influence macroplastics displacement (Fig. 2).

Table 2
One-way ANOVA p-value results for recovery depth of macroplastic pieces vs. original depth (for untagged, RFDI-tagged, and both combined) for each macroplastic size and tillage implement.

	Untagged		RFID-tagged		Combined	
Macroplastic size	Chisel	Disk	Chisel	Disk	Chisel	Disk
Small	0.618	0.612	0.055	0.793	0.060	0.597
Medium	0.083	0.049	0.620	0.055	0.370	0.009
Large	0.255	0.310	0.298	0.721	0.741	0.822

Table 3
One-way ANOVA p-value results for untagged and RFID-tagged macroplastic displacement for macroplastic size (for each tillage implement) and tillage implement (for each macroplastic size).

	Macroplastic size		Tillage implement		
	Chisel	Disk	Small	Medium	Large
Untagged	0.080	0.125	0.000	0.000	0.000
RFID-tagged	0.915	0.563	0.000	0.000	0.000

3.2. Differences in macroplastics and soil displacement

A comparison of macroplastic pieces displacement and soil displacement for each tillage implement used and depending on the macroplastic sizes is shown in Fig. 3, using probability density function (PDF) and cumulative PDF. Probability distribution curves (including peak and unimodal shape characteristics) for the horizontal displacement of the soil and the different macroplastic sizes per tillage pass were compared, showing a comparable probability distribution pattern (Fig. 3a, b) that expected only on a flat agricultural field (0° slope) [50]. Macroplastics displacement by tillage translocation showed a concentrated range of up to 0.25 m for the inversion disk tillage and a dispersed range of up to 0.50 m for the non-inversion chisel tillage (shown by the right bound of the grey-shaded area; Fig. 3c, d) covering 80 % of the distribution area of the tillage-induced displacement for all the macroplastic pieces. The orange-shaded area represents the range of displacement of the macroplastic pieces between 80 % of the total pieces and their 95-percentiles. Soil translocation distance followed a similar distribution pattern compared to that of different macroplastic sizes. The threshold point of soil displacement was 2.5 m for non-inversion chisel tillage and 1.5 m for inversion disk tillage, after the set of three tillage passes (presented as supplementary raw data). Soil displacement for the threshold points was 64 % greater in non-inversion chisel tillage plots compared to inversion disk tillage plots (mean of 0.36 m, 95-percentile 0.94 m, and 0.17 m, 95-percentile 0.56 m, respectively, per tillage pass). Furthermore, the mean displacement of soil was comparable to that of

Table 4
Macroplastic displacement (m; mean±SD) of untagged and RFID-tagged macroplastic pieces for each macroplastic size and tillage implement, and p-value results from one-way ANOVA.

Macroplastic size	Chisel			Disk		
	Untagged	Tagged	p-value	Untagged	Tagged	p-value
Small	0.32 ± 0.25	0.42 ± 0.23	0.094	0.14 ± 0.08	0.20 ± 0.22	0.045
Medium	0.36 ± 0.25	0.40 ± 0.24	0.063	0.14 ± 0.08	0.17 ± 0.17	0.056
Large	0.27 ± 0.21	0.41 ± 0.23	0.136	0.12 ± 0.06	0.19 ± 0.14	0.047

the different macroplastic pieces, both for the inversion disk and non-inversion chisel tillage (Fig. 4). Tillage-induced macroplastics and soil displacement by non-inversion chisel tillage substantially exceed inversion disk tillage by a factor of 2.4 and 2.1 respectively, under fixed tillage depth, speed, and topography. The soil redistribution rate was 65 kg m^{-1} and 31 kg m^{-1} per tillage pass for the non-inversion chisel and inversion disk tillage, respectively.

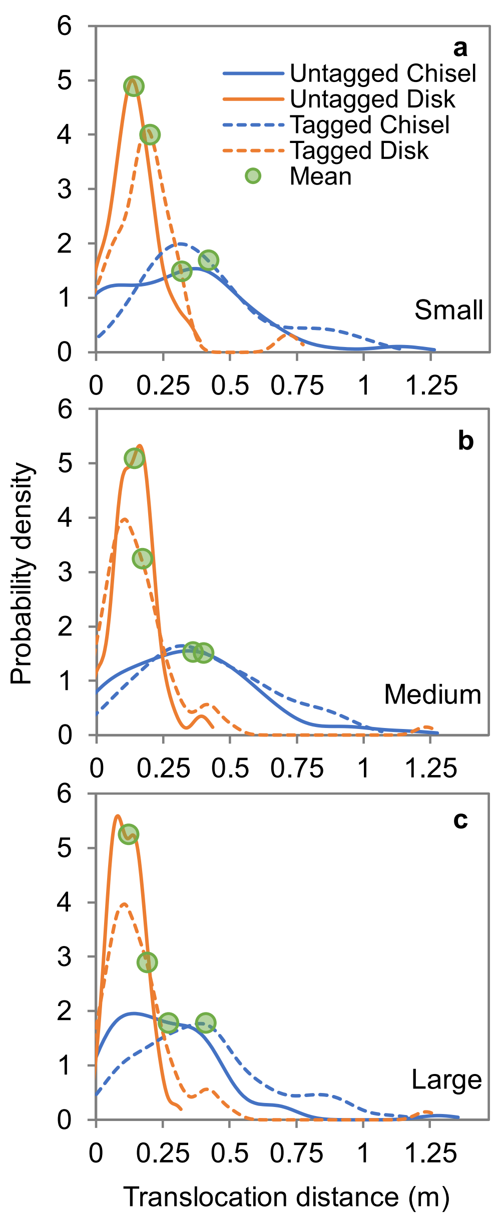


Fig. 2. Probability density functions for macroplastic pieces displacement for each combination of tillage implement (chisel and disk) and tracing method (untagged and RFID-tagged) for each macroplastic size: a) small, b) medium, and c) large.

3.3. *Macroplastics fragmentation*

Our observations indicate significant elongation and fragmentation of macroplastics due to tillage operation, which depended on the type of tillage implement. In non-inversion chisel tillage plots, not a single piece of fragmented macroplastics, including untagged and RFID-tagged macroplastics, was recovered. However, macroplastics fragmentation was high in the inversion disk tilled plots (n = 183; 41 %; Table 1). Number of fragmented macroplastics in inversion disk-tilled plots increased with increasing macroplastic sizes. The highest fragmentation affected the large-sized macroplastic pieces (76 % for RIFD-tagged and 55 % for untagged), followed by the medium-sized macroplastic pieces (44 % for RIFD-tagged and untagged). Plastic fragments were broken off and widespread in the plots from the original macroplastic pieces (Fig. 5d and S7). Inversion disk tillage caused significant elongation of the macroplastic pieces from their original sizes and smaller fragmented regions. Fragmented regions in the macroplastics were > 1 cm, 1–0.5 cm, and < 0.5 cm known as microplastics (Fig. 5 abc and S7). The shape and size of the fragmentation region of macroplastic pieces showed that microplastic was produced during inversion disk tillage.

4. Discussion

4.1. *Macroplastics redistribution by size and tillage implement compared to soil*

The hypothesis falsifies that horizontal and vertical redistribution of plastic by tillage will depend on the macroplastic sizes (Table 1). In contrast, regardless of macroplastic pieces size on average, 87 % of macroplastic pieces were distributed vertically in plow layer after three tillage passes, 37 % higher than the initial subsurface of macroplastic pieces, confirming the true hypothesis for inversion and non-inversion plow. For inversion disk tillage, the burial rate is larger due to the sideward soil movement by the rear set of disks [51]. Furthermore, soil and macroplastic pieces are displaced similarly in horizontal redistribution (Fig. 4), and macroplastic pieces should be found without a specific depth distribution. This indicates that tillage-induced has a distinct effect on the vertical redistribution of macroplastic pieces compared to horizontal. Tillage profoundly impacts the vertical distribution of soil constituents in the plow layer, as reported [37,52,53]. The vertical distribution of macroplastic pieces into the plow layer is an important new insight that has immense implications on plastic fate, the bioturbation process, and soil functioning. Based on these results, an additional hypothesis was formulated: tillage operations can preferentially bury macroplastics. A field-scale cross-chisel experiment in a two-dimensional plan was conducted only by placing RFID-tagged macroplastic pieces on the soil surface for robust testing of this hypothesis (Fig. 6). Results supported the hypothesis that the tillage process can preferentially bury the macroplastics, as 74 % of macroplastic pieces were recovered from the subsurface.

4.1.1. *Tillage-induced preferential burial of macroplastics, regardless of size*

Tillage-induced preferential macroplastics burial might impact plant performance and crop yield [31,54], soil physical properties [6,30], and runoff generation processes [29,55]. Moreover, it would delineate intrinsic and external mechanical limits for bioturbation processes, such as sub-terrain activities of earthworms and penetration of plant roots [56]. Various environmental factors control the rate of plastic fragmentation and degradation, such as higher temperatures and UV radiation exposure that would accelerate the degradation of plastics, while low moisture content could reduce the fragmentation rate [57–59].

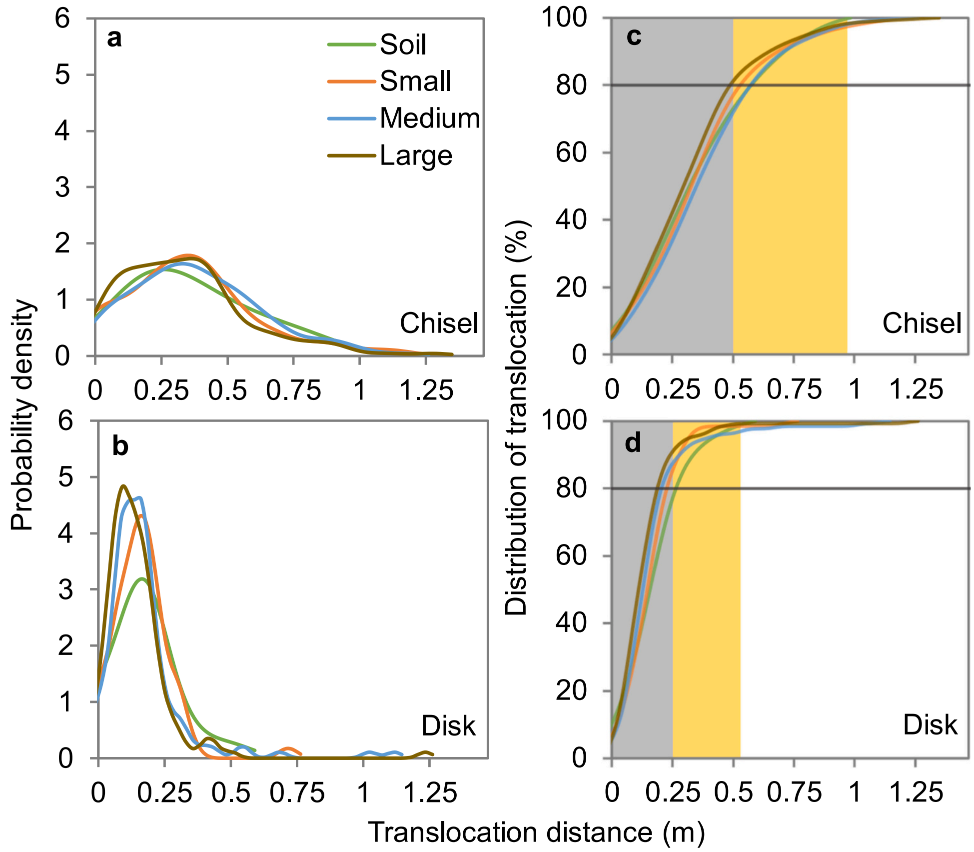


Fig. 3. Probability density functions (PDF; a, b) and cumulative PDF (c, d) for tillage-induced displacement of soil and different sizes of macroplastic, for each tillage implement: (a, c) chisel and (b, d) disk. The grey area covers 80 % of the displacement distances achieved (c and d), while orange represents the displacement of soil and macroplastic pieces between the lines of 80 % of displacement and their 95-percentiles (c and d).

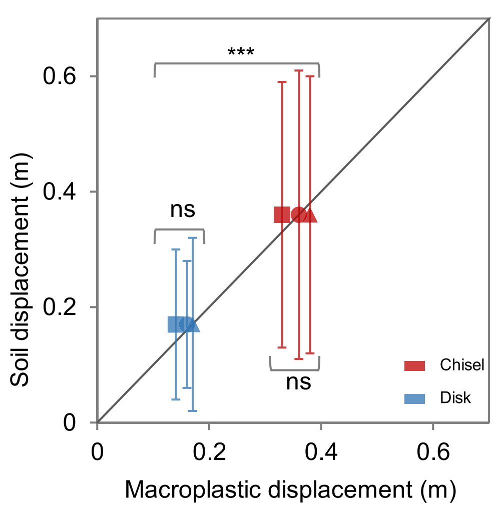


Fig. 4. Scatter plot of macroplastic and soil displacement (mean ± SD) per tillage pas for small, large, and medium macroplastic sizes (differentiated in the three different shapes of scatter points, respectively) for chisel plow plots (dark red) and disk plow plots (blue). Standard deviation was presented in error bars. Stars indicate the significance level of the difference between means (ns: p-value > 0.05, ***: p-value <0.0001).

Subsurface soil might vary in temperature, moisture content, or access to UV light radiation. Tillage-buried plastic (74 %) would restrain its degradation due to restricted exposure to solar UV radiation. Consequently, plastic would have a longer lifespan, and there would be less weathering and release of particulate plastic [60] and toxic chemicals [61] to terrestrial environments compared to soil surface plastic.

4.1.2. Tillage-induced displacement of macroplastics is driven by the type of implement, not by size of plastic

RFID tagging can be an alternative economic approach with tailored data collection options for fewer steps in natural settings. Overall, trends of RFID-tagged macroplastic pieces' recovery (surface and subsurface), displacement, and fragmentation were like untagged macroplastics regardless of sizes with not significantly different (Table 1, Fig. 2 and S7). Translocation of macroplastics on a flat agricultural field (0° slope) was comparable due to negligible influence of angular motion and inertia compared to an inclined field [50]. One could speculate that RFID-tagged macroplastics lead to induced farther macroplastic pieces. In contrast, the mean displacement of RFID-tagged macroplastic is not significantly different from untagged macroplastics (Table 4), while Pareto distribution has thoroughly explained these uncertainties (Fig. 3). For our experimental results, the Pareto distribution highlights a skewed system for only 20 % of macroplastics displacement, which may have caused variability due to long right tail, with macroplastics concentration at 0.56 m and 0.95 m per tillage pass, for inversion disk tillage and non-inversion chisel tillage. In comparison, 80 % of macroplastics displacement was concentrated up to 0.25 m and 0.50 m in the tilled layer for inversion disk tillage and non-inversion chisel tillage. The observed distribution is remarkable, given the general randomness expected by individual macroplastic pieces. Although changes in macroplastic sizes do not significantly influence the Pareto distribution function, tillage implements do. Thus, RFID tagging would be utilized to study the fate of plastic pieces at the catchment scale to tailor the monitoring of plastic litter load pathways from inland to coast to set the baseline. Moreover, for future experiments, RFIDs and their detection

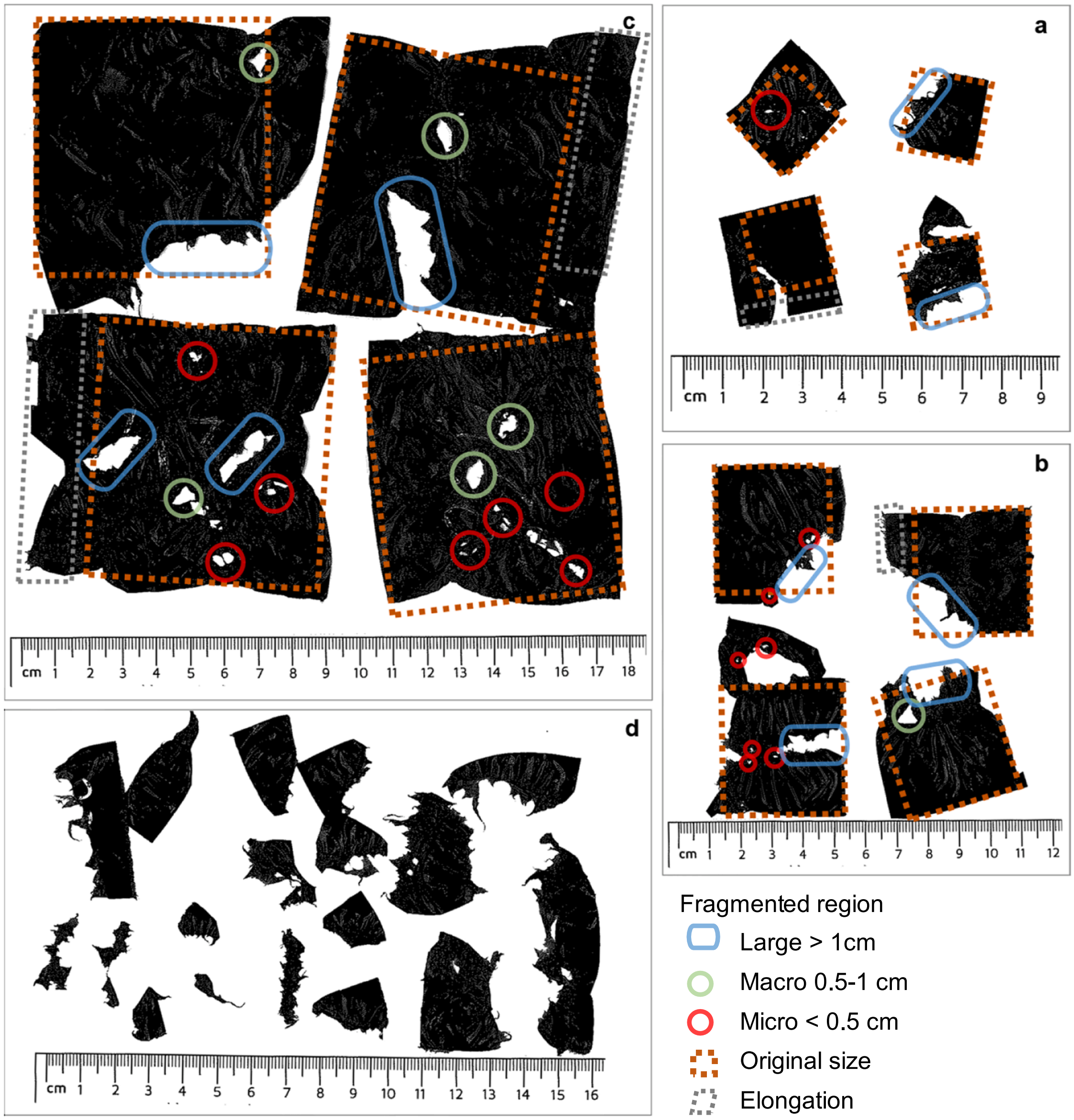


Fig. 5. Macroplastic fragmentation during disk plow in untagged macroplastic plots for different plastic sizes: a) small, b) medium, c) large and fragmented pieces of plastic were collected during the recovery process of untagged macroplastics in the disk plow plots. Similar fragmentation was observed in the RFID-tagged macroplastic plots (Fig. S6). Macroplastic was scanned for image acquisition using Xerox ™ VersaLink C7030 multifunction printer and illustrated in Microsoft PowerPoint 365.

antenna with a higher detection range and stickable on plastic pieces should be utilized.

The hypothesis that tillage-induced horizontal displacement of macroplastic pieces differs from bulk soil is falsified when comparing the mean of macroplastics and soil displacement. Instead, the results unequivocally demonstrated that tillage-induced macroplastics displacement was not substantially different from soil displacement (Fig. 4). A far larger soil displacement was found with zero slope gradient, which showed soil non-cohesiveness (soil moisture content 4.15 % w/w) due to the drought period during the experiment. The soil-sized micro-tracer utilised in this study accurately represents the soil particle flux under dry and disrupted soil conditions [39]. Additionally, the material of the tillage implement itself has a negligible impact on the redistribution of tagged soil [48]; having magnetic susceptibility does not mean a magnet, so it did not modify or alter bulk soil displacement. This study highlights that tillage-induced macroplastics displaced by non-inversion chisel substantially exceed primary inversion disk tillage practices by a factor of 2.4 under fixed tillage depth, speed, and topography. Likewise, tillage-induced soil erosion by non-inversion chisel substantially exceeds primary inversion disk tillage practices by a factor of 2.1. Öttl et al. [51] reported similar results of tillage-induced soil erosion by a factor of 1.3 to 2.1 between a non-inversion chisel tillage and an inversion moldboard tillage under constant tillage depth and speed. The displacement in tillage erosion is sensitive to operational conditions, soil properties, and topography [62]. Table 5 compares this soil displacement and redistribution rate with previously reported values for other tillage experiments and controlling factors, including speed, depth, and slope. These data demonstrate that the soil and macroplastics displacement would be expected to be greater on sloping landscapes than on flat ones.

4.2. Macroplastics fragmentation is driven by inversion disk tillage and plastic size

Inversion disk tillage displaced macroplastic pieces at a shorter distance than non-inversion chisel tillage but also fragmented them.

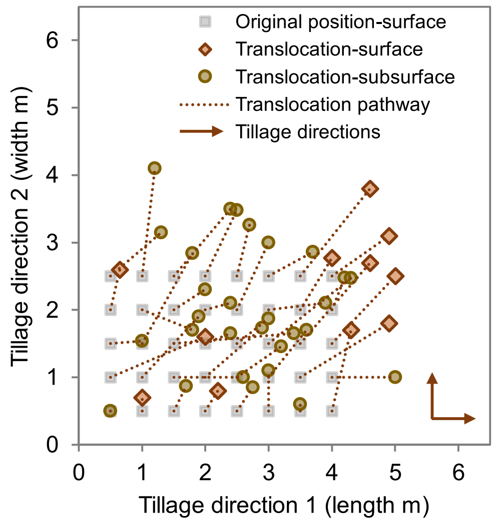


Fig. 6. Translocation of individual (n = 40) RFID-tagged macroplastics (large pieces) from original location after three sets of cross-tillage pass in direction 1 and direction 2 with chisel plow by same tillage speed (4.5 km h^{-1}) and tillage depth (15 cm).

Multiple drivers can explain the fragmentation process, including polymer elasticity, tillage implement shape, abrasion force, or soil conditions. For a given plastic, the stress applied by an inversion disk tillage must exceed the tensile strength and maximum elongation to cause fragmentation of plastic (Fig. 5). Lab studies also reported that increasing the stress applied on pristine LDPE film linearly increased the number of generated plastic fragments (up to 162 μm) [63]. In addition, biological fragmentation (e.g., rotifers) due to grinding stress was also found to be a primary cause of plastic fragmentation in aquatic systems [64]. Moreover, micro-plowing and micro-cutting occurred during abrasion with implement edges, leading to surface modification and fragmentation of macroplastics. It would accelerate with a coarse fraction of soil (i.e., sand or stone) [65] or if macroplastics are embedded and aggregated in soil [66]. Disk tillage inverts soil by cutting with a front set of disk plates, so cut plastic and move soil perpendicular to the tillage direction with a rear set of disk plates (as illustrated [31]). Likewise, implement type including inversion disks (notched, rippled, and plain), mulcher, or rotary-star tiller might also be important for partial to complete fragmentation and distribution of macroplastics in the soil. This could be relevant to managing biodegradable plastic residue in arable land as fragmentation accelerates degradation.

The hypothesis is true that the tillage implement affects redistribution pathways and plastic fragmentation. In horizontal distribution pathways, 80 % of macroplastic pieces were concentrated up to 0.25 m after inversion disk tillage, while they were spread out to 0.50 m after non-inversion chisel tillage (Fig. 3). On the other hand, fragmentation of macroplastic pieces only occurred after inversion disk tillage, which was size-dependent on plastic pieces (Fig. 5 and S7). On average, 41 % (maximum 76 %) of fragmented macroplastic pieces were recovered after the inversion disk tillage (Table 1). Fragmented pieces of macroplastic led to a lower recovery rate in the inversion disk tillage plots, as many fragments were unidentified due to their detachment from macroplastics (Fig. 5d). This could also give practical indications (like marking the different corners of the large pieces) to allow the tracing of fragmented macroplastic pieces in future experiments. Fragments were observed from micro (< 0.5 cm, microplastics) to macro (> 0.5 cm, macroplasitcs) level in sizes (Fig. 5). This indicates that inversion disk tillage increases microplastics abundance in arable land, addition to fragmentation of macroplastics by UV radiation for 17 % of macroplastics redistributed on the soil surface. Secondary microplastics derived from macroplastics are not regulated to reduce plastic pollution [67], which might have distinct and more harmful impacts in terrestrial environments. However, further microscopic and sieved-based analysis would be required for quantitative particle size distribution in future studies for comprehensively understand macroplastics fragmentation induced by inversion tillage shape.

4.3. Implication for tillage and plastic management

The general proposition is that non-inversion tillage (depth <0.25 m) reduces soil erosion and losses of soil organic matter, and farmers practice it widely, even in agro-intensive regions, as a soil conservation practice. This study sheds light on how a non-inversion chisel tillage substantially enhances macroplastics displacement and soil compared to an inversion disk tillage. Likewise, inversion disk tillage leads to the fragmentation of macroplastics into microplastics. Primary inversion disk tillage is always followed by non-inversion chisel tillage. Subsequently, tillage processes can pave a pathway for the widespread plastic pieces. Usually, a tillage event is applied after harvesting, and plastic has already photo-degraded can drive an abundance of microplastic, which is susceptible to transport into different environmental compartments (including atmosphere [68], aquatic systems [69], and vadose zone [70]). Both non-inversion chisel and inversion disk tillage buried the macroplastic in the plow layer; this sink function of soil consequences in a long-term microplastic source. This calls for proper agricultural plastic waste management in extensive plasticulture farmland to avoid substantial environmental risks. Likewise, this challenges the general tillage practices in arable land and encourages a shift from conservation tillage to no-tillage practices. However, this would not be readily possible to shift, especially in plasticulture. Meanwhile, low-intensity tillage would be adopted quickly and might be a promising approach to minimize the widespread macroplastics fragments in soil. On a landscape scale, tillage erosion might reduce crop yield, amplified by climate change, as draught conditions accelerate the tillage intensity and utilization of plastic products [71,72]. In conjunction with the contamination of macroplastics, tillage practice calls for severe concern. It provides another reason to shift from maximizing production (food, feed, and fibre) to sustainable production that seeks to balance productivity with environmental stewardship of the soil resource. Our findings suggest low-intensity tillage or no-tillage practices could reduce plastic fragmentation and distribution. Therefore, the decline in the intensity of tillage and depth would reduce the fragmentation and vertical distribution of macroplastics in the plow layer.

5. Conclusions

This study is, to our knowledge, the first attempt to trace the macroplastics fate during the tillage process by evaluating a low-cost RFID-tagging approach for in-situ utilization. The tagging method is promising for monitoring and assessing macroplastics fate in dynamic systems and the earth's surface processes. The results of this study suggest that macroplastics displacement is comparable to bulk soil displacement. Horizontal and vertical distribution was independent of macroplastic sizes. Preferentially, the tillage process drove the burial of surface macroplastics into the tilled layer, potentially affecting key soil functions and bioturbation processes, and restricting UV radiation exposure of plastics. Tillage-induced macroplastic and soil displacements increased by factors of 2.4 and 2.1, respectively, for non-inversion chisel tillage compared to inversion disk tillage. Meanwhile, inversion disk tillage generated fragmentation of plastic depending upon macroplastic sizes that would increase the abundance of microplastics in arable land. Therefore, fate of macroplastics in arable land depends upon tillage type implement, such as non-inversion tillage modulated plastic redistribution, and inversion tillage modulated fragmentation of plastic. This raises concerns about the effects of burial and fragmentation of macroplastics on soil ecosystems functioning and dynamics, requiring careful evaluation of the overall benefits and risks. Our findings encourage a

Table 5
Summary of the results from this study and tillage implement studies conducted at field scale in different countries with controlling factors to soil tillage erosion.

		Controlling factors					
Study	Location	Implement	Speed (km h^{-1})	Depth (m)	Slope (%)	Displacement (m)	Distribution rate (kg m^{-1})
This study	**Southern Spain**	**Disk**	**4.5**	**0.15**	**0**	**0.17**	**31**
			4.5	0.08	1.7	0.18	4
			9	0.08	1.7	0.31	10
Brož and Hula [73]	Czech Republic	Disk	14	0.08	1.7	0.37	17
			10	0.127	-	0.18	34
Zeng et al.[35]	Canada (lab)	Disk	10	0.063	-	0.13	12
Novara et al.[74]	Italy	Disk	2 - 5	0.15	0 - 17	0.33	-
Marques da Silva et al.[75]	Portugal	Disk	3.5	0.11	18	0.11	137
			5.3	0.28	4 - 32	0.46	90
Tiessen et al.[76]	Costa Rica	Disk	6.4	0.30	6 - 32	0.64	124
This study	**Southern Spain**	**Chisel**	**4.5**	**0.15**	**0**	**0.36**	**65**
Frauenfeld and Klik[77]	Austria	Chisel	8	0.15	5 - 20	0.24	95
Quine et al.[78]	Southeast Spain	Chisel	2.2	0.19	2 - 25	2.30	605
Poesen et al.[79]	Southern Spain	Chisel	2.3	0.16	2 - 41	-	282
Öttl et al.[51]	Northeast Germany	Chisel	7.1	0.25	3.5 - 11.8	-	1037
Govers et al.[49]	Belgium	Chisel	4.5	0.15	5 - 25	0.55	111

shift from conservation tillage to no-tillage or less intensive tillage practices that would have the additional benefit of reducing widespread plastic fragmentation and soil disturbance. However, perspective work would be needed to track plastic fate over time, across multiple seasons and tillage operations to help better understand the pathway from macro to microplastics. Moreover, other tillage implements should also be considered in the analysis of the impact of tillage on the temporal evolution of plastic redistribution and fragmentation in arable land.

Environmental implications

Tillage is a worldwide practice in crop production, and plastic has become an integral part of cropping systems. Our study highlights that disk tillage-induced fragmentation of plastic would lead to an abundance of microplastic in soils. Meanwhile, tillage can cause widespread and preferentially buried plastic. Consequently, plastic would be less exposed to UV light, affecting soil ecosystem services, including the bioturbation process and soil key functioning. We recommend adopting a no-tillage system or a lower tillage intensity to lessen the harm to plastic-contaminated soil.

Funding

European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie SOPLAS project (GA 955334). Horizon 2020 TUdi project (GA 101000224). Open Access cost covered by CSIC agreement with Elsevier.

CRediT authorship contribution statement

Ahsan Maqbool: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Gema Guzmán:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Peter Fiener:** Writing – review & editing, Resources, Funding acquisition. **Florian Wilken:** Writing – review & editing, Resources, Methodology. **María-Auxiliadora Soriano:** Writing – review & editing, Validation, Supervision. **José Alfonso Gómez:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data is provided in the supplementary file.

Acknowledgment

This research was conducted within the SOPLAS project, financed by the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie (GA 955334), with support also from the Horizon 2020-funded TUdi project (GA 101000224). Technicians' (Azahara Ramos, Clemente Trujillo, Manuel Redondo, and Francisco Mendez) support was greatly acknowledged during the field experiment. Feedback from four anonymous reviewers was also greatly appreciated to improve the content of the study.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2024.135318.

References

[1] MacLeod, M., Arp, H.P.H., Tekman, M.B., Jahnke, A., 2021. The global threat from plastic pollution. Science 373, 61–65. https://doi.org/10.1126/science.abg5433.
[2] Büks, F., Kaupenjohann, M., 2020. Global concentrations of microplastics in soils – a review. SOIL 6, 649–662. https://doi.org/10.5194/soil-6-649-2020.
[3] Yu, Y., Flury, M., 2021. Current understanding of subsurface transport of micro- and nanoplastics in soil. Vadose Zone J 20, 1–14. https://doi.org/10.1002/vzj2.20108.
[4] Shafea, L., Yap, J., Beriot, N., Felde, V.J.M.N.L., Okoffo, E.D., Enyoh, C.E., et al., 2023. Microplastics in agroecosystems: A review of effects on soil biota and key soil functions. J Plant Nutr Soil Sci 186, 5–22. https://doi.org/10.1002/jpln.202200136.
[5] Maity, S., Guchhait, R., Sarkar, M.B., Pramanick, K., 2022. Occurrence and distribution of micro/nanoplastics in soils and their phytotoxic effects: a review. Plant Cell Environ 45, 1011–1028. https://doi.org/10.1111/pce.14248.
[6] Maqbool, A., Soriano, M.-A., Gómez, J.A., 2023. Macro- and micro-plastics change soil physical properties: a systematic review. Environ Res Lett 18, 123002. https://doi.org/10.1088/1748-9326/ad0a1a.
[7] Le Juge, C., Grassl, B., Allan, I.J., Gigault, J., 2023. Identification of polystyrene nanoplastics from natural organic matter in complex environmental matrices by pyrolysis–gas chromatography–mass spectrometry. Anal Bioanal Chem 415, 2999–3006. https://doi.org/10.1007/s00216-023-04609-7.
[8] Heinze, W.M., Mitrano, D.M., Lahive, E., Koestel, J., Cornelis, G., 2021. Nanoplastic Transport in Soil via Bioturbation by Lumbricus terrestris. Environ Sci Technol 55, 16423–16433. https://doi.org/10.1021/acs.est.1c05614.
[9] Radford, F., Zapata-Restrepo, L.M., Horton, A.A., Hudson, M.D., Shaw, P.J., Williams, I.D., 2021. Developing a systematic method for extraction of microplastics in soils. Anal Methods 13, 1695–1705. https://doi.org/10.1039/D0AY02086A.
[10] Laermanns, H., Lehmann, M., Klee, M., J. Löder, M.G., Gekle, S., Bogner, C., 2021. Tracing the horizontal transport of microplastics on rough surfaces. Micro Nanoplastics 1, 11. https://doi.org/10.1186/s43591-021-00010-2.

[11] Veettil, B.K., Van, D.D., Quang, N.X., Hoai, P.N., 2023. Remote sensing of plastic-covered greenhouses and plastic-mulched farmlands: current trends and future perspectives. Land Degrad Dev 34, 591–609. https://doi.org/10.1002/ldr.4497.
[12] Biermann, L., Clewley, D., Martinez-Vicente, V., Topouzelis, K., 2020. Finding plastic patches in coastal waters using optical satellite data. Sci Rep 10. https://doi.org/10.1038/s41598-020-62298-z.
[13] G. Jakovljević, M. Govedarica, F. Alvarez Taboada, G. Jakovljević Bosnia, F. Álvarez Taboada, Mapping plastic based on multispectral UAV images, in: Volunteering for the Future - Geospatial Excellence for a Better Living FIG Congress, Warsaw, 2022: p. 11715.
[14] Pietz, O., Augenstein, M., Georgakakos, C.B., Singh, K., McDonald, M., Walter, M. T., 2021. Macroplastic accumulation in roadside ditches of New York State's Finger Lakes region (USA) across land uses and the COVID-19 pandemic. J Environ Manag 298, 113524. https://doi.org/10.1016/j.jenvman.2021.113524.
[15] D.Cindy Kawecki, Modelling the Emission of Micro-and Macroplastics to the Environment, Doctoral, ETH Zurich, 2019. ⟨https://www.research-collection.ethz.ch/bitstream/handle/20.500.11850/394144/Abstract_26515.pdf?sequence=12⟩ (accessed January 31, 2024).
[16] Cyvin, J.B., Ervik, H., Kveberg, A.A., Hellevik, C., 2021. Macroplastic in soil and peat. A case study from the remote islands of Mausund and Froan landscape conservation area, Norway; implications for coastal cleanups and biodiversity. Sci Total Environ 787, 147547. https://doi.org/10.1016/j.scitotenv.2021.147547.
[17] Treilles, R., Gasperi, J., Saad, M., Tramoy, R., Breton, J., Rabier, A., et al., 2021. Abundance, composition and fluxes of plastic debris and other macrolitter in urban runoff in a suburban catchment of Greater Paris. Water Res 192, 116847. https://doi.org/10.1016/j.watres.2021.116847.
[18] Hauk, R., van Emmerik, T.H.M., van der Ploeg, M., de Winter, W., Boonstra, M., Löhr, A.J., et al., 2023. Macroplastic deposition and flushing in the Meuse river following the July 2021 European floods. Environ Res Lett 18. https://doi.org/10.1088/1748-9326/ad0768.
[19] H.F. Castellón Petrovich, The stakes of announced growth Global plasticulture and the 2018 XXI CIPA Congress SPÉCIAL CONGRÈS, n.d. ⟨www.cipa-congress.com⟩.
[20] Stefano, N., Pleissner, D., 2022. Quantification and analysis of surface macroplastic contamination on arable areas. J Soils Sediment 22, 757–768. https://doi.org/10.1007/s11368-021-03114-7.
[21] Weber, C.J., Santowski, A., Chifflard, P., 2022. Investigating the dispersal of macro- and microplastics on agricultural fields 30 years after sewage sludge application. Sci Rep 12, 6401. https://doi.org/10.1038/s41598-022-10294-w.
[22] Le, V.R., Nguyen, M.K., Nguyen, H.L., Lin, C., Rakib, M.R.J., Thai, V.A., et al., 2023. Organic composts as A vehicle for the entry of microplastics into the environment: a comprehensive review. Sci Total Environ 892, 164758. https://doi.org/10.1016/J.SCITOTENV.2023.164758.
[23] Piehl, S., Leibner, A., Löder, M.G.J., Dris, R., Bogner, C., Laforsch, C., 2018. Identification and quantification of macro- and microplastics on an agricultural farmland. Sci Rep 8, 17950. https://doi.org/10.1038/s41598-018-36172-y.
[24] Liu, E.K., He, W.Q., Yan, C.R., 2014. White revolution' to 'white pollution'—agricultural plastic film mulch in China. Environ Res Lett 9, 091001. https://doi.org/10.1088/1748-9326/9/9/091001.
[25] Gündoğdu, R., Önder, D., Gündoğdu, S., Gwinnett, C., 2022. Plastics derived from disposable greenhouse plastic films and irrigation pipes in agricultural soils: a case study from Turkey. Environ Sci Pollut Res 29, 87706–87716. https://doi.org/10.1007/s11356-022-21911-6.
[26] Muise, I., Adams, M., Côté, R., Price, G.W., 2016. Attitudes to the recovery and recycling of agricultural plastics waste: a case study of Nova Scotia, Canada. Resour Conserv Recycl 109, 137–145. https://doi.org/10.1016/J.RESCONREC.2016.02.011.
[27] McKay, O., Pold, G., Martin, P., Sistla, S., 2022. Macroplastic fragment contamination of agricultural soils supports a distinct microbial hotspot. Front Environ Sci 10. https://doi.org/10.3389/fenvs.2022.838455.
[28] Guo, Y., Yin, W., Chai, Q., Yu, A., Zhao, C., Fan, Z., et al., 2021. No tillage and previous residual plastic mulching with reduced water and nitrogen supply reduces soil carbon emission and enhances productivity of following wheat in arid irrigation areas. Field Crops Res 262, 108028. https://doi.org/10.1016/J.FCR.2020.108028.
[29] Wen, Y., Li, H., Li, W., Gu, Z., Wang, Z., 2022. Responses of infiltration and evaporation to amounts and distribution characteristics of the residual plastic films within agricultural soil. Irrig Sci 40, 309–320. https://doi.org/10.1007/s00271-022-00774-2.
[30] Wen, Y., Liu, J., Zhang, J., Li, W., Ayantobo, O.O., Wang, Z., 2023. Effects of macro-plastics on soil hydrothermal environment, cotton yield, and fiber quality under mulched drip irrigation in the arid region of Northwest China. Field Crops Res 302, 109060. https://doi.org/10.1016/J.FCR.2023.109060.
[31] Hu, Q., Li, X., Gonçalves, J.M., Shi, H., Tian, T., Chen, N., 2020. Effects of residual plastic-film mulch on field corn growth and productivity. Sci Total Environ 729, 138901. https://doi.org/10.1016/J.SCITOTENV.2020.138901.
[32] Rodriguez, A.K., Mansoor, B., Ayoub, G., Colin, X., Benzerga, A.A., 2020. Effect of UV-aging on the mechanical and fracture behavior of low density polyethylene. Polym Degrad Stab 180, 109185. https://doi.org/10.1016/j.polymdegradstab.2020.109185.
[33] Weinstein, J.E., Crocker, B.K., Gray, A.D., 2016. From macroplastic to microplastic: degradation of high-density polyethylene, polypropylene, and polystyrene in a salt marsh habitat. Environ Toxicol Chem 35, 1632–1640. https://doi.org/10.1002/etc.3432.
[34] Song, Y.K., Hong, S.H., Jang, M., Han, G.M., Jung, S.W., Shim, W.J., 2017. Combined effects of UV exposure duration and mechanical abrasion on microplastic fragmentation by polymer type. Environ Sci Technol 51, 4368–4376. https://doi.org/10.1021/acs.est.6b06155.
[35] Zeng, Z., Thoms, D., Chen, Y., Ma, X., 2021. Comparison of soil and corn residue cutting performance of different discs used for vertical tillage. Sci Rep 11. https://doi.org/10.1038/s41598-021-82270-9.
[36] Marques da Silva, J.R., Alexandre, C., 2004. Soil carbonation processes as evidence of tillage-induced erosion. Soil Tillage Res 78, 217–224. https://doi.org/10.1016/j.still.2004.02.008.
[37] Summerton, L., Greener, M., Patterson, D., Brown, C.D., 2023. Effects of soil redistribution by tillage on subsequent transport of pesticide to subsurface drains. Pest Manag Sci 79, 616–626. https://doi.org/10.1002/ps.7229.
[38] Fechine, G.J.M., Rosa, D.S., Rezende, M.E., Demarquette, N.R., 2009. Effect of UV radiation and pro-oxidant on PP biodegradability. Polym Eng Sci 49, 123–128. https://doi.org/10.1002/pen.21230.
[39] Fiener, P., Wilken, F., Aldana-Jague, E., Deumlich, D., Gómez, J.A., Guzmán, G., et al., 2018. Uncertainties in assessing tillage erosion – How appropriate are our measuring techniques? Geomorphology 304, 214–225. https://doi.org/10.1016/j.geomorph.2017.12.031.
[40] Guzmán, G., Barrón, V., Gómez, J.A., 2010. Evaluation of magnetic iron oxides as sediment tracers in water erosion experiments. Catena (Amst) 82, 126–133. https://doi.org/10.1016/J.CATENA.2010.05.011.
[41] Zhang, J.H., Su, Z.A., Nie, X.J., 2009. An investigation of soil translocation and erosion by conservation hoeing tillage on steep lands using a magnetic tracer. Soil Tillage Res 105, 177–183. https://doi.org/10.1016/J.STILL.2009.07.006.
[42] Zumr, D., Li, T., Gómez, J.A., Guzmán, G., 2023. Modeling the response of a field probe for nondestructive measurements of the magnetic susceptibility of soils. Soil Sci Soc Am J 87, 1263–1274. https://doi.org/10.1002/saj2.20578.
[43] Le Breton, M., Liébault, F., Baillet, L., Charléty, A., Larose, É., Tedjini, S., 2022. Dense and long-term monitoring of earth surface processes with passive RFID — a review. Earth Sci Rev 234, 104225. https://doi.org/10.1016/j.earscirev.2022.104225.
[44] Gibbons, W.J., Andrews, K.M., Tagging, P.I.T., 2004. Simple technology at its best. Bioscience 54, 447–454. https://doi.org/10.1641/0006-3568(2004)054[0447:PTSTAI]2.0.CO;2.
[45] Sa'adu, I., Farsang, A., 2023. Plastic contamination in agricultural soils: a review. Environ Sci Eur 35, 13. https://doi.org/10.1186/s12302-023-00720-9.
[46] IFAPA RIA, Red de Información Agroclimática de Andalucía, (2024). ⟨https://www.juntadeandalucia.es/agriculturaypesca/ifapa/riaweb/web/estacion/14/6⟩ (accessed June 19, 2024).
[47] Guzmán, G., Laguna, A., Cañasveras, J.C., Boulal, H., Barrón, V., Gómez-Macpherson, H., et al., 2015. Study of sediment movement in an irrigated maize–cotton system combining rainfall simulations, sediment tracers and soil erosion models. J Hydrol (Amst 524, 227–242. https://doi.org/10.1016/J.JHYDROL.2015.02.033.
[48] Guzmán, G., Vanderlinden, K., Giráldez, J.V., Gómez, J.A., 2013. Assessment of spatial variability in water erosion rates in an olive orchard at plot scale using a magnetic iron oxide tracer. Soil Sci Soc Am J 77, 350–361. https://doi.org/10.2136/sssaj2012.0219.
[49] GOVERS, G., VANDAELE, K., DESMET, P., POESEN, J., BUNTE, K., 1994. The role of tillage in soil redistribution on hillslopes. Eur J Soil Sci 45, 469–478. https://doi.org/10.1111/j.1365-2389.1994.tb00532.x.
[50] Van Oost, K., Govers, G., Van Muysen, W., Quine, T.A., 2000. Modeling translocation and dispersion of soil constituents by tillage on sloping land. Soil Sci Soc Am J 64, 1733–1739. https://doi.org/10.2136/sssaj2000.6451733x.
[51] Öttl, L.K., Wilken, F., Hupfer, A., Sommer, M., Fiener, P., 2022. Non-inversion conservation tillage as an underestimated driver of tillage erosion. Sci Rep 12, 20704. https://doi.org/10.1038/s41598-022-24749-7.
[52] Wilken, F., Sommer, M., Van Oost, K., Bens, O., Fiener, P., 2017. Process-oriented modelling to identify main drivers of erosion-induced carbon fluxes. SOIL 3, 83–94. https://doi.org/10.5194/soil-3-83-2017.
[53] Rehm, R., Fiener, P., 2024. Model-based analysis of erosion-induced microplastic delivery from arable land to the stream network of a mesoscale catchment. SOIL 10, 211–230. https://doi.org/10.5194/soil-10-211-2024.
[54] Krehl, A., Schöllkopf, U., Májeková, M., Tielbörger, K., Tomiolo, S., 2022. Effects of plastic fragments on plant performance are mediated by soil properties and drought. Sci Rep 12. https://doi.org/10.1038/s41598-022-22270-5.
[55] Gómez, J.A., Vanderlinden, K., Nearing, M.A., 2005. Spatial variability of surface roughness and hydraulic conductivity after disk tillage: implications for runoff variability. J Hydrol 311, 143–156. https://doi.org/10.1016/j.jhydrol.2005.01.014.
[56] Ruiz, S., Or, D., Schymanski, S.J., 2015. Soil penetration by earthworms and plant roots—mechanical energetics of bioturbation of compacted soils. PLoS One 10, e0128914. https://doi.org/10.1371/journal.pone.0128914.
[57] Sun, J., Zheng, H., Xiang, H., Fan, J., Jiang, H., 2022. The surface degradation and release of microplastics from plastic films studied by UV radiation and mechanical abrasion. Sci Total Environ 838, 156369. https://doi.org/10.1016/J.SCITOTENV.2022.156369.
[58] Nishide, H., Toyota, K., Kimura, M., 1999. Effects of soil temperature and anaerobiosis on degradation of biodegradable plastics in soil and their degrading microorganisms. Soil Sci Plant Nutr 45, 963–972. https://doi.org/10.1080/00380768.1999.10414346.
[59] Chinaglia, S., Esposito, E., Tosin, M., Pecchiari, M., Degli Innocenti, F., 2024. Biodegradation of plastics in soil: the effect of water content. Polym Degrad Stab 222. https://doi.org/10.1016/j.polymdegradstab.2024.110691.

[60] Andrady, A.L., Heikkilä, A.M., Pandey, K.K., Bruckman, L.S., White, C.C., Zhu, M., et al., 2023. Effects of UV radiation on natural and synthetic materials. Photochem Photobiol Sci 22, 1177–1202. https://doi.org/10.1007/s43630-023-00377-6.
[61] Koelmans, A.A., Redondo-Hasselerharm, P.E., Nor, N.H.M., de Ruijter, V.N., Mintenig, S.M., Kooi, M., 2022. Risk assessment of microplastic particles. Nat Rev Mater 7, 138–152. https://doi.org/10.1038/s41578-021-00411-y.
[62] Van Oost, K., Govers, G., De Alba, S., Quine, T.A., 2006. Tillage erosion: a review of controlling factors and implications for soil quality. Prog Phys Geogr: Earth Environ 30, 443–466. https://doi.org/10.1191/0309133306pp487ra.
[63] Bhattacharjee, L., Jazaei, F., Salehi, M., 2023. Insights into the mechanism of plastics' fragmentation under abrasive mechanical forces: an implication for agricultural soil health. Clean (Weinh 51. https://doi.org/10.1002/clen.202200395.
[64] Zhao, J., Lan, R., Wang, Z., Su, W., Song, D., Xue, R., et al., 2023. Microplastic fragmentation by rotifers in aquatic ecosystems contributes to global nanoplastic pollution. Nat Nanotechnol. https://doi.org/10.1038/s41565-023-01534-9.
[65] A.C. Cugler Moreira, F. Wilken, M. Braun, et al. From intentionally used plastic films to soil microplastic contamination, in: EGU General Assembly Conference Abstracts, 2023: p. EGU-1899. https://doi.org/10.5194/egusphere-egu23–1899.
[66] Zhao, Z.Y., Wang, P.Y., Wang, Y.B., Zhou, R., Koskei, K., Munyasya, A.N., et al., 2021. Fate of plastic film residues in agro-ecosystem and its effects on aggregate-associated soil carbon and nitrogen stocks. J Hazard Mater 416, 125954. https://doi.org/10.1016/J.JHAZMAT.2021.125954.
[67] Mitrano, D.M., Wohlleben, W., 2020. Microplastic regulation should be more precise to incentivize both innovation and environmental safety. Nat Commun 11, 5324. https://doi.org/10.1038/s41467-020-19069-1.
[68] Rezaei, M., Abbasi, S., Pourmahmood, H., Oleszczuk, P., Ritsema, C., Turner, A., 2022. Microplastics in agricultural soils from a semi-arid region and their transport by wind erosion. Environ Res 212, 113213. https://doi.org/10.1016/J.ENVRES.2022.113213.
[69] Rehm, R., Zeyer, T., Schmidt, A., Fiener, P., 2021. Soil erosion as transport pathway of microplastic from agriculture soils to aquatic ecosystems. Sci Total Environ 795, 148774. https://doi.org/10.1016/j.scitotenv.2021.148774.
[70] Park, S., Kim, I., Jeon, W.H., Moon, H.S., 2023. Exploring the vertical transport of microplastics in subsurface environments: Lab-scale experiments and field evidence. J Contam Hydrol 257, 104215. https://doi.org/10.1016/J.JCONHYD.2023.104215.
[71] Quinton, J.N., Öttl, L.K., Fiener, P., 2022. Tillage exacerbates the vulnerability of cereal crops to drought. Nat Food 3, 472–479. https://doi.org/10.1038/s43016-022-00533-8.
[72] Gao, H., Yan, C., Liu, Q., Ding, W., Chen, B., Li, Z., 2019. Effects of plastic mulching and plastic residue on agricultural production: a meta-analysis. Sci Total Environ 651, 484–492. https://doi.org/10.1016/J.SCITOTENV.2018.09.105.
[73] Brož, P., Hula, J., 2023. Influence of primary tillage on the displacement of soil particles. Res Agric Eng 69, 101–106. https://doi.org/10.17221/76/2022-RAE.
[74] Novara, A., Novara, A., Comparetti, A., Santoro, A., Cerdà, A., Rodrigo-Comino, J., et al., 2022. Effect of standard disk plough on soil translocation in sloping sicilian vineyards. Land 11. https://doi.org/10.3390/land11020148.
[75] Marques Da Silva, J.R., Soares, J.M.C.N., Karlen, D.L., 2004. Implement and soil condition effects on tillage-induced erosion. Soil Tillage Res 78, 207–216. https://doi.org/10.1016/j.still.2004.02.009.
[76] Tiessen, K.H.D., Sancho, F.M., Lobb, D.A., Mehuys, G.R., 2010. Assessment of tillage translocation and erosion by the disk plow on steepland Andisols in Costa Rica. J Soil Water Conserv 65, 316–328. https://doi.org/10.2489/jswc.65.5.316.
[77] B. Frauenfeld, A. Klik, Soil Redistribution Affected by Tillage in Lower Austria Farmland, in: 12th ISCO Conference, 2002: pp. 491–496.
[78] Quine, T.A., Govers, G., Poesen, J., Walling, D., van Wesemael, B., Martinez-Fernandez, J., 1999. Fine-earth translocation by tillage in stony soils in the Guadalentin, south-east Spain: an investigation using caesium-134. Soil Tillage Res 51, 279–301. https://doi.org/10.1016/S0167-1987(99)00043-4.
[79] Poesen, J., van Wesemael, B., Govers aTb, G., Desmet, P., Vandaele, K., Quine, T., et al., 1997. Patterns of rock fragment cover generated by tillage erosion. Geomorphology 18, 183–197.