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Identifying hot-spots for microplastic contamination in agricultural soils—a spatial modelling approach for Germany

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E-mail: elke.brandes@thuenen.de**Keywords:** sewage sludge, compost, biowaste, plasticulture, mulch film, microplastic pathways, microplastic emissionsSupplementary material for this article is available [online](#)

Abstract

Microplastic (MP) contamination in agricultural soils has recently gained significant attention in science and society. The continuous plastic waste generation and its low degradation rates indicate a cumulative effect of MP in the environment that calls for more research on the amounts and impacts of this contaminant. The most discussed agricultural sources for MP contamination of cropland are sewage sludge, compost, and plasticulture residues. However, knowledge about how much MP has been emitted into agricultural soils is scarce. Since MP distribution in soils is expected to be highly heterogeneous, its analysis in field samples provides mainly point information. To quantify the various MP sources and pathways within and across ecosystems, data-driven models represent crucial tools to scale these analytic results to a landscape level and to simulate effects of mitigation measures. Some recent modelling studies have estimated MP emissions based on production and consumption statistics at national level, but as of yet, spatially explicit regional quantification of MP emissions into agricultural soils are virtually missing in the scientific literature. Using data on MP analysis results from the literature in combination with national and regional statistics on sewage sludge, compost and organic waste production, as well as speciality cropping areas, we estimated the spatial distributions of cumulative MP mass inputs into agricultural soils in Germany. Although these estimates are based on limited data availability, our results provide first indications about locations where detailed soil analysis could be useful to investigate *in situ* processes and impacts. The methodology can be applied to other regions and continuously adapted when more knowledge on relevant sources, transport, accumulation, and degradation rates of MP in soils is gained in the future.

1. Introduction

Over the last few years, researchers of many diverse disciplines have taken on the challenge to embrace a novel field in global change research: the continuous generation of plastic waste and consequently its release and accumulation, particularly in the form of microplastics (MPs), in the environment. There is some knowledge of MP pollution in the marine environment established. Quantities, movements, effects of biofilms, and degradation processes, amongst others, have been investigated in numerous studies

(Eriksen *et al* 2014, Andrady 2017). Although MP has also been detected in the terrestrial environment more than a decade ago (Zubris and Richards 2005), the necessity for a better understanding of MP sources and pathways in soil ecosystems has only recently been addressed in the scientific community (Rillig 2012). Attempts to quantify these potential pollutants in soil matrices have been made mainly on the larger particle fraction (Piehl *et al* 2018, Harms *et al* 2021). Since the preparation of soil samples to isolate and quantify MP particles of sizes <1000 μm brings about tremendous challenges (Thomas *et al* 2020),

few quantitative results exist and those that can be found in the literature are often difficult to compare, as they are based on different extraction and quantification methods as well as inconsistent size ranges (Fuller and Gautam 2016, Scheurer and Bigalke 2018, Zhang *et al* 2018). Hence, comprehensive knowledge of MP concentrations in soils is currently lacking. Besides accumulating in the soil, MP are also leaving the soil with water and wind erosion, although scientists are only beginning to shed light on these processes (Rehm *et al* 2021, Bullard *et al* 2021).

Despite this knowledge gap, the general public demands stricter regulations by the authorities to mitigate MP release, a call that is justified relating to the precautionary principle, but has partly been amplified by alarmist media coverage, interpreting potential risk as an immediate harm (Backhaus and Wagner 2019). Specifically, the agricultural sector has been recently brought into focus as a source of MP emissions into soils through contaminated compost and sewage sludge application (Nizzetto *et al* 2016, Weithmann *et al* 2018) as well as plasticulture (e.g. coverage for earlier harvest, mulching, or pest control nets, Steinmetz *et al* 2016). Even though other emission pathways, e.g. through tire wear or littering, have been estimated as prominent among the diverse sources on a national scale (Bertling *et al* 2018, Kawecki and Nowack 2019), MP inputs from agricultural practices play a significant role according to recent study results (Kawecki and Nowack 2019). Since these agricultural MP emissions are assumed to be distributed as a factor of cropping system (e.g. speciality crops) and management practices (e.g. organic soil amendments), their spatial distribution is assumed to be highly heterogeneous. Bearing in mind the complexity of measuring large numbers of soil samples, it appears reasonable to use modelled estimates as first approximations to identify areas of high MP pollution in agricultural soils that can be assessed in further observational studies.

In this paper we aim to relate input quantities of the three major agricultural MP sources and identify regional pollution hotspots. Germany, a country characterised by substantial, intensively managed agricultural area, the highest plastic demand in Europe (PlasticsEurope 2021) and a significant per capita plastic waste generation rate (Jambeck *et al* 2015), was chosen as a case study.

2. Methods

We estimated MP inputs into agricultural soils in Germany by the three sources most prominently discussed in association with agricultural practices: Sewage sludge and compost applied in agriculture, as well as plastic film used for earlier harvest or mulching of speciality crops (referred to as plasticulture for simplicity). Due to best data availability, we based our estimates on 2012 (for mulch film) and 2016

(for sewage sludge and compost) as the reference year and calculated annual additions for each previous year back to the initial year of MP emission for each of the three pathways. For plasticulture, we also estimated emissions for 2013–2016. In this way we were able to integrate annual emissions over the time spans relevant for each contamination source, resulting in cumulative MP emissions into soils. The spatial distribution was modelled on a modified NUTS3 (county) resolution, where administrative areas of cities were combined with surrounding NUTS3 regions. Table 1 summarizes the key parameters of the model. Table S1 (available online at stacks.iop.org/ERL/16/104041/mmedia) summarizes the data used in the model.

2.1. Sewage sludge

To estimate the amounts of MP entering the environment through sewage sludge and compost, an average MP concentration in the substrate was multiplied by the amount of the respective substrate associated to each regional unit. The accumulated MP amounts were then calculated as the sums of the annual substrate additions since the first year of considered application.

The national mean MP concentration in sewage sludge in 2016, C_{2016}^{SL} , of 0.56 wt. % MP DW⁻¹ is an estimate of MP amounts from the various emission pathways collected in sewage sludge (Bertling *et al* 2018) (SI). This estimate was chosen as a starting point since no mass-based analytic data on MP concentration have been published for Germany. The sewage sludge masses produced for agricultural use per NUTS3 region i in 2016, M_{i2016}^{SL} , were taken from the national and federal statistical services (Federal Bureau of Statistics 2016b). The MP masses in Mg per NUTS3 region i in 2016 were calculated accordingly:

$$MP_{i2016}^{SL} = C_{2016}^{SL} \times M_{i2016}^{SL}. \quad (1)$$

To account for a gradual increase of MP release into the waste water stream since the beginning of plastic use, MP concentrations in sewage sludge before 2016 back to 1983 (the year of the first statistical record of sewage sludge production in Germany) were estimated based on global polyester production numbers (IVC 2018). An exponential function was fitted to the global polyester production values from 1975 to 2015 (figure S1). A unitless annual correction factor ACF_k^{SL-C} to normalise the annual MP concentrations for each year k was calculated as:

$$ACF_k^{SL-C} = \frac{PET_k}{PET_{2016}}, \quad (2)$$

where PET_k and PET_{2016} refer to the fitted global polyester production in year k and the actual polyester production in year 2016, respectively. The annual mean MP concentration in sewage sludge in year k was then calculated as:

$$C_k^{SL} = C_{2016}^{SL} \times ACF_k^{SL-C}. \quad (3)$$

Table 1. Selection of key assumptions and parameters for the applied model. DW = dry weight, N/A = not applicable.

	Sewage sludge	Compost	Tarps and mulch films
Reference year	2016	2016	2012
Start year	1983	1990	1960
Last year	2016	2016	2016
Years of application	34	27	57
MP concentration in reference year (mg kg ⁻¹ DW)	5645	368.5	N/A
Temporal dynamics of MP concentration	Increase	Constant	N/A
Basis for spatial distribution	Production	Production	Application

To integrate the annually added MP amounts over the whole time period, a scaling factor I^{SL} was calculated as:

$$I^{SL} = \frac{\sum_{k=1983}^{2016} (C_k^{SL} \times M_k^{SL})}{C_{2016}^{SL} \times M_{2016}^{SL}}, \quad (4)$$

where M_k^{SL} is the national sum of sewage sludge used in agriculture in year k (figure S2). Finally, the cumulative MP amounts in each NUTS3 region i were calculated using this scaling factor:

$$MP_i^{SL} = MP_{i2016}^{SL} \times I^{SL}. \quad (5)$$

2.2. Compost

In contrast to sewage sludge, statistical data on compost production are not available on a NUTS3 resolution. Therefore, regional compost production in 2016 was estimated from biowaste collection data (Federal Bureau of Statistics 2016a) and then scaled to the amounts at NUTS1 (federal state) level. For 2016, data of produced compost was provided by the Statistics Bureaus of the federal states.

The potential compost mass \tilde{M}^{CO} that was produced from biowaste mass M^{BIO} in NUTS3 region i was calculated by a simplified equation, assuming that a mass reduction of 50% occurs during the composting process:

$$\tilde{M}_i^{CO} = M_i^{BIO} \times 0.5 \times F_{cd}. \quad (6)$$

The factor F_{cd} was derived from comparing the masses of biowaste collected and biowaste delivered to the composting plants (Federal Bureau of Statistics 2018) in Germany between 2004 and 2016, resulting in 1.53. This means that 1.53 times of the biowaste recorded by household collection systems was delivered to the composting plants in total. The offset describes the share of biomass from sources other than households (e.g. public parks, industry).

To account for the fact that not all of the produced compost ended up on agricultural land, a correction factor CF^{CO} was calculated for each NUTS1 region j , using the compost data of 2016 $M^{CO}_{destatis}$ (total compost produced for agricultural use) and the sums of potential compost of 2016:

$$CF_j^{CO} = \frac{M_j^{CO}_{destatis}}{\sum \tilde{M}_i^{CO}}. \quad (7)$$

Then, the compost amounts produced for agricultural use in 2016, M^{CO}_{2016} , were estimated by multiplying \tilde{M}_i^{CO} with the NUTS1 specific correction factor CF_j^{CO} :

$$M_{i2016}^{CO} = \tilde{M}_i^{CO} \times CF_j^{CO}. \quad (8)$$

The national mean MP concentration in compost, C^{CO} , of 0.037 wt. % MP DW⁻¹ was taken from results of compost samples analysed visually in 2016 and 2018 by the German Compost Quality Assurance Organisation (Bundesgütegemeinschaft Kompost e.V.). Since only plastic particles >2 mm were considered, we added 10% to account for the smaller MP fraction, as suggested by Kehres (2019). Due to lack of historic data, we assumed that this concentration did not change over time since 1990. We calculated the MP amounts from compost in 2016 per NUTS3 region i similarly to those originating from sewage sludge equation (1) as:

$$MP_{i2016}^{CO} = M_{i2016}^{CO} \times C^{CO}. \quad (9)$$

For years before 2016, compost masses per NUTS3 region were assumed to change proportionally with the annual masses of compost used in agriculture, M_k^{CO} . These were available from statistics for some years (Federal Bureau of Statistics 2018), for others they were gap-filled and linearly extrapolated from biowaste data (figure S3). To integrate the annually added MP amounts over the whole time period, a scaling factor I^{CO} was calculated as:

$$I^{CO} = \frac{\sum_{k=1990}^{2016} (C^{CO} \times M_k^{CO})}{C^{CO} \times M_{2016}^{CO}}. \quad (10)$$

This factor I^{CO} was then applied to the 2016 NUTS3 region data to calculate the cumulative MP amounts in the soil:

$$MP_i^{CO} = MP_{i2016}^{CO} \times I^{CO}. \quad (11)$$

Table 2. Coefficients used to calculate MP emissions from plastic mulch film and cover tarps. Crop categories shown are asparagus (ASP), strawberries (STR), cucurbits (CUC, including cucumbers, summer squash, and winter squash), lettuce (LET), and early potatoes (EPO). AP_{2012}^{SC} is the fraction of the area of the respective speciality crop category on which plastic mulch film or cover tarp was actually applied in 2012. L^{SC} is the loss factor as a function of film thickness TH . D^{LDPE} is the density of light density polyethylene, and FM^{SC} is the mass of foil per ha.

Crop category	AP_{2012}^{SC}	L^{SC}	TH (m)	D^{LDPE} (kg m ⁻³)	FM^{SC} (kg ha ⁻¹)
ASP	1.0	0.0010	0.000 100	917.5	917.500
STR	0.5	0.0027	0.000 040	917.5	367.000
CUC	1.0	0.0094	0.000 030	917.5	275.250
LET	0.5	0.0100	0.000 025	917.5	229.375
EPO	1.0	0.0100	0.000 025	917.5	229.375

2.3. Plasticulture

We based our calculations for MP emissions by plasticulture on production data of speciality crops usually grown with the use of plastic cover tarp (asparagus) or mulch film (strawberries, lettuce, cucurbits, early potatoes). We considered only these two types of film, since they represent a major share of plastics used on the field throughout the growing season. We categorized crops into asparagus (ASP), strawberries (STR), cucurbits (CUC, including cucumbers, summer squash, and winter squash), lettuce (LET), and early potatoes (EPO). Production data of vegetable categories and strawberries are available from a 2012 survey conducted in those NUTS3 regions with highest speciality crop cultivation areas in Germany (table S1). For each crop category, NUTS3 regions without information were gap-filled by equally distributing the difference between the sum of the NUTS3 regions with information and the sum of the next higher administrative area (NUTS2) per ha polygon area. In case of missing data, the same was performed for the next higher level (NUTS1) until all NUTS3 regions were filled with a crop area (figure S4).

Crop areas for early potatoes, a crop that is commonly grown with plastic film in Germany, was surveyed for the last time in 2007 (RDC Germany 2018a), whereas the latest nationwide statistical data for total potato cropping areas on NUTS3 resolution are available for 2010 (RDC Germany 2018b). 2012 early potato crop areas were assumed the same as 2010 areas. These were calculated for each NUTS3 region i from the ratio of early potato to total potato crop area in 2007 as:

$$A_{i2012}^{EPO} = A_{i2010}^{EPO} = A_{i2012}^{POT} \times \frac{A_{i2007}^{EPO}}{A_{i2007}^{POT}}, \quad (12)$$

where A_i^{EPO} and A_i^{POT} are the cropping areas of early potatoes and total potatoes, respectively. For the regions with missing data for early potatoes, a share of 3% of the total potato crop area was assumed.

With these combined crop area data sets as a basis, we calculated the amount of MP that remained in the soil in 2012 from each crop category SC, based on some simplifying assumptions described below, as:

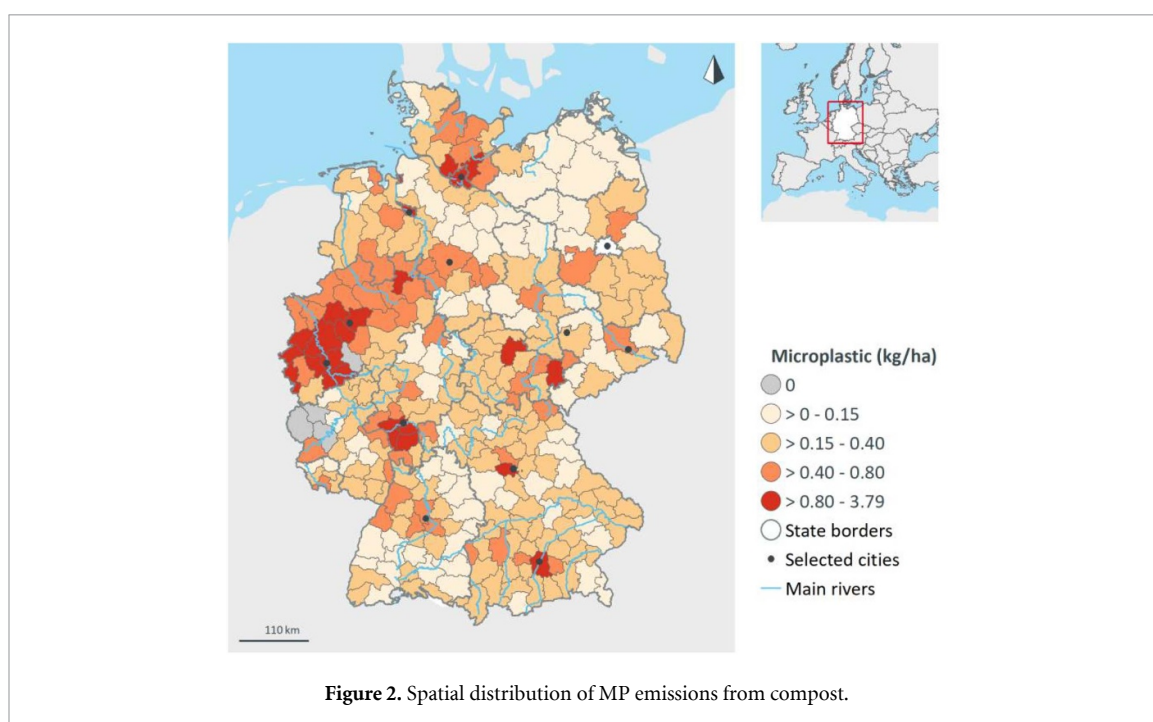
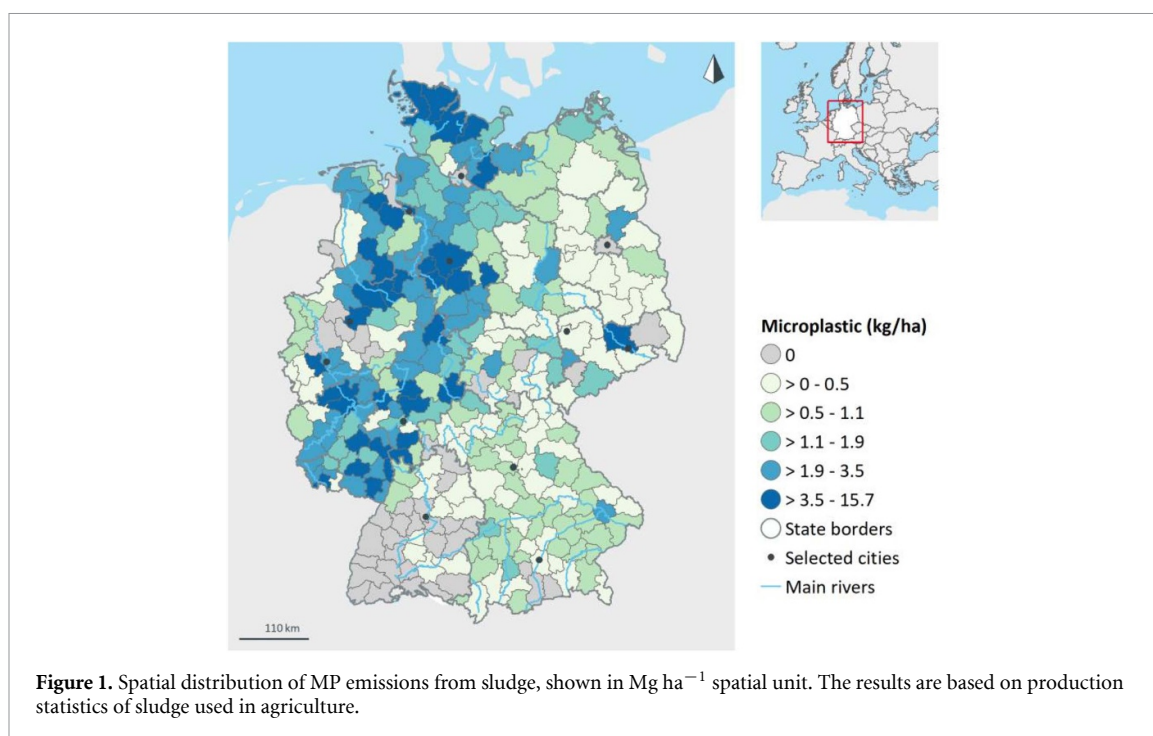
$$MP_{i2012}^{SC} = A_{i2012}^{SC} \times AP_{2012}^{SC} \times L^{SC} \times FM^{SC}, \quad (13)$$

where A_{i2012}^{SC} is the area of the respective speciality crop category grown in NUTS3 region i . AP_{2012}^{SC} is the fraction of A_{i2012}^{SC} on which plastic mulch film or cover tarp was actually applied in 2012 (1 for asparagus, cucurbits, and early potatoes, 0.5 for strawberries and lettuce). L^{SC} is the crop specific loss factor, describing the percentage of foil remaining on the field per year on average as a function of foil thickness TH . FM^{SC} is the mass of foil per ha (depending on plastic material and foil thickness), calculated as $FM^{SC} = TH \times 10000 \times D^{LDPE}$, where D^{LDPE} is the density of LDPE (light density polyethylene), the most commonly used plastic type for agricultural film. Crop specific parameters are shown in table 2.

To account for MP input in the years before and after 2012, a scaling factor was calculated from an assumed increase in plastic use in agriculture since 1960 derived from the literature (Hussain and Hamid 2003, Kasirajan and Ngouajio 2012, figure S5).

2.4. Mean inputs per soil mass

To estimate MP cumulative inputs into a kg of agricultural soil, it was assumed that MP is mixed homogeneously into the ploughing horizon (typically the upper 30 cm), and that the bulk density of soil is 1.2 kg l⁻¹. The most uncertain variable, the total application area of all considered years, was approximated by a lower and upper boundary value based on two assumptions. The lower boundary was calculated by assuming that both soil amendments were distributed across the total agricultural area. The upper boundary was calculated by assuming that the allowed maximum application rate (5 Mg ha⁻¹ and 30 Mg ha⁻¹ every three years for sludge and compost, respectively) had been applied throughout the years. In other words, these are the maximum amounts of MP that could have been incorporated into a field in accordance with current regulation. For MP cumulative inputs from plasticulture, the lower boundary was calculated by using the total cropping area of all vegetables, early potatoes, and strawberries in 2012 as reference area. The upper boundary was calculated by using the total cropping area of those crops considered to be grown with mulch film and cover tarp in 2012.



3. Results and discussion

The results show estimates of MP masses that have been cumulatively emitted into soils by application of sewage sludge and compost, as well as through residuals of cover tarp and mulch film used in agriculture.

3.1. Regional distributions of MP inputs

On the NUTS3 scale, cumulative MP inputs, expressed as kg ha^{-1} of the spatial unit, range between 0 and 15.7 kg ha^{-1} for sludge (figure 1),

between 0 and 3.79 kg ha^{-1} for compost (figure 2) and between 0 and 5.18 kg ha^{-1} for plasticulture (figure 3). The area-weighted mean values, 1.34 kg ha^{-1} , 0.32 kg ha^{-1} , and 0.07 kg ha^{-1} for sludge, compost, and plasticulture, respectively, are larger than the median (table 3), and only one NUTS3 region lies above 10 kg MP ha^{-1} from sludge and above 1 kg MP ha^{-1} from plasticulture, respectively. The emissions associated with the sludge pathway show clear differences between the federal states due to differing state practices and regulations. High MP emissions in the north-west region of Germany

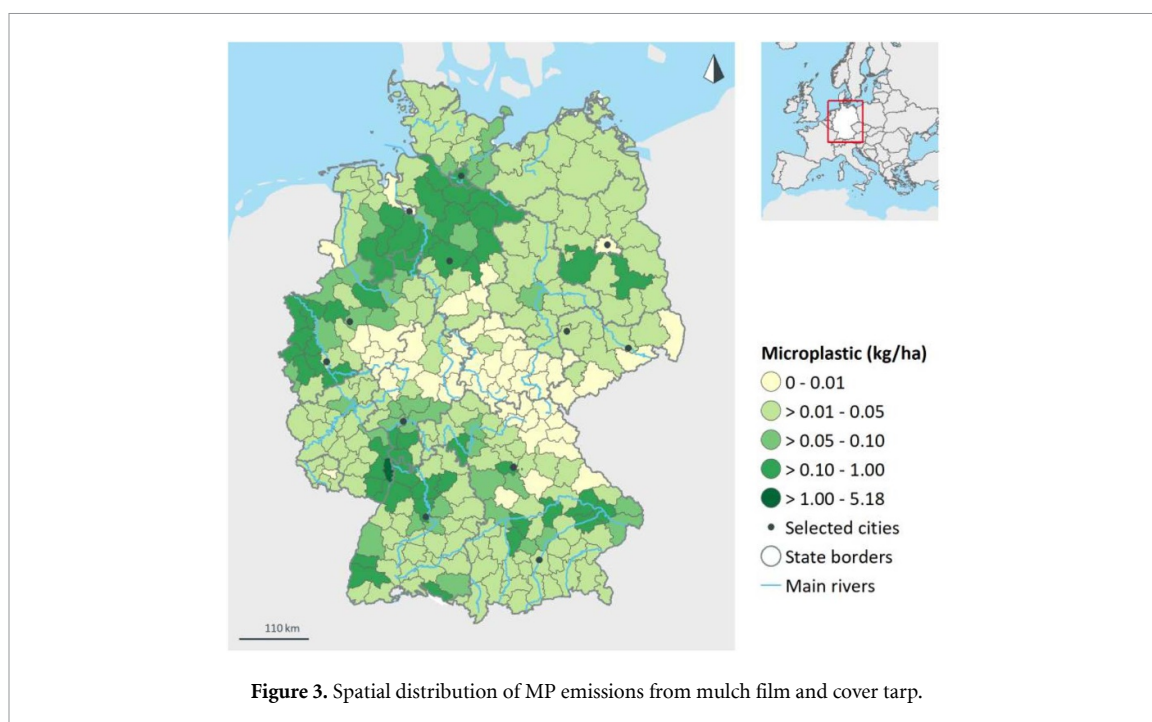


Figure 3. Spatial distribution of MP emissions from mulch film and cover tarp.

Table 3. Modelling results of MP inputs on national scale and statistics.

	Sewage sludge	Compost	Tarps and mulch films
MP in reference year (Mg)	2391	606	98
Cumulative MP (Mg)	45 393	10 436	2490
Area-weighted mean of cumulative MP (kg ha^{-1})	1.34	0.32	0.07
Minimum (kg ha^{-1})	0.00	0.00	0.00
25th percentile (kg ha^{-1})	0.18	0.14	0.02
50th percentile (median, kg ha^{-1})	0.72	0.26	0.03
75th percentile (kg ha^{-1})	2.05	0.42	0.06
Maximum (kg ha^{-1})	15.26	3.78	4.92

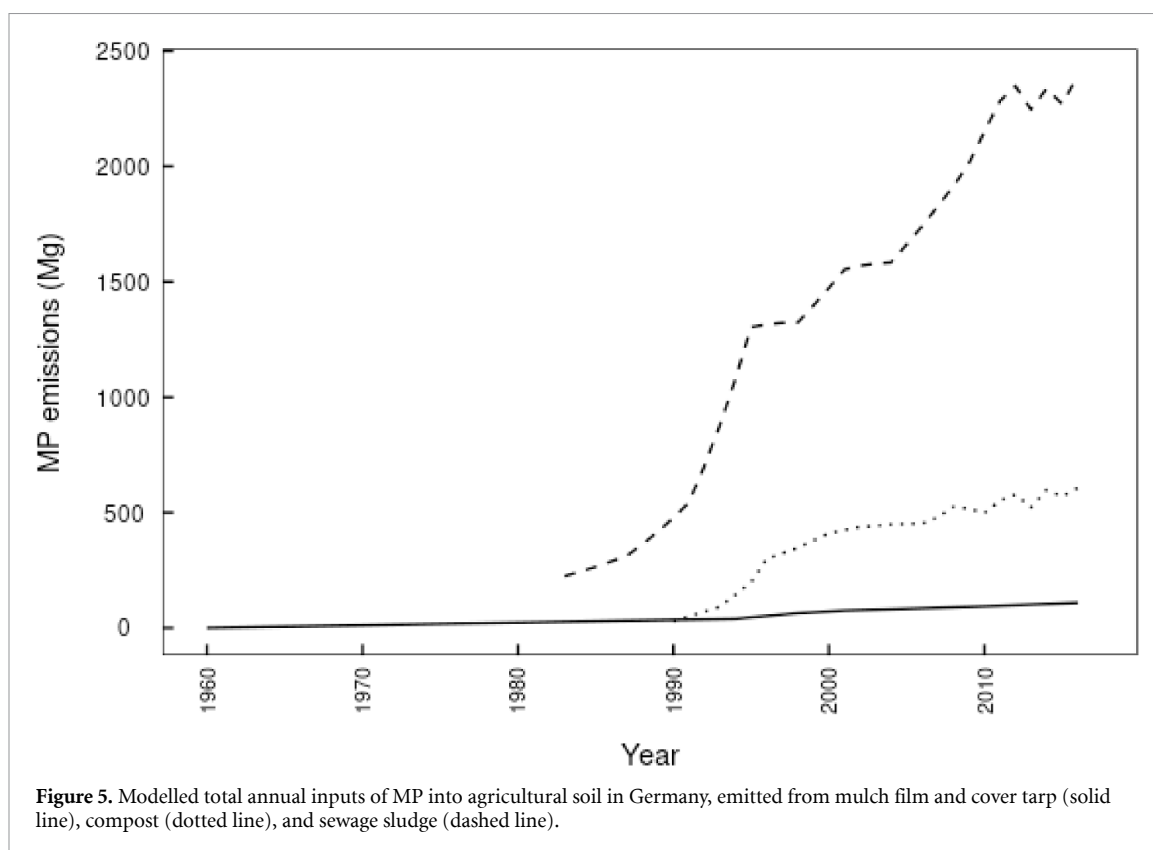
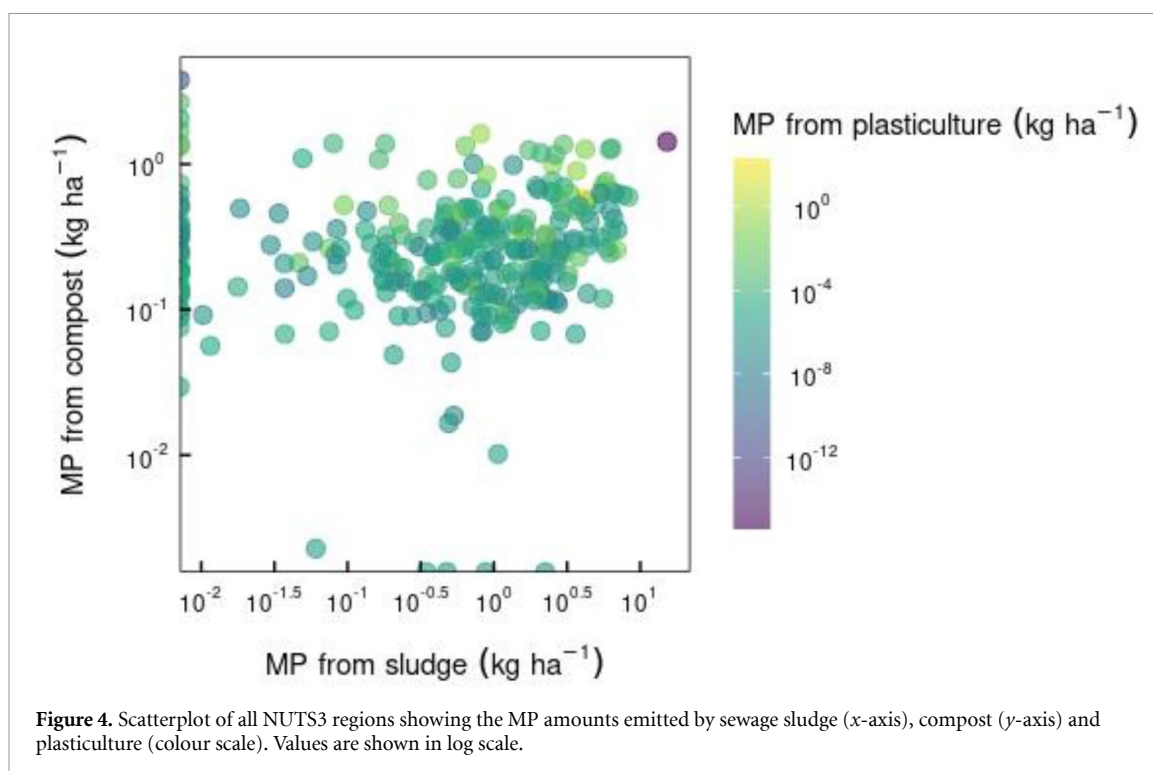
(figure 1) are caused by both high sludge production due to high population density, and high rates of agricultural utilization. Highest MP emissions from compost are localized around agglomeration areas such as the Ruhr district in the west and the city of Hamburg in the north (figure 2). Although at much lower amounts in general, MP emissions from plasticulture are spatially represented as two geographical belts of comparably high impact, one spanning from west to north Germany, and the other from southwest to southeast Germany (figure 3). These areas overlap with regions where primarily speciality crops are produced for climatic and historico-cultural reasons.

An explorative analysis of possible connections between the results of all three input pathways for each NUTS3 region does not reveal any correlation between MP emission amounts of the three sources (figure 4). The quantities per region are not evenly distributed, but strongly skewed toward 0 for all sources (note the log scale in figure 4). This lack of correlation indicates that factors influencing MP input amounts from the three analysed sources are independent from each other.

3.2. Trajectories of total MP inputs

National MP sums highlight that, according to our assumptions, highest cumulative MP inputs came from sewage sludge application, followed by compost application, and plasticulture (table 3). In the reference years (2016 for sewage sludge and compost, and 2012 for plasticulture), emissions were estimated to be 2391, 606, and 98 Mg for sewage sludge, compost, and plasticulture, respectively.

The considerable differences in cumulative MP inputs from the three sources are also reflected in the historical annual inputs on the national scale (figure 5). Although plasticulture shows the longest history of MP input, the amounts added each year are much lower than those emitted by the other sources considered (4% and 16% of MP added by sewage sludge and compost, respectively, in 2012). Statistical records on sewage sludge application in agriculture include only the western states until 1990. However, sewage sludge production in the 'German Democratic Republic' was negligible (Kraus 2003), and the use of technical advances in sewage processing increased strongly in the 1990s. Although sewage sludge application in agriculture decreased



steadily since 1995 (figure S2), assumed exponential increase in MP concentrations caused a continuous increase in total MP amounts until 2012. At stable MP concentrations in sewage sludge in the future, the impact of this source on soil MP contamination is likely to decline in Germany, as sludge application

in agriculture has decreased strongly with a Fertilizing Ordinance amendment in 2017 (Federal Bureau of Statistics 2021). However, trends in sludge usage are varying in Europe, and agricultural application is still a major disposal pathway in many countries (Kelessidis and Stasinakis 2012).

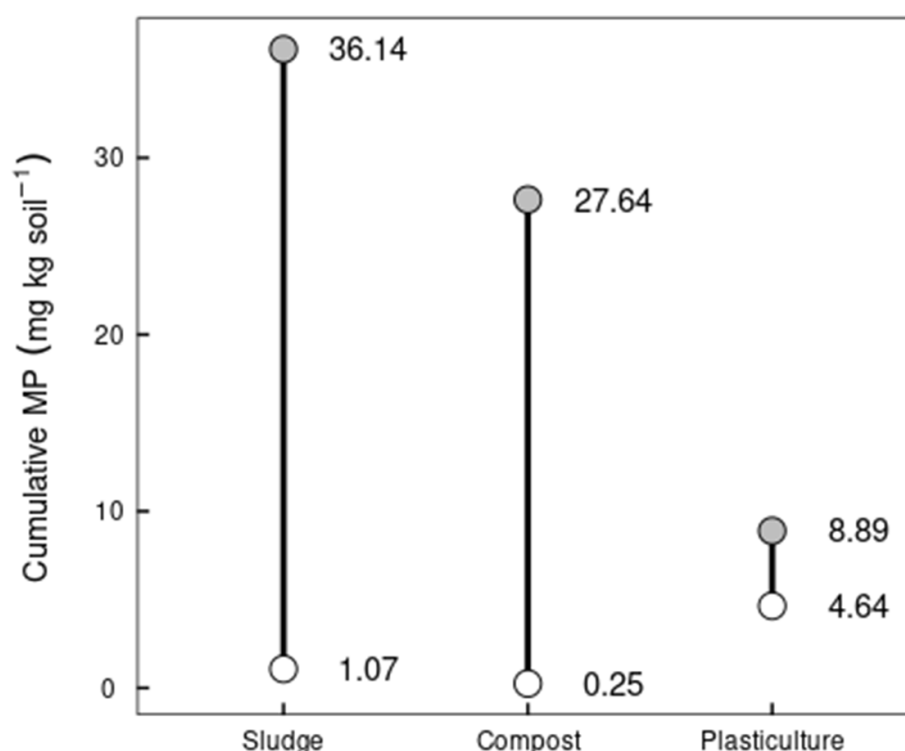


Figure 6. Lower and upper boundary estimates of cumulative mean MP inputs into 1 kg of soil from the three considered sources. The results are based on country wide total inputs shown in table 2, and two assumptions for the reference area: (a) a maximum reference area leading to a minimum MP input (white circles), and (b) a minimum reference area leading to the maximum MP input (grey circles).

Due to a lack of data, we assumed a constant MP concentration in compost based on 2016 and 2018 data. However, it is possible that MP concentrations in compost were lower in the past before the introduction of biobased and biodegradable single-use plastic products that are often discarded with household biowaste. Although large scale public compost production started only in 1990 with the collection of municipal biowaste in Germany, compost application in agriculture is assumed to increase in the future due to political efforts toward a circular economy and improving soil organic carbon storage (European Commission 2015). Due to insufficient knowledge of its origin, we have not included digestates of anaerobic biogas plants into our analysis. While anaerobic digestors have proliferated in Germany as a consequence of the Renewable Energies Act, they are mostly fed with energy crops and manure (Corden *et al* 2019). Nevertheless, food wastes constitute an additional feedstock that carries the risk of plastic contamination and should be considered in future studies.

Finally, intentional plastic use in agriculture is projected to increase in the future as a means of profit optimization and risk reduction. This usage is not limited to mulch film and direct cover but also includes high and low tunnels, irrigation pipes, and protection nets (Scarascia-Mugnozza *et al* 2011). As these potential emission sources can be highly

concentrated in certain regions specialized for fruit and vegetable cultivation, improved spatial data, as well as information on plastic release by these plastic materials are needed to further investigate MP pollution hotspots in horticulture and agriculture.

3.3. Mean MP inputs into soil

The estimates of cumulative MP input expressed in mg MP kg⁻¹ soil show largest ranges between the lower and upper boundary for MP in sludge and compost, and relatively small ranges for plasticulture (figure 6). These results appear plausible, since sludge and compost can be potentially applied to a large area (>11 million ha of agricultural land in 2016), with some restrictions for sludge, which would imply maximum dilution of MP in the soil. In contrast, the spatial concentrations of speciality crop cultivation indicate less variability in the range of potential MP inputs into soil. Areas of vegetable and strawberry production in Germany are relatively small (figure S3) compared to total agricultural land and the focus growing areas have been constant over time. The upper boundary concentrations for sludge and compost should, however, be regarded as theoretical, since these contents would be only reached at maximum allowed application rates. Even though these numbers are very rough approximations, they provide indications on the concentration ranges that can be expected in the field under

a theoretical scenario where all MP stays where it has entered the soil, not considering other sources (e.g. atmospheric deposition). Literature data on MP masses in soils are scarce, and some have been estimated from particle-based analysis results (e.g. Corradini *et al* 2019). The concentrations we found in the literature fall inside our estimated input ranges; Corradini *et al* (2019) reported 0.7–10.3 mg kg⁻¹ in fields with various sludge application rates. In contrast, higher MP amounts of up to 55.5 mg kg⁻¹ were found in flood plain soils in Switzerland (Scheurer and Bigalke 2018). These findings indicate the impact of different processes in riverine areas as compared to agricultural fields on MP accumulation. However, more field data are needed to ground truth our first indicative modelling results.

3.4. Data limitations

In this first approach to a spatially explicit MP emissions model, the absolute numbers should be interpreted with care, since the underlying data basis involves large uncertainties. The statistics on sludge and biowaste data used here only inform about the amounts produced in each NUTS3 region and applied in agriculture, but not on where they were applied. Since transport of nutrient-rich sludge and compost is not uncommon, especially in regions with high manure surplus from animal production, undisclosed application records would yield more accurate results, but would also involve laborious collection of hard copy records and data protection issues. Likewise, the estimates of plastic inputs from cover tarp and mulch film have to be regarded as a first approximation. Accurate, high resolution information on speciality crops relevant for plastic emissions are needed for future research. This could be achieved with a combination of remote sensing, statistical, and survey data of management practices. These data are not only pivotal for plastic contamination estimates, but also for other emissions from agricultural soils that are strongly dependent on land use and management, e.g. of nutrients or greenhouse gases (Kuhr *et al* 2013, Richards *et al* 2017). The very limited information on the emission factors (i.e. MP concentrations in sludge and compost, loss factor of plastic film) does not allow probability distributions as inputs, but this should be done in future iterations of the model, once more data become available. Since MP particle characteristics strongly affect their interaction with the environment, MP composition of sizes, polymer types, and shapes in the different sources should also be included in the model.

3.5. Relevance of modelling MP input into soils

Our results indicate that MP inputs to agricultural land are strongly place-dependent, stressing the importance of spatially explicit estimations on the highest resolution possible. The regional MP loads presented here describe one segment of MP pathways

within the environment. As such, our approach is part of a system level approach needed in order to understand global MP cycles (Rillig and Lehmann 2020). Transport out of the soil and into other ecosystems, such as rivers, lakes, forests, and nature reserves are not accounted for in this study, but mass fluxes, especially by water and wind erosion, can be expected. In observation-based studies, Crossman *et al* (2020) showed that 99% of MP emitted with sewage sludge application can leave the field by runoff and erosion, whereas Corradini *et al* (2019) found an accumulative effect in soils after several sewage sludge applications. These seemingly conflicting points observed emphasise the need for spatial models simulating MP inputs as well as mass flows and behaviour during transport processes. Using an atmospheric model and observed MP depositions, Brahney *et al* (2021) estimated that 5% of MP in the atmosphere is re-emitted from agricultural soil dust in the western U.S., MP amounts leaving the soil through water erosion and runoff have not yet been published. A transfer of MP into waterways is likely driven by episodic rain events and soil properties as shown for soil carbon (Wilken *et al* 2017). First experimental results indicate a preferential emission of MP during both water (Rehm *et al* 2021) and wind erosion (Bullard *et al* 2021). Our area-covering estimates of MP quantities accumulating in soils can be used as input data for hydrological models to calculate MP amounts transported from diffuse sources into the surface water and groundwater systems, and thereby complementing modelling studies on MP point sources to rivers (Siegfried *et al* 2017).

4. Conclusions

Although based on disparate and scarce input data, this first modelling study for Germany provides initial estimates of potential emissions from agricultural activities into soils. In a first approximation, our results identify regions of high risk for MP contamination from the agricultural sector in Germany that should be investigated further. In combination with spatial modelling of other MP entry pathways, such as tire wear or deposition of urban dust, our distributions could indicate the relevance of the investigated sources and draw conclusions on effective mitigation strategies. Our results can be used as input into downstream models that estimate the fate and transport pathways of MP in freshwater ecosystems and the marine environment. In this way, models of different focus and system boundaries should be coupled in future research projects to connect the disparate data on MP abundances in different ecosystems. Our study also reveals the need for a joint effort from government agencies and scientists to provide and analyse data sets that are not publicly available to date. Although this study covers Germany, the generic approach can be implemented to other regions of

the world. Given the need for a systems approach to understanding sources, pathways and fates of MP in the environment, the present model provides a first step in a suite of spatio-temporal models needed to inform effective decision-making.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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