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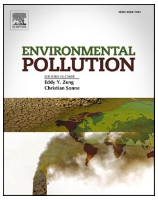

Microplastic appraisal of soil, water, ditch sediment and airborne dust: The case of agricultural systems☆

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ABSTRACT

Although microplastic pollution jeopardizes both terrestrial and aquatic ecosystems, the movement of plastic particles through terrestrial environments is still poorly understood. Agricultural soils exposed to different managements are important sites of storage and dispersal of microplastics. This study aimed to identify the abundance, distribution, and type of microplastics present in agricultural soils, water, airborne dust, and ditch sediments. Soil health was also assessed using soil macroinvertebrate abundance and diversity. Sixteen fields were evaluated, 6 of which had been exposed to more than 5 years of compost application, 5 were exposed to at least 5 years of plastic mulch use, and 5 were not exposed to any specific management (controls) within the last 5 years. We also evaluated the spread of microplastics from the farms into nearby water bodies and airborne dust. We found 11 types of microplastics in soil, among which Light Density Polyethylene (LDPE) and Light Density Polyethylene covered with pro-oxidant additives (PAC) were the most abundant. The highest concentrations of plastics were found in soils exposed to plastic mulch management (128.7 ± 320 MPs.g-^{1} soil and 224.84 ± 488 MPs.g-^{1} soil, respectively) and the particles measured from 50 to 150 μm. Nine types of microplastics were found in water, with the highest concentrations observed in systems exposed to compost. Farms applying compost had higher LDPE and PAC concentrations in ditch sediments as compared to control and mulch systems; a significant correlation between soil polypropylene (PP) microplastics with ditch sediment microplastics (r^2 0.7 $p < 0.05$) was found. LDPE, PAC, PE (Polyethylene), and PP were the most abundant microplastics in airborne dust. Soil invertebrates were scarce in the systems using plastic mulch. A cocktail of microplastics was found in all assessed matrices.

1. Introduction

The problems caused by microplastics in terrestrial systems are complex. In recent years, scientists have described how agricultural soils exposed to fertilizers (compost or sludge) or plastic mulch are contaminated with microplastics (van Schothorst et al., 2021, van den Berg et al., 2020; Corradini et al., 2019, Beriot et al., 2021). Unfortunately, this exposure has caused agricultural soils to become sources and sinks of microplastics. Microplastics slowly move from the soil surface towards deeper layers where they accumulate and eventually spread further into the environment with the help of water and animals (Bullard et al., 2021; Beriot et al., 2021; Huerta Lwanga et al., 2022).

Soil conditions are vulnerable to agricultural practices, and soil health is jeopardized when these practices introduce microplastics into the soil environment. Microplastics are known to be harmful to soil biota (reduced biomass, increased mortality (Huerta Lwanga et al., 2016),

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Acronyms: MP, Microplastics; PP, Polypropylene; LDPE, Light density polyethylene; PE, Polyethylene; PES, Polyester; PVC, Polyvinyl chloride; PS, Polystyrene; PACs, Pro-oxidant additive containing plastics; Polyethylene Terephthalate, PET; PMMA, Polymethylmethacrylate; PU, Polyurethane.

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affecting several soil functions and soil properties (e.g., infiltration, carbon resources, soil aggregates (de Souza Machado et al., 2019), which in turn affect soil microbial habitats (Zhang et al., 2021). These changes then affect energy fluxes and food webs just like we see in aquatic ecosystems (Nava and Leoni, 2021). Therefore, knowledge concerning the concentration of microplastics in soils under different agricultural managements is crucial.

Microplastics in the terrestrial environment affect the ecosystem, communities, populations, and individuals, as well as enzyme levels (Windsor et al., 2019). Moreover, soil particles are not static: once the soil matrix is polluted with microplastics, these particles will likely pollute surrounding water bodies. Microplastic particles may also be released into the air by either wind erosion or tillage activity in the fields, causing secondary pollution as the particles fall back to the Earth's surface.

The aim of this study was to determine the concentration and type of microplastics present in soils from agricultural systems under different managements and to assess the resulting concentrations of microplastics in the surrounding water bodies, ditch sediments and airborne dust. We expect to find high concentrations of microplastics in water and sediments in those systems where microplastic content in soils is also high. Furthermore, soil health assessments based on soil macroinvertebrate diversity and abundance were also carried out to compare the situations among the selected agricultural systems. To study these topics, measurements were performed on soil and water samples collected from different farms located in a sandy region in the Netherlands.

2. Material and methods

2.1. Farm selection

The study was carried out in the southern part of the Netherlands (Fig. S1), in the provinces of Brabant and Zeeland. Farms were selected according to the duration of plastic mulch and compost application. For our study, only farms with at least 5 consecutive years of plastic mulch or compost application were selected. All farms were located close to each other to avoid extreme differences in soil conditions, such as soil texture and organic matter content (Table 1). 80% of the selected farms cultivated sugar beets (*Beta vulgaris*) as the main crop in their rotations. The remaining 20% of farms grew carrots (*Daucus carota*), asparagus (*Asparagus officinalis*), pumpkins (*Curcubita moschata*), apples (*Malus domestica*), and pears (*Pyrus pyrifolia*) as the main crops.

Table 1

Farm characterizations. *Crop types at the sampling moment. T: Treatment, SOM: soil organic matter, Tex: Texture, S: sandy, C: > 5 years under control (no use of compost or plastic mulch), PM: > 5 years under plastic mulch, COM: > 5 years with compost application.

T	Farms & no. fields	Crop*	SOM (w %)	Tex
C	F1(1)	*Triticum aestivum*	2.4 ± 0.6	S
C	F3(1)	*Daucus carrota*	3.3 ± 0.4	S
C	F2(1)	*Curcubita moschata*	3.3 ± 0.2	S
C	F4(1)	*Curcubita moschata*	4.3 ± 0.13	S
C	F9(1)	*Beta vulgaris*	4.5 ± 0.3	S
PM	F2(2)	*Asparagus officinalis, Foeniculum vulgaris*	3.5 ± 0.2 3.4 ± 0.3	S S
PM	F4(2)	*Beta vulgaris*	4.5 ± 0.1, 4.2 ± 0.4	S S
PM	F6(1)	*Beta vulgaris*	2.4 ± 0.2	S
COM	F5(1)	*Malus domestica, Pyrus pyrifolia*	8.1 ± 1.9	S
COM	F7(2)	*Beta vulgaris*	4.3 ± 0.0 4.0 ± 0.3	S S S
COM	F8(2)	*Beta vulgaris*	3.4 ± 0.4 4.0 ± 0.1	S S
COM	F10(1)	*Zea mays*	5.2 ± 0.09	S

2.2. Experimental design

The experimental design included 3 treatments: 1) plastic mulch use for more than 5 years, 2) compost application for more than 5 years, and 3) no plastic or compost application in the last 5 years (the control). Five fields (replicates) were assessed for each treatment (Table 1). In order to guarantee farmer anonymity, no farm coordinates have been presented (Fig. S1).

2.3. Sample collection

2.3.1. Soil, water and ditch sediment samples

Soil, water, and ditch sediment samples were collected at the beginning of the growing season (March–April). Macroplastics (>5 mm) and indicators of soil quality, soil macroinvertebrate abundance, and biomass were assessed visually in soil using the ISO/TSBF protocol (Lavelle et al., 2022; Anderson & Ingram, 1993) consisting of 25 × 25 × 30 cm soil monoliths. Soil macroinvertebrate diversity was determined using the Shannon-Wiener index (Spellerberg, 2008).

Three 100 g topsoil samples were randomly collected per field at a depth of 0–30 cm with an auger. Using glass containers and a lever, three additional sediment samples were randomly collected from surrounding ditches and three water samples from water bodies, such as canals or ditches, surrounding the crops. Water samples were taken in spring and autumn when the water volume was expected to be at its peak in the agricultural channels.

2.3.2. Airborne dust samples

Soil samples from two farms exposed to high compost and plastic mulch applications (Farm 4 and Farm 5) were transported to the wind tunnel of the Department of Earth and Environmental Science, KU Leuven, Belgium. Placed on an experimental tray, the samples were then subjected to wind erosion. The wind-eroded sediment was collected at various distances downwind from the tray so that different size fractions could be sampled. We also sampled the residue from the particles that were blown away. For a description of the experimental procedure in the wind tunnel, see Bento et al. (2017).

2.4. Microplastic extraction

Soil, ditch sediment, and water samples were covered and transported to the Soil Physics and Land Management laboratory, Wageningen University, the Netherlands. Soil and ditch sediment samples were dried at <40 °C. The extraction procedure was adapted from the method used by Corradini et al. (2019) (Annex, Figs. S2a, S2b, S2c), and included two digestion steps using HCl followed by filtration in ethanol and subsequent digestion with H_20_2, and finally, extraction with NaH_2P0_4. All details are described in the supplementary materials. Once the microplastics were extracted from the different matrices (soil, ditch sediment, water, or airborne sediment), they were further analysed using a Laser Direct Infrared Imaging system (LDIR), Agilent, Wageningen, The Netherlands. The diameter, area, perimeter and solidity of all measured microplastics were also determined by the LDIR. Microplastic recovery rate after extraction was 77–98% (Corradini et al., 2019).

2.5. Microplastic standardization or uniformization calculation

To better understand the relationship between the number of microplastic particles in soil and the number found in ditch sediment and water samples for each treatment, standardization ratios were calculated using equations (1) and (2) below, modified from Rehm et al. (2021):

$$Std\ ratio\ MPsed \Big/ soil = \frac{100\ MPs\ soil(\text{ɱ}TMPsed)}{\text{ɱ}TMPsoil} \tag{1}$$

$$Std\ ratio\ MPwat \Big/ soil = \frac{100\ MPs\ soil(\text{ɱ}TMPwat)}{\text{ɱ}TMPsoil} \tag{2}$$

where Std ratio MP sed/soil is the standardization ratio of microplastics in ditch sediment relative to microplastics in soil, 100 MPs soil is 100 microplastic particles in soil, ɱTMPsed is the content mean of microplastics found in the ditch sediments, and ɱTMPsoil is the content mean of microplastics found in the soil. STd ratio MPwat/soil is the standardization ratio of microplastics in water relative to microplastics in soil, and ɱTMPwat is the content mean of microplastics found in water.

2.6. Risk assessment: correlation of microplastics in different matrices

The risk assessment connected to the effect of microplastics on the environment was calculated using the correlation between the concentration of microplastics in each studied matrix (soil, water, ditch sediment, and airborne dust). Therefore, a correlation matrix was constructed with the concentration of microplastics in soil, water, ditch sediment and airborne dust in each of the two systems (system with compost application and system under plastic mulch, Fig. S2).

2.7. Accumulation of microplastics through the food chain of soil invertebrates

The accumulation or potential accumulation of microplastics along the food chain of soil invertebrates was estimated by assessing (1) the concentration and number of different microplastics in the soil and (2) the number and type of soil macroinvertebrates:

$$AcMpr = In\ (MPst^{*}(EWD^{*}H))$$

where *AcMpr* is the risk of microplastic accumulation or transport along the soil food chain, *MPst* is the concentration of microplastics multiplied by the number of different microplastic types found in the respective soil sample, *EWD* is the number of earthworms found per m^2 in the respective sample, and H is the Shannon index of the macroinvertebrates found on the respective farm.

2.8. Statistical analysis

Data from the different matrices (soil, ditch sediment, water, airborne dust, and MP accumulation in soil food chain) was analysed with one-way ANOVA and a correlation matrix, according to statistical assumptions (normal distribution, homogeneity of variance). If these assumptions were not met, a non-parametric analysis was conducted using STATISTICA software. A principal component analysis based on correlations was performed with the concentration of microplastics per type of plastic in the soil matrix. In addition, a canonical analysis was developed with microplastic characteristics from soil microplastics and ditch sediment microplastics using CANOCO software.

3. Results

3.1. Macroplastics

We observed a large variety of macroplastics from chunks of plastic mulches to individual plastic fibres (Fig. S4). Macroplastics were mainly composed of PE or PVC. The size of the macroplastics ranged from 1 cm to 15 cm and the main colours were black, grey, green and no colour (Fig. S4).

3.1.1. Microplastics in soils

Eleven types of microplastics (between 1 μm and 5 mm) were found: Bio Mulch, LDPE mulch, PAC mulch (also polyethylene but with oxidative products, which has another spectrum), PE (mainly from packaging), PET, PMMA, PP, PS, PU, PVC and synthetic rubber (Table 2). From all the soil samples, 97 ± 5% of the total microplastics were petroleum-based plastics, and 2.7 ± 5% were bio-based plastics. Considering all the soil samples, the most abundant plastic particles derived from LDPE mulch (128.7 ± 320 MPs.g^{-1}soil) and PAC mulch (224.84 ± 487.6 MP g^{-1} soil, Table 2). Microplastic colours were similar to those observed for macroplastics (Fig. S4).

The highest concentrations of microplastics were observed in fields with mulch use (Fig. 1a), and the most abundant size of those microplastics was between 50 and 150 μm (Fig. 1b). PE, PMMA, and PS were mainly present in the soil samples where compost was applied, whereas PP and PAC were present in soils exposed to plastic mulch (Fig. S5).

3.2. Microplastics in soils for each agricultural field

The quantity of microplastics in agricultural sites varied according to the treatment used. The highest content was found in soils exposed to plastic mulch, with the highest content per field reaching 1109 MP g^{-1} of soil (Farm 2, Table S1) and the lowest content per field reaching 67.34 MP g^{-1} (Farm 6, Table S1). The highest microplastic content measured in soils with compost application was 890.2 MP g^{-1} of soil per field. Soils from the control treatment clearly had the lowest quantity of microplastics per field. Four fields had a mean quantity of 40 MP g^{-1} of soil, while one control field measured 342 MP g^{-1} of soil (Table S1).

3.3. Microplastics in water

Nine different types of plastic residues were found in water samples. In spring, the most abundant residue was PAC mulch (Fig. S6), present in all studied samples. The water in the ditches from fields where compost was applied in the last 5 years had more plastic particles than the water from other treatments, and the most abundant plastic was PAC. In autumn, the diversity of microplastics was lower than in spring (Table S2), but the concentration was higher near fields where compost was applied (11 ± 4.7 particles per litre of water, Table S3). Here, the most abundant plastic types were LDPE mulch and PAC, in black, grey and white.

3.4. Microplastics in ditch sediments

Microplastics in the ditch sediments showed a different pattern compared to soils: the highest amounts of microplastics were observed in the sediments close to the fields exposed to compost applications (Table S4). It seems that microplastics have accumulated in these sediments over the years. The most abundant type of plastic was PAC, the microplastic type with the highest number of particles in the sediments,

Table 2
Microplastic heterogeneity in soil samples.

	MPs.g^{-1} of soil				
Plastic type	**No**	**Mean**	**Minimum**	**Maximum**	**Std. Dev.**
Bio mulch	47	4.0	0.0	52.9	10.3
LDPE mulch	47	128.7	0.0	1878.6	320.0
PAC mulch	47	224.8	0.0	2981.6	487.6
Polyethylene (PE)	35	3.2	0.0	43.2	8.1
Polyethylene Terephthalate (PET)	35	0.0	0.0	0.9	0.2
Polymethylmethacrylate (PMMA)	35	0.1	0.0	2.0	0.4
Polypropylene (PP)	35	4.5	0.0	31.4	5.9
Polystyrene (PS)	35	0.8	0.0	2.0	0.8
Polyurethane (PU)	14	0.3	0.0	2.0	0.7
Polyvinylchloride (PVC)	35	0.1	0.0	0.9	0.2
Rubber	35	0.2	0.0	2.0	0.5

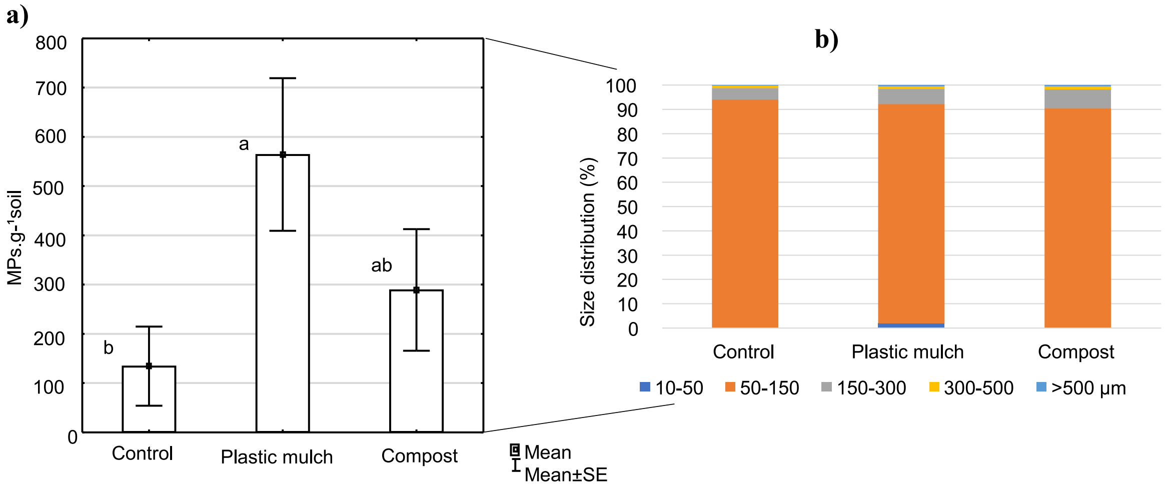

Fig. 1. Soil microplastic characterisation: a) content, b) size distribution.

followed by LDPE mulch. Both types of plastic could be directly linked to agricultural practices and were present in all samples (Tables S4 and S5). The colours of the plastic were mainly white and black.

3.5. Prediction of microplastics in water and ditch sediment based on 100 g of microplastics in soils

The most abundant microplastic types found in soil, water, and ditch sediment were LDPE mulch, PAC mulch, PE, and PP; therefore, the calculations for the standardization were done only with these plastic types (Table 3). Taking 100 MP g^{-1} of soil from all soil samples as a starting value and following the trends observed above allows us to predict the amount of microplastics in ditch sediment and water. Sediment and water from ditches near fields with compost treatment had, according to the prediction, the highest content of LDPE mulch per 100 MP g^{-1} of soil, while sediment samples from ditches near plastic mulch treatments had the highest content of PE (Table S4). The sediment and water samples collected from the control area, according to the standardization for 100 MP g^{-1} of soil, had the highest content of PP (Table 3).

3.6. Microplastics in airborne dust samples

When comparing the concentration of microplastics in the wind-eroded sediment to the concentration in the soil from which they blew away from, a clear enrichment was observed for each of the two tested farms. The enrichment ratio ($MP_{\text{wind-eroded}}/MP_{\text{soil}}$) was equal to 8.6 for Farm 4 and 4.7 for Farm 5. Low-density microplastics are, therefore, more easily eroded by wind than the particles of soil from which they originate(mass density around 2.6 g cm^{-3} for most soil particles). As a result, the residue left behind becomes barren in terms of microplastics: for both farms, the enrichment ratio for the residue dropped to less than unity (0.4 for Farm 4 and 0.1 for Farm 5).

PAC and LDPE were the dominant plastic types in the wind-eroded sediment (44.2% PAC and 41.2% LDPE for Farm 4, and 48.6% PAC and 37.6% LDPE for Farm 5), followed by Polypropylene (10.4% for Farm 4 and 7.3% for Farm 5). In the residue that was left behind, PAC, LDPE, and PP were still the dominant microplastics, but there was a difference in behaviour between PP on the one hand and PAC and LDPE on the other. The proportion of PP (in the total sample) was substantially lower in the wind-eroded sediment as compared to the residue, whereas for LDPE and PAC, it was lower or almost equal in the residue (Table 4). This highlights the fact that PP was less sensitive to wind erosion than LDPE and PAC mulch in the wind tunnel experiments. Further research is necessary to verify this observation.

When looking at the diameter of the three dominant microplastics, no consistent trend was observed. In Farm 4, the microplastics in the

Table 4
Microplastic percentage proportion and size per plastic type in the wind-eroded sediment (WES) and residue (R) per farm (two farms with the highest concentration of microplastics in soil exposed to plastic mulch and compost, respectively).

Farm	sediment type	microplastics %			microplastic diameter (μm)		
4		PP	LDPE mulch	PAC mulch	PP	LDPE mulch	PAC mulch
	wind-eroded sediment	10.4	41.2	44.2	102 ± 45	125 ± 103	93 ± 45
	Residue	20.7	32.8	46.6	60 ± 64	63 ± 24	30 ± 7
5							
	wind-eroded sediment	7.3	37.6	48.6	110 ± 57	54 ± 5	58 ± 12
	Residue	41.7	16.7	33.3	44 ± 18	199 ± 260	179 ± 232

Table 3
Microplastic concentration in water and ditch sediment samples after standardization to 100 MPs per gram of soil, per treatment during the spring season. No statistical analysis was performed because the mean value per treatment was used.

		LDPE mulch	PAC mulch	Polyethylene (PE)	Polypropylene (PP)
per 100 $Mps.g^{-1}$soil	Standardization	$MPs.g^{-1}$ or $MPs.litre^{-1}$			
Control	ditch sediment	332.0	104.9	73.8	210.9
	Water	0.3	0.6	4.7	9.6
Plastic	ditch sediment	35.4	49.3	345.8	93.4
Mulch	Water	0.1	0.1	5.9	4.1
Compost	ditch sediment	736.5	323.4	171.6	80.2
	Water	0.8	0.5	0.5	1.2

wind-eroded sediment were finer than in the residue, whereas for Farm 5 this was only true for PP (Table 4).

3.7. Microplastic comparisons between matrices

The largest biodegradable plastic fragments were found in airborne dust and soil (Fig. 2). The plastics with the highest solidity were also found in these two matrices (Fig. S7).

When analysing the concentration of microplastics from all the farms, a robust and significant Pearson correlation was found between the concentration of PP microplastics in soils and the concentration of PP microplastics in ditch sediments ($r^2 = 0.77$; $p < 0.05$; Fig. 3). No such correlation was observed with other plastics, nor with the other two matrices (water and airborne dust). The correlation of microplastic types and concentrations between compost or manure on the one hand and soil on the other was significant, based on the Spearman correlation index ($R = 0.6$; $p < 0.05$; Fig. S8): higher concentrations were found per type of plastic in manure or compost compared to soils (Fig. S8).

When performing a closeup per farm using all tested matrices, in farm 4 (the farm with the highest concentration of microplastics in soil, Table S1), we noticed that PAC mulch was the most abundant plastic type in all four matrices, followed by LDPE mulch. The comparison between the physical characteristics of the plastic particles in the soil and ditch sediments in this farm after a canonical analysis showed no correlation (Fig. S9, 70% described in axis 1 & 2). For airborne dust, no clear correlation came to light either (Table S6). Moreover, the oil-based plastics (LDPE in this figure) and bio-based plastics (MZ27 = PE with starch-based film, in this figure) were opposed along the factorial plan, indicating that they were not correlated. However, the particles were larger in ditch sediment than in soils, which may have triggered a stronger degradation in soils as compared to ditch sediment, but further studies are needed to better understand the degradation process of microplastics in soils and ditch sediments. The diameter of plastic particles in the soil and on the soil surface was weakly but significantly correlated for Farm 4 ($R = 0.222$; p:001, Table S6), whereas the diameter of plastic particles in airborne dust was negatively correlated with the diameter of plastic particles in soils ($R = -0.13$; $p < 0.05$). More data are required to acquire higher correlations and provide a holistic picture of the particle trend among matrices on the same farm.

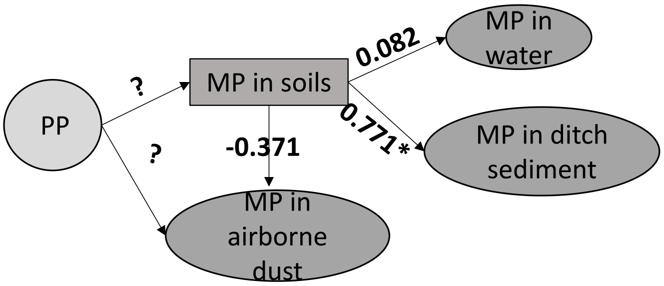

Fig. 3. Microplastic correlation among the different matrices. Polypropylene (PP) concentration (microplastics/g); Pearson correlation among the different matrices; * = significant at $p < 0.05$ (soil n: 38, water n: 20, sediment n:13).

3.8. Soil health assessment

Even though the abundance of earthworms in the systems with compost application was high (28.9 ± 85 ind. m^2), it was not significantly different from the control (Fig. S10). The soil invertebrate diversity among treatments was significantly higher for the control management and farms with compost application than the diversity under plastic mulch (Table S7, Fig. S11). Plastic fibres (>3) were found in earthworm guts. Due to the scope of this research and logistic problems, more information related to plastic particles found inside earthworms cannot be given in this paper.

3.9. Potential accumulation or transport of microplastics along the soil food chain

In general, the highest abundance and diversity of soil invertebrates are found in the most vulnerable sites. Even though plastic particles are present in lower concentrations in farms without plastic mulch or compost application (control) than in highly polluted areas (with plastic mulch application), the invertebrates could transport low concentrations of microplastics in their bodies. Therefore, these vulnerable sites are expected to face the greatest accumulation and transport of microplastics along the soil food chain. In this study, these sites were the farms with soils where compost was applied as well as the control sites, where the highest values of the accumulation index were obtained (Fig. 4). Although this index is complex to understand, it sheds light on the high risks present in the areas where the invertebrates still linger. In soils exposed to plastic mulch, with the highest concentrations of microplastics and a lower abundance and diversity of soil invertebrates, there was no such risk due to the prior extinction of most soil invertebrates. The soils exposed to plastic mulch were jeopardized due to the extreme scarcity of soil invertebrates and soil ecosystem functions, such as infiltration, nutrient cycling, water infiltration, and percolation

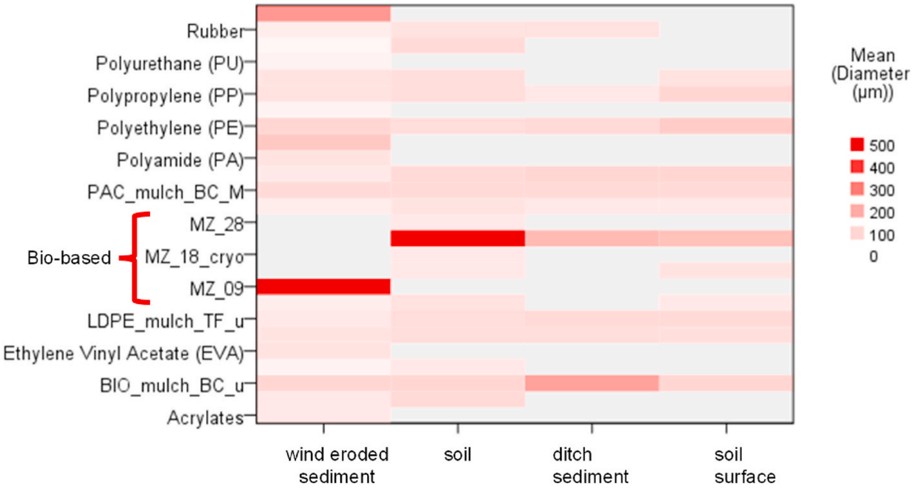

Fig. 2. Plastic heat map of microplastic diameter from the farm with highest microplastic concentration in soil (using plastic mulch, F4). MZ_09 = Poly(ethylene furanoate), MZ_18 = Blend oil + biobased plastic, and MZ_28 = PE starch multilayer film.

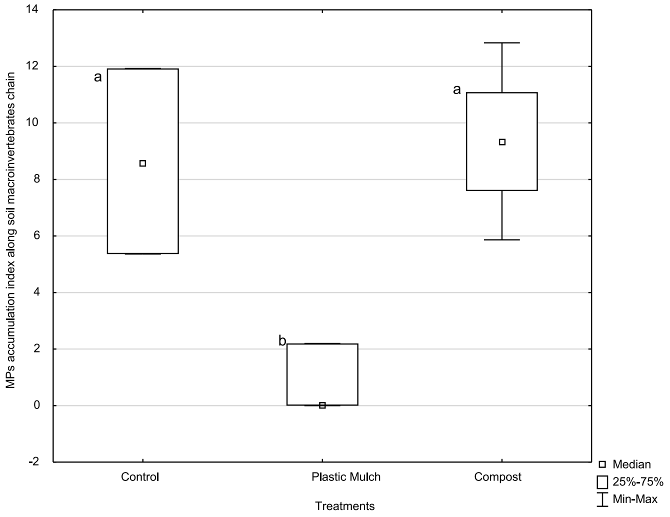

Fig. 4. Microplastic accumulation index along the soil invertebrate food chain.

(Creamer et al., 2022). In this case, no risk was present in these areas but there was a high risk of biological degradation.

4. Discussion

It is evident that microplastics are non-static particles: they migrate from one matrix to another depending on the physical and chemical characteristics of the plastics, the conditions and dynamics of the environment, and the soil type. In the case of agricultural systems, the management factor also plays a role. Once the plastic particles are in the soil matrix, these residues will migrate vertically and/or horizontally via water or wind (Huerta Lwanga et al., 2022). A noteworthy observation to make in this study is that polyethylene plastic residues were the most abundant in the soil, water, ditch sediment, and airborne dust samples. It was also evident that the agricultural sites exposed to plastic mulch were the ones with the highest number of plastic particles in the soil as compared to the systems applying compost.

This study sheds light on the effect of management inheritance on soil, ditch sediment, and airborne dust conditions. Twenty years ago, polyethylene coated with additives (known as PAC) was promoted as a promising biodegradable alternative to non-biodegradable plastics (van Schothorst et al., 2021). This material was mainly made up of LDPE and contained a pro-oxidant additive to enhance oxidation and photo-degradation (Selke et al., 2015; Beriot et al., 2021), and it was claimed to be a solution to avoid finding plastic particles in the soil. Unfortunately, this is not the case. Although PAC has already been banned (after 20 years of use), we still found many PAC residues in all the sampled soils, even where no mulching was used.

Even though the concentrations of microplastics found in these agricultural soils under plastic mulch were significantly higher (>500 MPs.g-^{1}) than those found in previous studies (i.e., agricultural soils of China under 20 years of Plastic mulch, 1075.6 MPs. Kg-^{1}, Huang et al., 2020), we see that the use of plastic mulch enhances the presence of plastic particles in agricultural soils (Huang et al., 2020). A correlation of r^2 0.6 $p < 0.05$ between plastic mulch use and plastic particles in soils and the concentrations of polyethylene in this study (3 MPs.g-^{1}) were similar to those found in agricultural soils in Spain under intensive use of plastic mulch (>2116 MPs.kg-^{1}, Beriot et al., 2021; van Schothorst et al., 2021).

4.1. Microplastic behaviour

Although a strong correlation was found between the concentration of microplastics in the ditch sediments and soil, further studies are required in order to understand this behaviour. We did infer that rainfall might play a relevant role in dragging microplastics from the soil into ditch sediments. Similar phenomena were observed by Shultz (2001) with the transport of pesticides from orchards to river sediments after rainfall.

Since the characteristics of microplastics in these matrices differ, it is possible to infer that the fragmentation or degradation in soils occurs faster or is more efficient than in ditch sediments. In the latter, the sediment is purely anaerobic and hampers fragmentation due to the lack of wind action or UV light. However, more studies are needed to enhance the understanding of the evolution of microplastics in ditch sediment.

Why did we find a robust correlation between PP in soils and ditch sediments? It is difficult to say since PP was not the dominant microplastic found in soils. However, due to its physical and chemical characteristics, it is extremely resistant to environmental conditions (Tiwari et al., 2020), and therefore liable to accumulate in sediments. Further studies are required to understand the accumulation process of the plastic found in ditch sediments.

Bio-based plastic fragments are found in soils, soil surface sediments, and airborne dust. In the latter, particle sizes are larger than those found in soils. It is important to note that the words biobased and biodegradable plastics are not synonymous. Biodegradable plastics, oil or biobased, should be subjected to a degradation process in soil conditions, if their presence in airborne dust, soil surface sediments or ditch sediment is not wanted, even though the EU norm (EN 17033) indicates that biodegradable mulch may prevail for 2 years in soils, plastic debris are then moved by soil invertebrates and abiotic factors, oil based or plant based plastic debris, even the biodegradable microplastics are also moved to different matrices over the course of these 2 years.

The correlations between microplastic concentrations in compost or manure and soil observed in our study highlight that the management practices using these treatments urgently need to be modified. Research has shown that composts serve as vehicles for microplastics (van Schothorst et al., 2021; Weithmann et al., 2018), and this study confirms previous findings.

The concentrations of MPs found in the ditch sediments of these agricultural areas were smaller than those found in riverine sediments of urban and suburban areas in southern China (6060–37610 particles/kg, Ji et al., 2021a, 2021b).

4.2. Diversity and concentration of plastics in water

The diversity of microplastics in the soil seems to depend on the abundance of the different plastic types present on the market. Polypropylene is the most produced plastic worldwide (61 870 000 tons, PlasticEurope, 2016; Ryberg et al., 2018). This type of plastic was the dominant plastic found in the water from the ditches. It is inferred that this type of plastic comes from composts (the concentration of microplastics in compost is around 2800 ± 616 MPs kg$-^{1}$ in municipal compost and 1253 ± 561 MPs kg$-^{1}$ in garden and green house compost, van Schothorst et al., 2021). However, more studies are necessary to evaluate how to decrease the concentration of this plastic in composts (and therefore in water ditches) during the composting process. Microplastic concentrations in water had seasonal fluctuations. Since there is more rainfall in autumn and the number of microplastics increased, we assume that the high amounts of rainwater wash the microplastics out of the fields where compost had been applied (and plastic mulch fragments were present) more intensively and more frequently. Thus, more organic material was carried to the ditches together with water, leading to a higher transport of microplastics to the ditches. Nevertheless, more studies are still needed to correlate the number of microplastics with the rain's intensity and frequency on the field scale.

4.3. Potential accumulation of microplastics in the soil invertebrate food chain

According to Ji et al. (2021b), who conducted a meta-analysis, microplastics hamper soil fauna, impacting: 1) the gut system, 2) behaviour (sensory, and muscular functions), 3) fitness, 4) the immune system (immune response genes), as well as 5) metabolism and DNA. To understand what occurs in agricultural systems concerning the diversity of organisms, it is important to look at the different compartments. In this study, the control treatment had the highest soil invertebrate diversity. Under the plastic mulch treatment, no invertebrates were found except for some scarce Coleoptera larvae, Dipteran larvae, and Myriapods, which are resistant to perturbation, and generalists (Sánchez-Bayo and Wyckhuys, 2019).

The index of microplastic accumulation (*AcMpr*) along the soil invertebrate food chain gives insight into the soil biota vulnerability present under conditions of microplastic pollution. This pollution exists in a cocktail of microplastics (11 different types) which interact with soil properties, impacting soil structure, composition and functioning (De Souza Machado et al., 2019). Pollution leads to pressure on soil biota; soils exposed to compost and the control were the most vulnerable, since soil biota were ingesting and transporting microplastics in low concentrations through the soil system (Huerta Lwanga et al., 2022). Soil biota under plastic mulch were eliminated, and biological degradation was observed. This can be explained by the long exposure and concentration of the microplastics on soil invertebrates, studies have shown that microplastics in high concentrations can produce macroinvertebrates loss of biomass and dead (Huerta Lwanga et al., 2016) and in this study it is translate in a complete decrease of soil macroinvertebrates diversity and abundance. Although this index is complex to understand since it describes the risk or vulnerability of a soil system under a complex stressor, it is innovative because it encompasses soil macroinvertebrate abundance, diversity under the concentration and diversity of microplastics.

Several questions arise from this study such as why do soil health conditions in agricultural systems with microplastics cannot be promising or what does minimal microplastic concentration allow migration through (or from) the soil and affects neighbouring systems? In this study, we observed that LDPE was present in all the studied matrices, and we presume that this is the microplastic ingested by the soil invertebrates and is, therefore, available to vertebrates such as birds. However, what happens when these plastic particles migrate to other systems? In this study, we witnessed the accumulation of PP particles in water and ditch sediments that most likely originated from compost or manure sources. Therefore, more studies are required to understand how microplastics behave under biotic and abiotic transport and elucidate the impacts of such behaviour on the environment. In aquatic environments, we know how microplastics introduce toxic compounds to organisms, threatening aquatic diversity (Guzzetti et al., 2018). The same phenomenon is expected to occur in terrestrial systems.

4.4. Challenges and perspectives

There is a current urge to standardize a methodology for microplastic evaluation. Hitherto, we report the number of particles per gram/kilogram/litre, but an estimation based on weight would be more reliable.

Although we utilized one of the most-used methodologies to extract microplastics from environmental samples, the current methodologies have pitfalls that could lead to particle loss throughout the process due to several transferences needed for this multistep approach. Further efforts to standardize and optimize microplastic extractions are ongoing. Even though LDIR stands out as one of the best options on the market to identify microplastic particles and spectra, the technique is still time-consuming, struggles to include all the particles from the samples, and can not handle large volumes, such as occurs when more than 10,000 particles remain on the glass slide.

5. Conclusions

Agricultural practices determine the degree of soil pollution. The soil houses a cocktail of microplastics (11 different sorts in our study) and soil management is responsible for their presence, abundance and distribution.

Farms with high concentrations of soil microplastics also have high concentrations of microplastics in sediments.

Soils exposed to plastic mulch had more microplastics than soils exposed to compost applications. Over the last 20 years, plastic mulch use has been encouraged to increase yields (i.e., vegetables) in sites exposed to extreme environmental conditions (low soil moisture, low temperature). However, this (innovative) technology leaves its footprint on the environment, i.e., plastic mulch, whether fossil or bio-based, has traditionally been incorporated into the soil instead of removed.

Ditch sediments from farms exposed to compost application accumulate more microplastics. Although compost application is considered to be an environmentally friendly practice, this really depends on the compost quality. Low-priced compost contains all kind of residues, glass, metals and plastic. Thus, the use of this compost introduces microplastics to agricultural sites.

PE and PAC were abundant in soil, water, airborne dust and ditch sediments. PE is the main plastic found in packing and in plastic mulches and PAC has been used for at least the last 20 years. Due to the different abiotic and biotic transport processes, these microplastics are not only found in soils, but also in water, ditch sediments, and airborne dust. Therefore, it is urgent to find alternatives for plastic in agriculture.

The concentration of PP in ditch sediments is correlated with PP in soils. This correlation results from the transport of this type of microplastic. Its physical and chemical characteristics allow it to remain on sediments and be transported by rainfall. Further studies are required to understand this phenomenon.

Soils with fewer microplastics (control farms) had a higher diversity of soil invertebrates than soils with a high concentration of microplastics. Although it is difficult to determine the cause for the decrease in soil invertebrate diversity in farming systems due to different factors, the control systems in this study (systems with the lowest concentration of microplastics in the different matrices) turned out to have the highest soil biota diversity.

This research helps to understand how microplastics move from soil to water, ditch sediments and airborne sediments. The plastic debris found in high concentrations in soils are also found in high concentrations in the different matrices.

Credit authors statement

EHL: conceptualization, methodology, visualization, investigation, writing - review & Editing; IvR: methodology; DRM: methodology, review & Editing; KM: methodology; MR: methodology, review & Editing. DG: methodology, review & Editing. JB: methodology; NA: methodology; JO: methodology; MK: methodology; PP: methodology; VG: supervision, edition; CR: visualization, resources.

Authors statement

No experimentation with human was taken place in this study.

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 will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2022.120513.

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