Journal of Soils and Sediments (2022) 22:757–768
https://doi.org/10.1007/s11368-021-03114-7

SOILS, SEC 1 • SOIL ORGANIC MATTER DYNAMICS AND NUTRIENT CYCLING • RESEARCH ARTICLE

Quantification and analysis of surface macroplastic contamination on arable areas

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Received: 27 June 2021 / Accepted: 21 November 2021 / Published online: 3 December 2021

Abstract

Purpose The present study provides quantitative data on the degree of macroplastic contamination of two conventionally treated arable areas in North Rhine-Westphalia (Germany), which differ only in the use of organic fertilizers (e.g., compost).
Methods The plastic contamination of both areas was determined by means of field sampling. The study areas were divided into edge and central areas to minimize and identify direct influences from the boundaries. After cleaning and drying, the collected macroplastic particles were analyzed by phototechnical and optical methods for number and size of particles.
Results The arable area with compost fertilization showed a substantially higher macroplastic pollution with 9247 particles per hectare compared to the 220 particles per hectare found on the arable land without compost application. Furthermore, the differences in plastic forms and types on both areas, the presence of plastic directly related to household and garden products, and the homogeneous distribution of plastic particles on the arable area with compost application allow to conclude that compost can be regarded as reason for substantially higher pollution. Areas close to a road showed a higher degree of contamination and differences in the found plastic products compared to the center areas, which indicates littering as a further considerable entry path.
Conclusions The causes of plastic contamination of the investigated arable areas (e.g., contaminated compost by improper waste management and littering) are predominantly external to agricultural practices. The knowledge gained contributes to the knowledge about quantities, impacts, and fate of plastic in the environment.

Keywords Macroplastic coverage · Pollution · Agricultural activities · Arable area

1 Introduction

In recent decades, public perception regarding plastic has shifted towards a problem with global reach (Barnes et al. 2009). Started by first studies on the plastic pollution of beaches and coastal areas in the 1970s (Carpenter et al. 1972; Scott 1972), the situation of the oceans regarding accumulation, fragmentation, impact, and fate of plastic was first brought into focus (Bergmann et al. 2015). Even though the source of marine pollution is land-based activities (Jambeck et al. 2015), systematic research on pollution of terrestrial ecosystems started much later in the 2010s (Rillig 2012). Despite growing research activity (Leifheit and Rillig 2020), many questions remain unanswered to this day about the sources, amounts, and fate of macroplastic and microplastic in the terrestrial environment and their effects on soils, plants, and animals (Bläsing and Amelung 2018; Hurley and Nizzetto 2018). However, estimates suggest that the terrestrial environment represents a sink of plastic that is 4 to 23 times larger than the aquatic environment, and thus, more attention should be paid to this environmental compartment (Hodson et al. 2017).

Inputs of plastic to the terrestrial environment are overridingly attributed to emissions from (i) household and industry, (ii) atmospheric deposition, and (iii) agricultural activities,

Responsible editor: Xilong Wang

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which enter the environment by direct or indirect pathways (Bläsing and Amelung 2018). From littering along roads, it was estimated that 13 kg of polyethylene terephthalate (PET) per ha and year are emitted in Switzerland (Kawecki and Nowack 2020). This amount represents 81% of PET macroplastic emissions. In soil samples from areas with a high marine litter in Norway, a number of macroplastic particles ranging from 73,552,294 to 1,484,006,547 per kg was determined (Cyvin et al. 2021). Huerta et al. found very high levels of macroplastic contamination of 744,000 ± 204,000 polyethylene bottles and 74,000 ± 65,000 plastic fragments per ha when they surveyed 10 home gardens in rural Mexico (Huerta Lwanga et al. 2017). Liu et al. detected macroplastic levels of 50–260 kg per ha on an arable area with long-term (> 10 years) mulch film use in China (Liu et al. 2014). Zylstra found evidence of atmospheric transport of plastic over long distances (> 2 km) using a survey in Sonoran Desert National Park and determined macroplastic concentrations of 0.056–0.354 particles per ha (plastic bags) and 0.392–0.627 particles per ha (balloon composites) (Zylstra 2013). Eventually, the emission of macroplastic to soils may result in a wash-off and transport via rivers. For instance, the mean mass transport of macroplastic from Rhine river to the North Sea was calculated with 1.3–9.7 kg per day (Vriend et al. 2020). Generally, different pathways (aerial, terrestrial, and aquatic) result in a transport of macroplastic particles from one area to another and more quantitative data on macroplastic emissions are urgently needed to identify sources and consequences on ecosystems and economy (Lechthaler et al. 2020).

Agricultural soil plays a special role in this context of macroplastic contamination, as its nature is of importance for the food supply. The soil resource is in any case exposed to multiple stressors, such as the use of agrochemicals, intensive fertilizer application, and climatic change (Rillig et al. 2019). Thus, plastic emissions represent a global factor influencing soil health and consequently may also negatively influence plant growth (Ferdous et al. 2021). The impact of macroplastic contamination on plant growth is of particular importance for arable areas. The degree of contamination of arable areas has been quantitatively investigated by only a few studies so far (Piehl et al. 2018; Sexlinger et al. 2019). Especially organic soil improvers, such as sewage sludge, composts, and digestate, are substantial input streams of macroplastic as well as microplastic into the terrestrial environment and especially onto arable and forestry areas (Bläsing and Amelung 2018; Weithmann et al. 2018; Zubris and Richards 2005). In addition, external factors, such as littering and road runoff, also represent diffuse inputs to arable areas, which, however, are difficult to quantify (Bertling et al. 2018; Kawecki and Nowack 2019). Thus, the aim of this paper was to investigate the degree and composition of macroplastic contamination on two fields in North Rhine-Westphalia (Germany) where different fertilization strategies (mineralized fertilizer and liquid manure as well as mineralized fertilizer, liquid manure, and compost) were applied. Furthermore, this study aimed for revealing the extent to which different parts of fields (central, edge, and a connection to roads and arboreous plots) impact the degree of contamination and whether conclusions can be drawn about possible input pathways. The results are expected to contribute to the discussion on the relevance of fertilization and littering on the appearance of macroplastic but also microplastic particles on arable areas.

Fig. 1 Scheme illustrating the extent and adjacencies of Fields 1 and 2 ▸

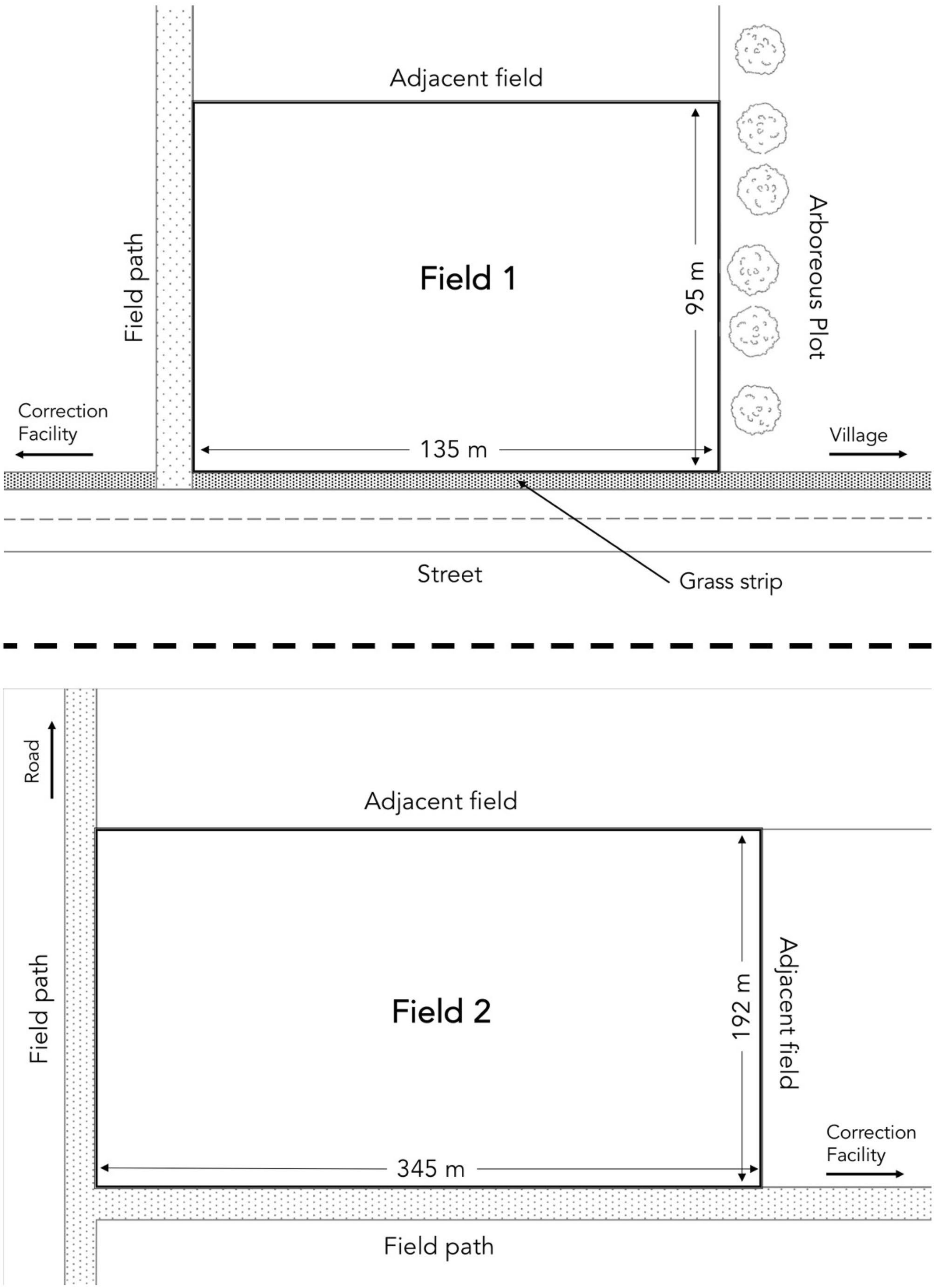
2 Material and methods

2.1 Sampling areas

To determine the surface macroplastic contamination on arable areas, two fields in the western part of North Rhine-Westphalia (Germany) were selected. The investigated fields are located within the Lower Rhine Lowland. The region is a river terrace landscape and almost universally located at an altitude of 10–60 m above sea level. Characteristic of the region's soils is parabrown soil from loess-covered, loamy-sandy terrace deposits. Sampling was carried out during March to April 2020. At the request of the operating farmers, the exact location data of the studied plots is not disclosed.

2.1.1 Field 1

Field 1 is an arable area on which classic cash crops (e.g., winter wheat, corn, sugar beet, barley) are grown in conventional cropping systems. The field covers an area of 1.28 ha (135 × 95 m^2). Mineral fertilizers and liquid manure have been used for fertilization. Neither sewage sludge nor organic fertilizers have been applied. In general, the field is managed using classical arable tillage, seeding, and harvesting methods. It should be emphasized that no agricultural plastic products, such as mulch films, protective nets, irrigation systems, or similar, has been used on Field 1 and the last plowing was in 2018. The site is adjacent to a rural road, an arboreous plot, a field farmed by the same farmer, and a dirt road, which in turn is adjacent to more arable areas. The nearest village (about 5000 inhabitants) is located about two kilometers away, and a correction facility is located 1 km away. Figure 1 schematically shows the extent and adjacencies of Field 1. At the time of the 1st sampling, no arable crop was present, no soil cultivation measures have been carried out, and no fertilizers have been applied. The 2nd sampling was done after tillage by different cultivators and


Adjacent field
Field path
Field 1
95 m
Arboreous Plot
Correction Facility
135 m
Village
Street
Grass strip
Road
Adjacent field
Field path
Field 2
192 m
Adjacent field
Correction Facility
345 m
Field path

harrows as well as fertilization (liquid manure and mineral fertilizer).

2.1.2 Field 2

The second study area has been used conventionally for the cultivation of arable crops. Field 2 covers a total area of 6.6 ha (345 × 192 m^2) and differs from Field 1 in the way of fertilization and adjacencies. Besides the use of mineral fertilizers and liquid manure, organic fertilizers in the form of municipal compost and champost (also mushroom soil or worn mushroom growing medium; consisting of horse manure, straw, lime, and peat) have been applied. Tillage, seeding, and plant protection have been performed in the same manner as described for Field 1. In 2017, the study area was lastly plowed. Analogous to Field 1, no agricultural plastic products have been used. Field 2 is bordered by two additional croplands and two dirt roads, which in turn border additional arable areas and grasslands. In the northern direction, a path leads to the next country road in about 1 km, and in the eastern direction, it leads across the above-mentioned correction facility and in the direction of the nearest village (Fig. 1).

2.2 Sampling

Sampling of the study sites was carried out on three sampling days following the method reported earlier (Piehl et al. 2018). The study areas were divided into edge and central areas to minimize and identify direct influences from the boundaries. For Field 1, edge and central areas were sampled before and after initial tillage and fertilization, respectively. An area of 1500 m^2 (30 × 50 m^2) was staked out and analyzed. During the 1st sampling, the edge areas were analyzed over the entire respective area length and a width of 5 m from the area exterior (edge-road and edge-field correspond to 85 × 5 m and edge-arboreous plot as well as edge-path correspond to 135 × 5 m). For the 2nd sampling, based on the experience of the 1st sampling in terms of number of particles found and time required for sampling, the area of the boundary surfaces was reduced to 5 × 50 m. For Field 2, only one sampling of the central area could be done due to sowing and fertilizing already done at the time of sampling.

The sampling was carried out by two persons simultaneously. The persons walked at about 1 m along the long edge of the respective area. In this way, both persons observed the same section of the surface at the same time to reduce the risk of overlooking macroplastic particles. In total, the central areas were walked 30 times by both individuals. Ground markers in the form of wooden posts were used to delineate the plots, and if available, the troughs of agricultural machinery were used as landmarks to grid the plot in a straight line. The plot division and gridding are shown schematically in Fig. 2. During sampling, all surface plastic particles (> 5 mm) that were visible by eye were collected and stored for further analysis. Macroplastic particles located within soil agglomerates were taken and soil removed during further sample preparation to reduce the risk of damage to the macroplastic particles.

2.3 Sample preparation and analysis

2.3.1 Cleaning and drying

After sampling, particles were cleaned and separated from soil deposits or other organic-mineral adhesions without damaging the particle. Subsequently, the samples were given in a sieve (hole diameter 1–2 mm) and placed in a water bath at room temperature for 1–2 h. Afterwards, the water was changed, and one or two more cleaning loops were performed depending on the degree of contamination. Larger, three-dimensional, or hollow macroplastic particles, such as hoses or bottles, were cleaned by hand. Even though sample preparation was carried out carefully, it cannot be completely ruled out that particle damage occurred during this process. After cleaning, the particles were air dried for 24–48 h and subsequently weighed. If the material could not be clearly determined based on visual or haptic characteristics, the hot point test (Rodríguez-Seijo and Pereira 2017) was performed to identify plastic materials. In this test, a hot metal needle is held against the particle to see if it adheres or leaves a mark on the particle. If this happens, it gives a good indication that a plastic material is present. If this did not apply, meaning no traceable mark detectable or no adherence, the test was classified negative and the particle in question discarded.

2.3.2 Optical and phototechnical sample analyses

For the analysis of the samples, a phototechnical method as reported earlier (Sexlinger et al. 2019) was used. For this purpose, the cleaned and dried plastic particles were placed on a non-reflective surface using tweezers or, depending on the size, by hand. For this purpose, a commercially available wooden plate (800 × 400 × 20 mm) was covered with a white, non-reflective, and cleanable adhesive film. The placed particles were photographed using an SLR camera (Nikon D3100) and tripod (Velbon P-Max). For size referencing, a scale was placed on the lower edge of the image section. The image section was adjusted to the width of the base (approximately 35–40 cm) and all camera settings were manually adjusted to the respective lighting situation. To achieve the best possible illumination of the image area, all images were taken with the flash function and care was taken to ensure that the image was as shadow-free as possible. The plastic particles were placed on the support in their respective

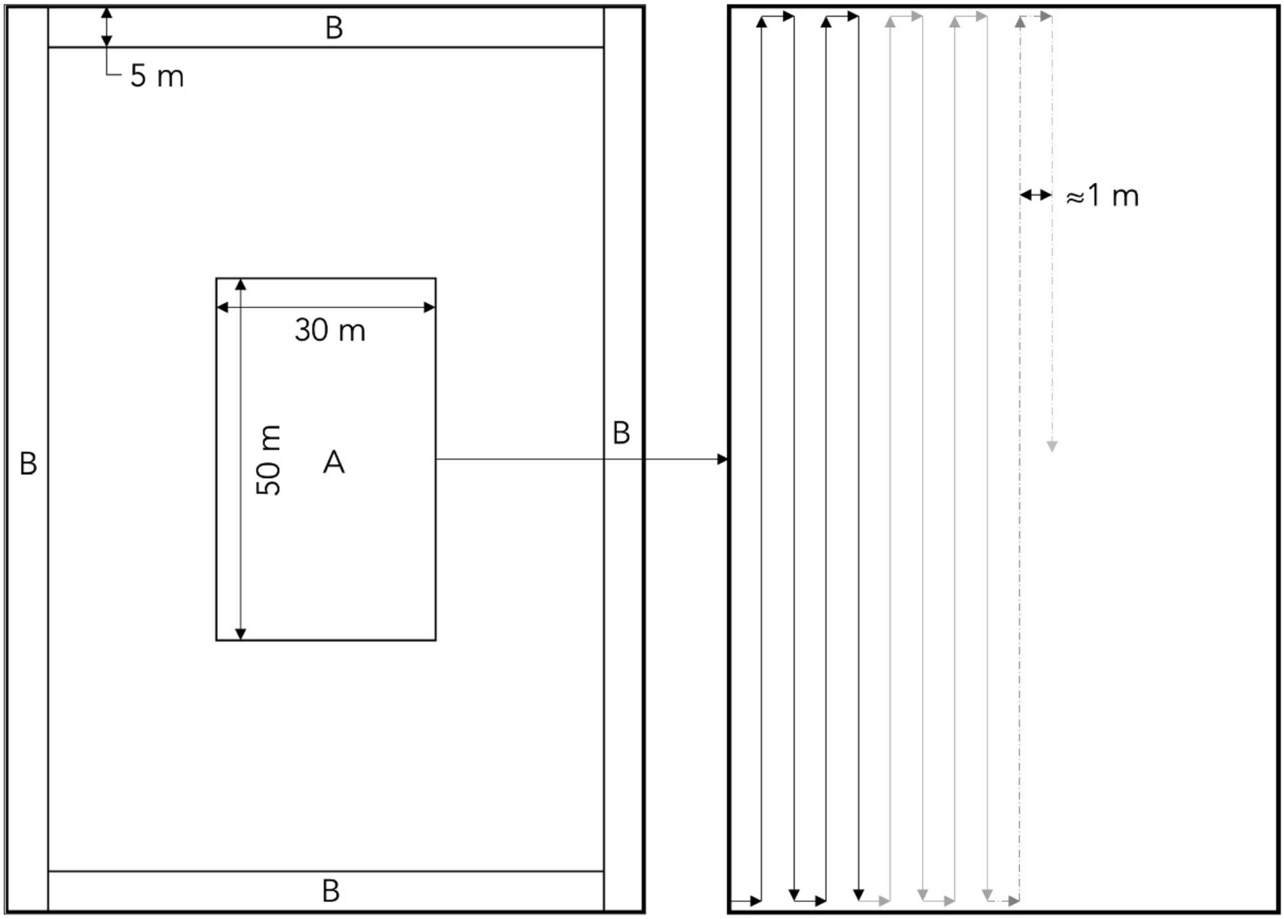


Fig. 2 Scheme of plot division and gridding

form and not manually unfolded or smoothed (e.g., in case of highly compressed films or packaging). After each photograph, the surface was cleaned with a microfiber cloth to remove soil or dust particles from the support.

The image processing and analysis program Fiji (https://imagej.net/Fiji) was used to analyze the particles. Fiji represents a bundled version of the program ImageJ, which has been used scientifically since 1997. Fiji is commonly used to enumerate and measure structures on microscope images in medicine and microbiology. In the context of this work, the program was used to analyze the macroplastic particles found. The following information of the plastic particles could be determined with the help of Fiji: number of macroplastic particles per hectare, area of particles, shape, color, and condition (fragmented-complete).

Unlike Sexlinger et al., who calculated the sum of area of all particles by relating the pixel number of plastic particles to the total pixel number of the image, here, the area of each particle was determined. The method works by subtracting pixels with low color intensity from the total number of pixels, so that the area of the remaining pixels can be determined and the area of the plastic particles inferred (Sexlinger et al. 2019). Even though this procedure is very fast to perform, there is a risk of not considering particles with low color intensity. With the method used here, it was possible to relate the size ratios of pixels to centimeters by using a reference length available in the image (see scale in Fig. 3). In this way, it was possible to infer the real size ratios of the structures present on the image and to calculate the areas of these. To test the applicability of the method, several simply shaped objects (e.g., with a square or rectangular shape) with a known or easily determinable area were measured. Prior to particle measurement, a length calibration was performed in each case to achieve the most accurate relationship between pixels and length. For this purpose, a horizontal line was drawn along 5 cm on the scale using Fiji, and thus, the line length could be determined in pixel. This resulted in the relation of, for example, 121.94 pixels per cm (see Fig. 3). To minimize measurement errors, the process was repeated 10 times and the average line length was used to reference the size relationships. A new length referencing

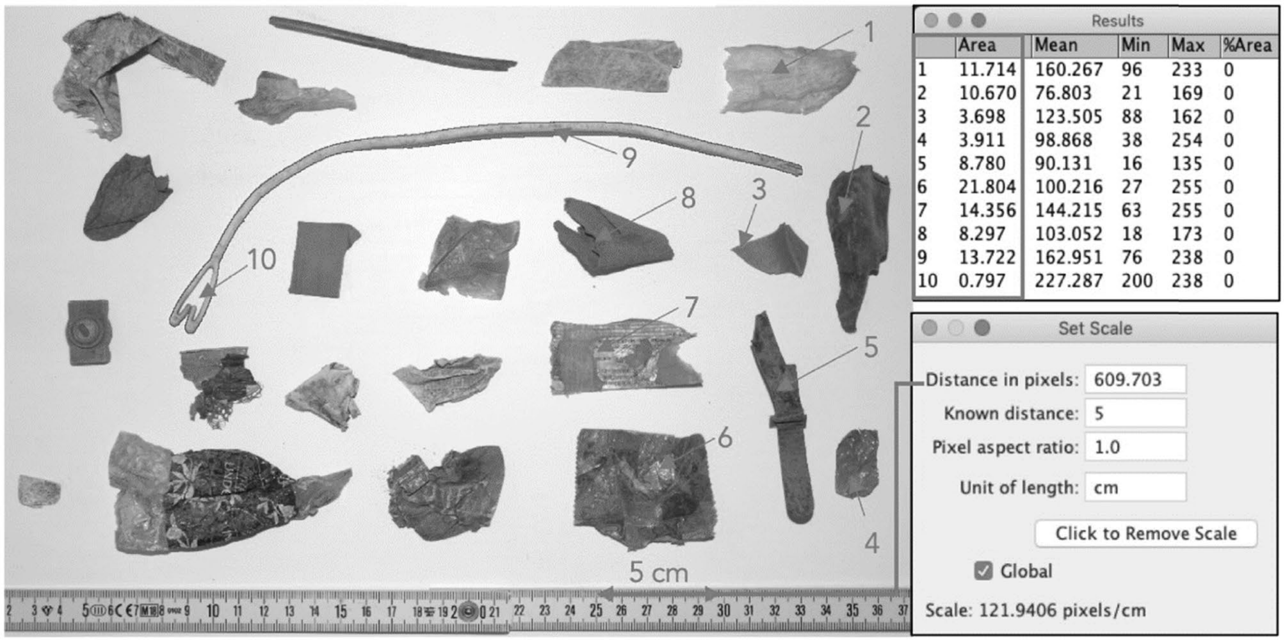


Fig. 3 Application of Fiji-software to calculate the areas of various particles

was performed for each field area or for images taken on different days.

Subsequently, the Fiji wand (tracing) tool was used to determine the size of each particle. By manually clicking on an image structure, the tool compares the grayscale values (0–255 in RGB color space) of the clicked pixels to the surrounding pixels. As soon as the difference of the surrounding grayscale values (transition from particle to background) exceeds an adjustable tolerance value (0–255), the selection is terminated. In this way, the last selected pixels represent the outer outlines of the particle, if grayscale values of the particle and the background differ. By means of the adjustable tolerance value, it is possible to detect particles within a large color range or even multi-colored structures and to separate them from the background. To simplify the selection, it is recommended to use high-contrast images or to manually adjust the contrast or brightness values of the image in advance of the analysis. Particularly in the case of white or transparent macroplastic particles, difficulties can arise during selection, since the tool can no longer distinguish between the gray values of the particle and the background. Furthermore, shadows present in the image can falsely enlarge the particle area, so care should be taken to ensure good image illumination. Holey or hollow plastic particles, such as fragmented or perforated films, are not automatically subtracted from the particle area by the tool, but only the outer perimeter of the structure is determined. For particles with large interior free areas, the outer and inner areas were also calculated by the wand tool and then subtracted from each other. In Fig. 3, this is exemplarily demonstrated for particle 9. Manual subtraction was performed only for internal structures that accounted for more than 2% of the total area of the structure. After measuring the particles, the measured values were transferred to Excel and analyzed.

The sum of area of all plastic particles was related to the size of the study area, and the plastic fraction was calculated in $cm^2\ m^{-2}$, which corresponds to the calculation of the optical contamination degree (Sexlinger et al. 2019). However, to avoid confusion with the other data collected, this will be referred to macroplastic coverage in the following.

The categorization of particle shapes, the color spectrum of the particles found, and the condition of the particles were performed manually following the size determination. The following four shape categories were identified: films, fragments (predominantly solid, non-bendable, and three-dimensional plastic parts with a wall thickness greater than 1 mm, e.g., lids, clips, or tubes), fibers (e.g., textiles or containers), and others (multi-component products made of different plastic materials, e.g., lighters or cosmetic cans). Figure 4 shows examples of particles of the described shape categories.

When considering the color spectrum, a distinction was made between ten colors (red, brown, orange, yellow, green, blue, gray, black, white, transparent, and multicolor). In addition, the condition of each particle or the completeness of the particles was documented. It was recorded whether the plastic found was fragmented plastic (e.g., a perforated film or a broken coffee cup) or still complete plastic products (e.g., complete plastic bottles). Even if this does not allow conclusions to be drawn about the degree of polymer

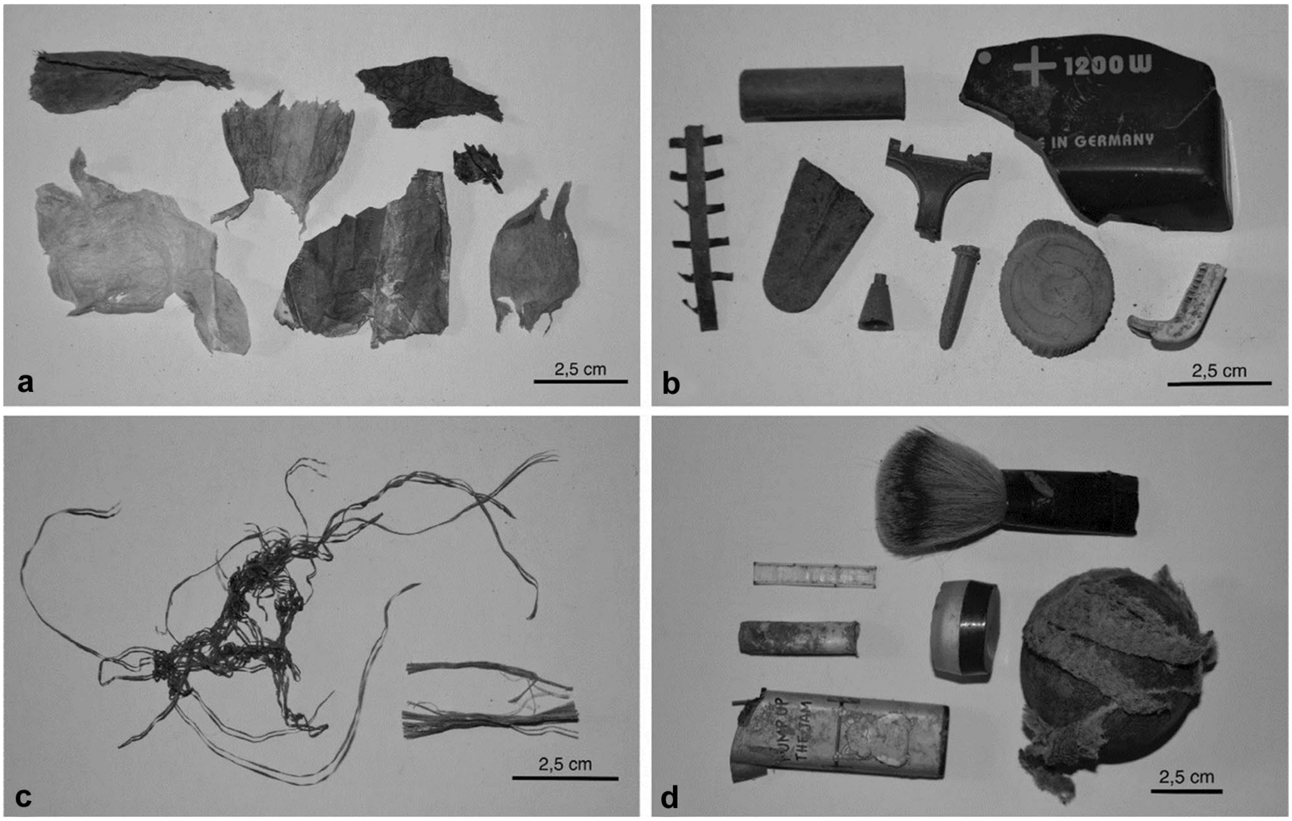


Fig. 4 Illustration of particles found on arable area (**a** = foils, **b** = fragments, **c** = fibers, and **d** = others)

degradation and the location at which fragmentation processes have occurred, it can be used to qualitatively assess whether most of the plastic found have already disintegrated into smaller plastic particles during their use and fate.

3 Results

3.1 Field 1

For Field 1, two samplings of the central and edge areas were carried out. Due to the different size of sampling areas, the macroplastic particles found were extrapolated to a reference area of 1 ha. Figure 5 A shows the extrapolation for both samplings and areas.

On the central area, 33 particles were found on an area of 1500 m^2 both before (1st sampling) and after tillage (2nd sampling), which after extrapolation corresponds to 220 macroplastic particles per ha. On the edge areas, particle counts averaging 1022 particles per ha were found for both samplings (edge-field: 993 and 1080 particles ha^{-1}, edge-arboreous plot: 1035 and 880 particles ha^{-1}, and edge-path: 1106 and 1040 particles ha^{-1} for the 1st and 2nd samplings, respectively). On the roadside edge area, 3096 and 3960 particles ha^{-1} for the 1st and 2nd samplings, respectively (Fig. 5A) were found.

Not only the particle counts were different between areas but also the mass of macroplastic particles. The 1st sampling revealed a mass of 0.06, 5.76, 1.00, 0.56, and 0.57 kg ha^{-1} for the central area and for the edge areas: road, field, arboreous plot, and path, respectively. The 2nd sampling revealed masses of 0.05 kg ha^{-1} for the central area and 0.58 kg ha^{-1} for the edge-path area, while 3.70, 0.05, and 3.93 kg ha^{-1} were found on the edge areas: road, field, and arboreous plot, respectively (not shown).

From the particle areas determined by phototechnical analysis, the following areas (sum of all plastic particles found on the study area) were found for the 1st and 2nd sampling: central area: 229.74 and 576.47 cm^2, edge-road: 3648.97 and 2260.23 cm^2, edge-field: 1080.24 and 190.11 cm^2, edge-arboreous plot: 464.21 and 495.67 cm^2, and edge-path: 730.70 and 269.98 cm^2, respectively (not shown).

In relation to the respective study area, the macroplastic cover of the soil was calculated in $cm^2\ m^{-2}$ (Fig. 5B). Here, a similar tendency in comparison to the number of particles was found between the different areas. The macroplastic coverage of the central area was 0.15 and 0.38 $cm^2\ m^{-2}$ for the 1st and 2nd samplings, respectively. The coverage of the edge areas: field, arboreous plot, and

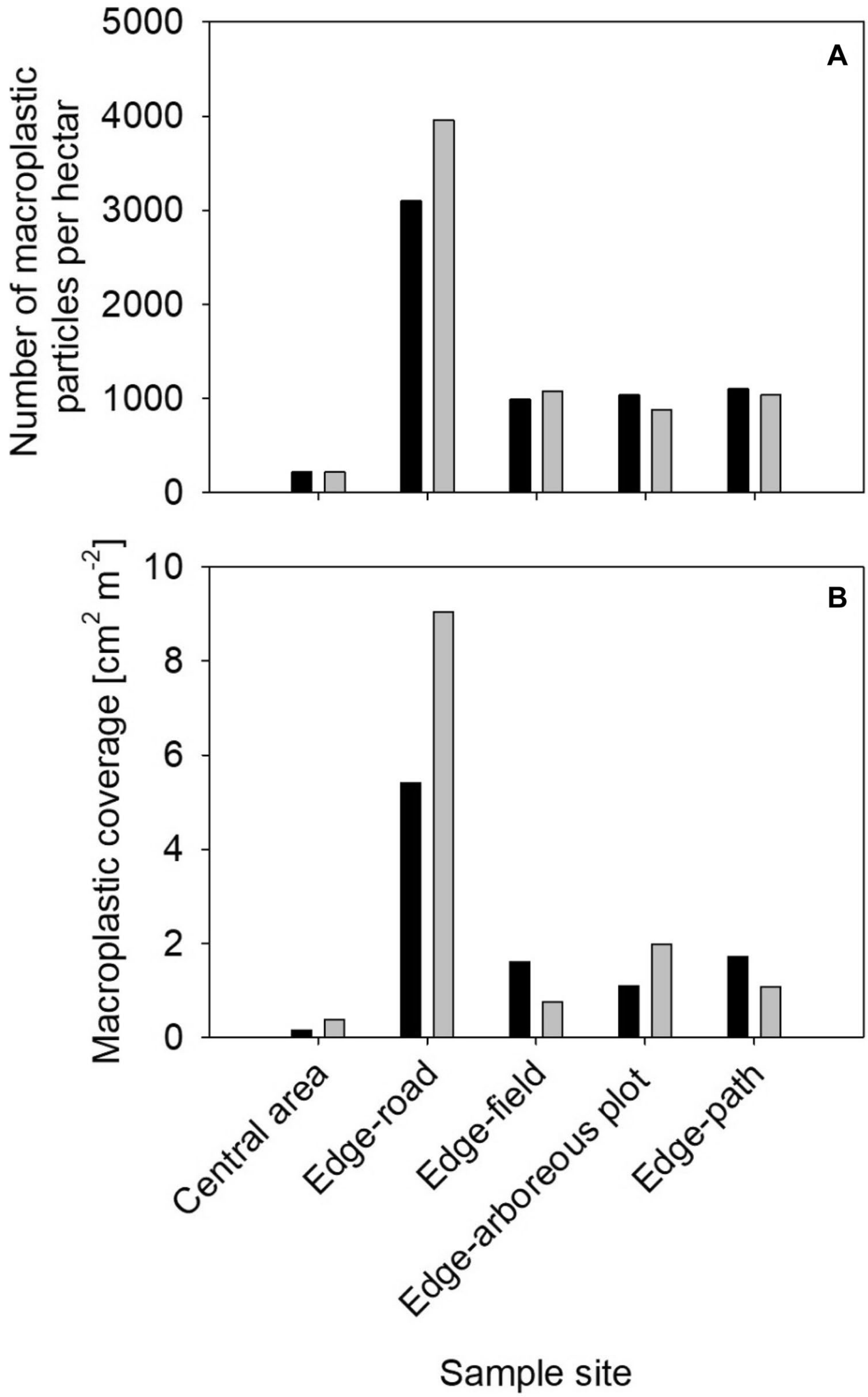


Fig. 5 Number of particles per hectare **A** and microplastic coverage **B** found on Field 1 at different sampling sites during 1st (black) and 2nd (gray) sampling

path was in average 1.37 cm^2 m^{-2} (range of values between 0.76 and 1.98 cm^2 m^{-2}), and of the edge area road 5.41 and 9.04 cm^2 m^{-2}, respectively.

The size distribution of the plastic particles found is shown for both samplings in combined form in Fig. 6. The particle areas of the 1st and 2nd samplings ranged between

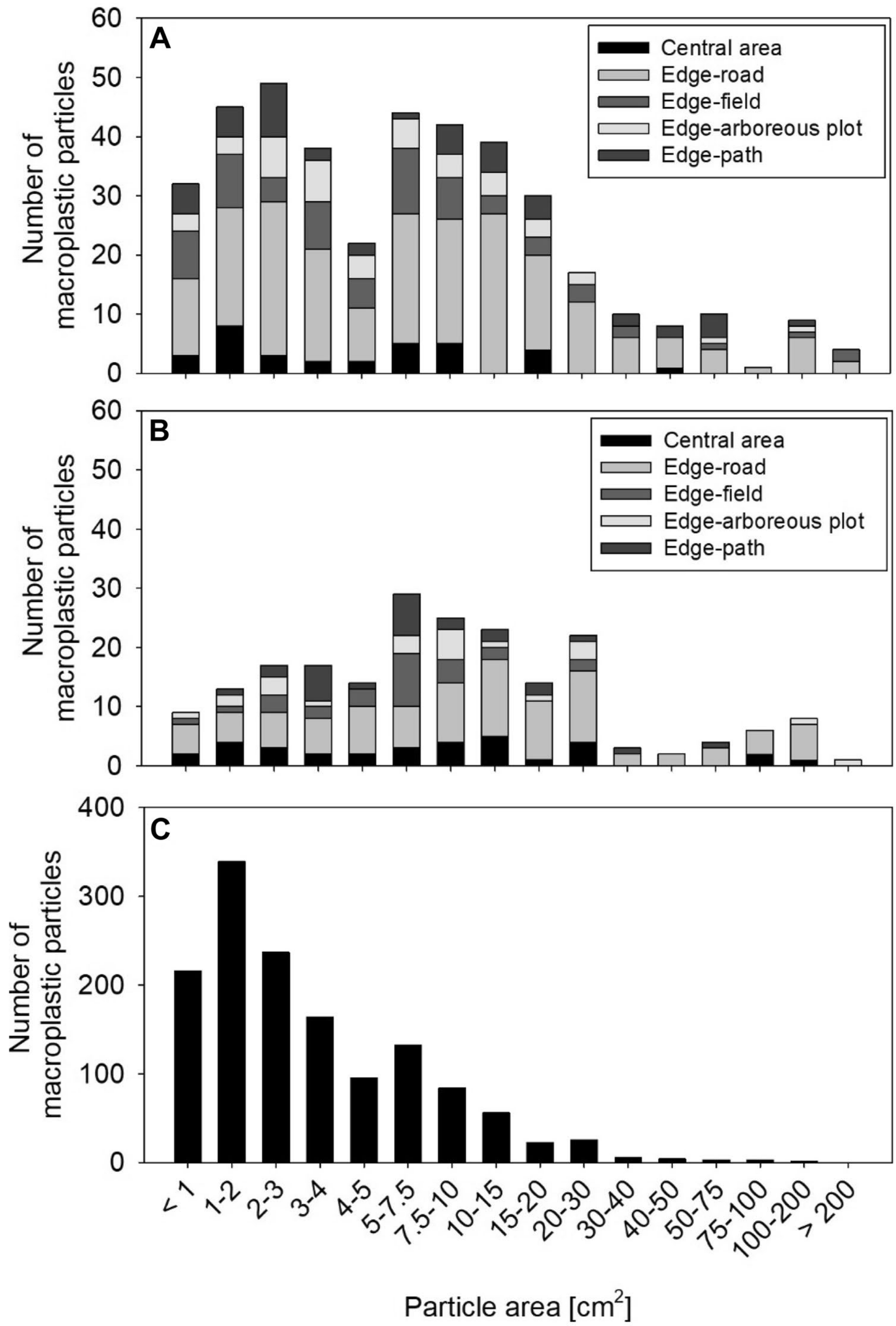


Fig. 6 Number of particles of specific size found at different sampling sites during the 1st sampling **A** and 2nd sampling **B** of Field 1 as well as Field 2 **C**

0.21–440.8 cm^2 and 0.27–210.3 cm^2, respectively. The 1st sampling (Fig. 6A) revealed that more than 85% of the particles found had an area smaller than 20 cm^2. For the 2nd sampling (Fig. 6B), 77.8% were smaller than 20 cm^2. In total, 502 particles were found during the two samplings with an area < 20 cm^2 and 22 particles with an area > 100 cm^2.

Overall, 75.1% (456) of the particles consisted of films, 22.2% (135) of fragments, 2.0% (12) of particles in the category other, and 0.7% (4 particles) of fibers. By comparing 1st and 2nd samplings, the categories other and fibers showed low values between 0 and 4.5%. The comparison of the categories foils and fragments, however, showed larger differences (1st sampling: 70.5% foils and 26.5% fragments, 2nd sampling: 84.1% foils and 14.0% fragments). It should be emphasized that in both samplings, the highest percentage of fragments was found on the edge-road area (34.9% and 21.2% of the particles found, respectively, not shown).

The color analysis revealed that the particles sampled were black (33.6%), multicolored (22.7%, at least 2 recognizable colors, imprints, or coatings), white (16.3%), transparent (15.3%), and blue (5.9%). The category other (6.1%) includes other colors (green, red, gray, yellow, orange, and brown), which were grouped together due to the small individual percentages of the total number of particles. A total of 98.0% of all particles found were in fragmentary condition, and only 2.0% were found unfragmented.

3.2 Field 2

The central area of Field 2 could only be examined once due to sowing at the time of sampling. A total of 1387 particles were found on the investigated area of 1500 m^2. Extrapolated to 1 ha, this corresponds to 9247 particles (not shown).

Photo-analysis of the particles found resulted in a total area of 6443.18 cm^2 for the central area and a macroplastic coverage of 4.30 $cm^2\ m^{-2}$. Individual particle areas ranged from 0.12 to 161.53 cm^2 and had a mean particle area of 4.65 $cm^2 \pm 8.31$ cm^2. The amount of macroplastic was 3.14 kg ha^{-1} (not shown).

The size analysis of the plastic revealed that 97.0% (1345 particles) had an area smaller than 20 cm^2 and 75.8% (1,051 particles) had an area smaller than 5 cm^2, while 24% (339 particles) were found between 1 and 2 cm^2. The particle areas ranged between 0.1 and 161.5 cm^2, with only 7 particles having an area larger than 50 cm^2 (Fig. 6C).

In total, 56.2% (779 particles) of the particles were in the shape category foils, 35.9% (498 particles) in the category fragments, 5.3% (73 particles) in the category other, and 2.7% (37 particles) in the category fibers. The color analysis revealed a color distribution of multicolored (18.9%), blue (18.5%), white (16.4%), transparent (15.8%), black (11.5%), green (10.5%), and other (8.4%). Most particles were fragmented or incomplete (96.8%, 1,342) and only 3.2% (45) were complete.

4 Discussion

The results obtained from the central areas of Fields 1 and 2 indicate significant differences in the total number of particles, macroplastic coverage (Figs. 5 and 6), plastic types, and mass. Furthermore, the substantial differences in quantity, particle shapes, sizes, and distribution across the study areas indicate differing macroplastic input pathways. The increased proportion of macroplastic particles on the central area of Field 2 (Fig. 6) indicates that particles were deliberately spread and less likely transported by atmospheric processes. Piehl et al. investigated a conventionally managed arable area for macroplastic and microplastic in rural areas, and Sexlinger et al. investigated a total of 13 agricultural areas for microplastic and macroplastic on behalf of the Institute for Environmental and Food Safety of the State of Vorarlberg, Austria (Piehl et al. 2018; Sexlinger et al. 2019). Furthermore, few studies exist on plastic pollution in the context of other land uses (Huerta et al. 2017; Liu et al. 2014; Zylstra 2013). The area studied by Piehl et al. was comparable to Field 1 in terms of management conditions, with the biggest difference being the road perimeter of Field 1 compared to the area surrounded by other croplands (Piehl et al. 2018). Only on-farm manure from cows and pigs as well as ammonium nitrate fertilizer were applied. Piehl et al. found a total of 81 macroplastic particles on a study area of circa 0.39 ha and calculated a macroplastic concentration of 206 particles per ha. This shows, compared with the determined macroplastic concentration of 220 particles per ha on Field 1, that the found macroplastic concentration agrees with previous published studies. The degree of coverage on the studied area of Piehl et al. corresponds to 0.46 $cm^2\ m^{-2}$ (own calculation using the study area of 0.39 ha and the determined sum of area of particles of 0.18 m^2) and is thus by a factor of 1.2 to 3.1 higher than for Field 1 (Fig. 5B). The mass analysis of the macroplastic particles turns out to be very similar for Field 1 with an average of 0.055 kg per ha to the 0.066 kg per ha found by Piehl et al. Contamination of Field 2 shows discrepancy to both results with 3.14 kg per ha. Compared with the results of Field 2, the pollution found on Field 1 and the results of Piehl et al. can be considered relatively low (Piehl et al. 2018). The overall size of Field 2 (6.6 ha), and thus the large distance to all field boundaries and edges, reduces the probability of finding littered plastic products in homogeneous distribution in the center area. Both the central area and the remaining area exhibited relatively homogeneous plastic contamination (e.g., distance between particles and finding multiple individual parts of a particle). This was noticeably different from the central area of Field 1, where the distribution appeared largely inhomogeneous and generally a lower number of plastic particles were found. Although inputs from littering, atmospheric processes, or plastic products dislodged or falling from agricultural machinery during ongoing farming operations cannot be ruled out, it is assumed that such input pathways would lead to an inhomogeneous distribution of plastic on the area even in the case of large input amounts. During the sample analysis of Field 2, numerous particles were found that could be related to compost or garden waste. To mention are products, such as plastic stickers for fruit products, labels with a clear reference to horticulture, cosmetic, or care products (e.g., make-up brushes or toothbrushes). From this, it can be concluded that improper waste management and eventually spreading by compost application might be the major reason for the significantly higher macroplastic contamination of Field 2.

A substantial influence of compost use on plastic pollution of agricultural soils was also found in earlier studies (Bläsing and Amelung 2018; Weithmann et al. 2018). Sexlinger et al., during their investigation of 13 agricultural plots for macroplastic and microplastic, determined very high soil coverage rates of 14 and 48 $cm^2 m^{-2}$, respectively, on two arable plots where farm manure (bedding from ski production waste) was used (Sexlinger et al. 2019). On three croplands with the use of sewage sludge compost, values between 2 and 8 $cm^2 m^{-2}$ were determined, which are in a similar order of magnitude to the coverage of 4.30 $cm^2 m^{-2}$ on the central area of Field 2. In contrast, Sexlinger et al. determined comparatively low coverages of 0–2 $cm^2 m^{-2}$ on four reference plots that were managed organically and to which only on-farm fertilizers were applied (Sexlinger et al. 2019).

In general, the least plastic contamination was found in the central area compared to the peripheral areas. This trend was evident for the 1st and 2nd samplings of Field 1 (Fig. 5). Both samplings also showed a similar tendency between the edge areas. The edge areas field, arboreous plot, and path with an average particle count of 1022 particles per ha and an average coverage of 1.37 $cm^2 m^{-2}$ showed noticeably lower macroplastic pollution compared with the edge area road with an average particle count of 3528 particles per ha and an average coverage of 7.22 $cm^2 m^{-2}$ (Fig. 5B). The high particle counts in both sampling events, the increased number of fragments, and the multiple findings of food packaging, such as beverage bottles, candy wrappers, or beverage cups, on the road edge plot indicate inputs from littering. Statements of the farmer of Field 1 confirmed the increased amount of litter. During the sampling, glass bottles, beverage cans, and other foreign materials were found. The inhomogeneous distribution of plastic particles on the central area and on the edge areas indicate diffuse input paths, such as littering or the accidental loss of plastic products. The results of the edge analysis confirm the substantial plastic input pathway through littering on agricultural land. This is in line with earlier studies where a mismanagement of waste (littering, dumping, and other types of improper disposal) was responsible for most plastic emissions (Kawecki and Nowack 2019, 2020). For general statements with statistical certainty about the differences between plastic contamination on different areas of agricultural land, or the influence of tillage, more areas need to be investigated.

5 Conclusions

The quantitative data obtained in this study contribute to the classification of the extent and input pathways of plastic contamination on arable land without agrotechnical plastic use. By directly comparing two areas, which differed mainly in the use of organic fertilizers, the influence of compost use on the contamination of arable area with macroplastic was shown. In addition, the differences in field contamination on the different field areas made it possible to identify the diffuse macroplastic input on arable land due to littering. The method of phototechnical particle analysis used for this purpose offers the possibility to determine pollution levels of different fields in a comparatively simple way. The knowledge gained in this study will contribute to the often uncertain, incomplete knowledge about quantities, impacts, and fate of plastic in the terrestrial environment.

Author contribution Nikolas Stefano: Conceptualization, Methodology, Investigation, Reviewing and Editing. Daniel Pleissner: Conceptualization, Writing — Original draft preparation, Reviewing and Editing.

Funding Open Access funding enabled and organized by Projekt DEAL.

Availability of data and material Not applicable.

Code availability Not applicable.

Declarations

Conflict of interest Not applicable.

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