Material flow analysis of plastic in organic waste in Switzerland

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Abstract

Soils have been shown to be a major sink for plastic that is released to the environment. Several agricultural practices have been identified that can result in large plastic flows onto soils, among them the use of plastic-polluted compost and digestate. However, the magnitude of this flow is currently still unclear. The aim of this work was to quantify the flows of plastic with compost and digestate onto soils based on data from Switzerland using Material Flow Analysis (MFA). Input data to the model were based on published data on organic waste management and plastic content in compost. In order to quantify the plastic in the biomass input, measurements were made at an anaerobic digestion plant. Together with published data on the plastic content in compost, the full fate of plastic in organic waste in Switzerland could be obtained from 1985 to 2017. 6300 t/y of plastic enter the system together with organic waste and 6200 t/y are removed and are incinerated. 34.5±7.1 t/y are contained in the solid digestate, 50±11 t/y in compost, 12.4±3 t/y in windrow compost and 2.0±0.4 t/y in solid digestate from codigestion. Overall, 71±11 t/y of plastic are transferred to agricultural soil, 22.4±3.3 t/y to horticulture and 3.6±0.7 t/y to private consumers. Using dynamic MFA, we predict that 1390±390 tonnes of plastic have accumulated in Swiss soils through compost addition since 1985. These values can serve as basis for evaluating the contribution of composting to the plastic pollution in soils.

Highlights

- A full material flow analysis of plastic in organic waste in Switzerland was performed
- The flows of plastic with compost and digestate to soils were quantified
- A total of 1390±390 tonnes of plastic have been transferred to soils in Switzerland since 1985

Introduction

Compost and digestate from organic matter treatment are widely used as fertilizers in agriculture as they are rich in nutrients and organic carbon. Their application onto soil leads to an improvement of soil quality and an increase in crop yields and they can help reduce the carbon footprint of the production chain by reducing the use of synthetic fertilizers (Arthur et al., 2011; Diacono and Montemurro, 2011; Pergola et al., 2018; Ros et al., 2006). In order to take full advantage of these environmental and economic benefits, the quality of the compost and digestate needs to be guaranteed. Along with compost and digestate, various pollutants and pathogens are transferred onto soil (Marcoux et al., 2013; Wei et al., 2017). Many foreign materials may also be improperly disposed of and collected along with organic matter. Insufficient separation causes these foreign materials to remain in the finished products and be released onto soils. One of these common materials contaminating compost is plastic. Plastic pollution has received a lot of attention in past years due to its ubiquity in the environment and its possible adverse impacts on environmental organisms (Burns and Boxall, 2018; Lambert et al., 2014). Plastic in the environment is either present as large objects commonly named macroplastic or as particles smaller than 5 mm called microplastic (Hartmann et al., 2019).

Most of the research on plastic in the environment has focussed so far on water environments, mainly the oceans, while soil pollution by plastics remains mostly unexplored (Blasing and Amelung, 2018). The majority of studies that provide release estimates of plastic to the environment don't distinguish between soil and water and just report overall environmental releases. One reason is that little quantitative knowledge about the sources of plastic to soils is available.

Several reviews have listed the possible flows of plastic onto soils based on a qualitative analysis of plastic uses in agriculture and other sectors (Blasing and Amelung, 2018; Chae and An, 2018; de Souza Machado et al., 2018a; Kalberer et al., 2019; Ng et al., 2018; Nizzetto et al., 2016; Rillig et al., 2017a). Large amounts of plastic are suspected to enter soil environments each year through compost, digestate and sewage sludge application onto fields, irrigation of fields with waste water, plastic mulching in agriculture and littering (Blasing and Amelung, 2018; Ng et al., 2018). However, very few studies have actually quantified the magnitude of plastic flows onto soils. Kawecki and Nowack (2019) were the first to predict the plastic flows to water and soils separately and concluded that 540 ± 140 g/capita/year are emitted to soil as macroplastic and 73 ± 14 g/capita/year as microplastic. Soils therefore receive 40 times more plastic than surface waters (Kawecki and Nowack, 2019). The release of micro-rubber from tires to soils is another very relevant flow of an anthropogenic polymer (Sieber et al., 2020; Sommer et al., 2018; Wagner et al., 2018; Wik and Dave, 2009).

A few studies are available reporting plastic levels in various compost products: concentrations of visible plastic items in compost produced in a plant in Germany ranged from 2.38 to 180 mg kg^{-1} compost, with evidence of additional smaller plastic pieces (Blasing and Amelung, 2018). An average plastic concentration of 1200 mg kg^{-1} was found in a composting plant in Slovenia (Blasing and Amelung, 2018). Depending on the amount of compost and digestate applied and the contamination of the product, the annual input of plastic onto land may be considerable, reaching 0.016-6.3 kg per hectare (Blasing and Amelung, 2018). Also microplastics can be added to soils by sludge-based fertilizers, as evidenced by analysis of fertilizer products and amended soils (Zhang et al., 2020).

The variability of the plastic content in compost and digestate in Switzerland is available from a sampling study in which 139 samples of compost and digestate were analyzed for plastic items larger than 1 mm (Schleiss, 2017) but no data are available for the plastic content in the input to composting or anaerobic digestion (AD) facilities. Blasing and Amelung (2018) state only that a major fraction of the plastic in the source material is removed during the composting process but do not give any quantification. No study is so far available that quantifies the amount of plastic in the raw biomass. A full analysis of the mass flows of plastic associated with biomass is therefore not possible given the current data and no such analysis has been performed.

The waste management system in Switzerland reaches very high collection rates and recovery shares (BAFU, 2017; Hoornweg and Bhada-Tata, 2012) and therefore the contamination of collected organic waste by plastic is a major issue, especially because farmers are only interested in clean compost. Switzerland has already banned the application of sewage sludge on soils in 2003 as an implementation of precautionary provisions for the protection of soils and public health (The Federal Council, 2003). It is therefore also important to get an estimate of the flows of plastic to agricultural soils by the use of compost and digestate.

The aim of this study was to quantify the flows of plastic onto soils in Switzerland together with processed organic waste. This was done by quantifying the flows of organic waste and by deriving the plastic concentrations in the different waste fractions and their behaviour during the treatment process. The approach used to quantify the flows of organic matter and plastic was Material Flow Analysis (MFA), the standard method to quantify stocks and flows of materials within a well-defined system boundary (Brunner and Rechberger, 2004). MFA has been used for example for track the flows of plastic and rubber through society and to the environment (Kawecki and Nowack, 2019; Kawecki et al., 2018; Sieber et al., 2020). Using this approach, we could for the first time quantify the full flows of plastic associated with the treatment of organic waste.

Materials and methods

Estimation of the plastic concentration in produced compost and digestate

The variability of the plastic content in compost and digestate is available from a published sampling study in which 139 samples of compost and digestate from Switzerland were analyzed for plastic items larger than 1 mm (Schleiss, 2017). From this study, the probability distributions of the plastic content in compost and digestate produced in Switzerland can be estimated. A total of 368 facilities treating organic matter exist in Switzerland with different capacities (Mandaliev, 2016): 167 sites with an average capacity of 492 t/a per facility, 131 sites with an average capacity of 2220 t/a per facility, 31 sites with an average capacity of 6183 t/a per facility, and 39 sites with an average capacity of 17724 t/a per facility. Since no information regarding the origin of the samples in the study from (Schleiss, 2017) is available, no correlation can be made between the facility's size and the plastic amount released through it. Instead, one can attribute a randomly drawn plastic content C_i (unit: kg/kg) from the variability distributions to each facility i. One can then multiply it with the amount of compost and digestate produced V_i (unit: tons/year) to obtain an estimate of the total amount of plastic released through this facility, M_i, in tons/year.

$$M_i = V_i \cdot C_i \qquad \text{Eq [1]}$$

If this is done for each facility *i* separately, and the resulting plastic content is summed over all of Switzerland, $\sum_i M_i$, then divided by the total compost and digestate produced in Switzerland V_{CH} (unit tons/year), one obtains an estimate of the plastic content in percent in all the produced compost and solid digestate in Switzerland, C_{CH}:

$$C_{CH} = \frac{\sum_i M_i}{V_{CH}} \cdot 100 \qquad \text{Eq. [2]}$$

The calculation was performed in R and repeated a total of 10'000 times to obtain a probability distribution of the plastic content in compost and solid digestate in Switzerland.

Analysis of plastic content of materials in an anaerobic digestion facility

In order to obtain a first estimate for the removal efficiency during composting and AD, samples of organic waste and solid digestate from an AD facility were used to identify the types of plastic found in collected organic waste and in solid digestate and to estimate the quantity of plastic at different processing stages. The Kompogas® plant with BioMethan Biogas Upgrading located in Winterthur, Switzerland, was chosen as a sampling site, for the convenience of access to the site and the willingness of the plant manager to collaborate. The facility handles source-separated organic waste from municipalities, gardens, and private individuals. It processes approximately 23000 t/a of kitchen and green waste every year from more than 78000 households in the Winterthur and Frauenfeld area, and produces 1050000 Nm^3/a of methane, 10000 t/a of liquid fertilizer and 10000 t/a of solid digestate. Samples were taken from three stages within the treatment process:

1. the conveyor band carrying shredded waste sieved by a 10 cm mesh to the fermentation tank,
2. the sieving residues containing wood pieces, plastics and other foreign bodies that will be sent to incineration,
3. the final solid digestate.

Sampling was performed on five different days over three months (June-August 2017, 15 samples in total), to reflect variations in daily input as much as possible. Samples from the three stages were collected on each day. For each stage, 4.5 L of waste were taken every 40 minutes over two hours. All the collected waste was then mixed and a sample of 4.5 L was taken, weighed, and kept in a plastic bag. The mass, volume, and plastic content of each sample were measured, which generated an overall of three replicates of each sampling point. The waste samples were washed under a running water tap over a 6-mm mesh of 50 x 35 cm diameter and the retained mass dried over a metal tray for four days in an oven at 40°C. The samples were spread on a tray and plastics pieces were collected by visual inspection. The plastic pieces were washed and dried, then weighed and the product type was identified by visual inspection.

In addition, three samples of compost and three samples of solid digestate samples available from the extensive sampling study (Schleiss, 2017) were analysed to obtain their bulk density.

Material flow analysis

The flows of organic matter used for composting and AD as well as the plastic contained in them are modelled using material flow analysis (MFA). Most of the organic waste generated in Switzerland is treated in AD or composting plants. The organic waste processed by other methods is mostly originating from agricultural activities and is considered to contribute less to plastic contamination in compost (Weithmann et al., 2018). The processes considered in the material flow analysis were therefore the organic waste collection and the treatment of the organic waste through composting or AD, excluding organic waste originating from manure and agricultural additives.

A static material flow model was developed using STAN (Cencic and Rechberger, 2008) for the year 2013 for both organic matter and plastic. This year was chosen based on the availability of data for organic waste collection in Switzerland (Mandaliev, 2016). The transfer coefficients calculated within STAN were then exported and used for a dynamic probabilistic material flow analysis (DPMFA) using a package developed in Python (Bornhöft et al., 2016) for the years 1985-2017. The dynamic MFA allows calculating the flows of materials over time.

Parameters for the static MFA of organic matter

Approximately 349000 tonnes of organic waste were collected in the year 2013 in Switzerland from horticulture and landscaping activities, 260000 tonnes from industry and 660000 tonnes from municipalities (Mandaliev, 2016). On top of these amounts, a further 606000 tonnes of organic waste originated from agricultural activities. This agricultural organic matter mostly consists of solid and liquid manure and is most of the time separately handled from the other sources of organic waste. The water content in this kind of waste is generally high and the foreign body content is expected to be low (Mandaliev, 2016). These flows are therefore not further considered. The collected organic waste can be handled in various ways: 42.0% are composted in facilities, 38.8% are digested in anaerobic digestion (AD) facilities, 11.0% in codigestion processes and 7.9% are composted on windrows (Mandaliev, 2016). The remaining 0.3% of that collected waste corresponds to mass losses during transfers which can be explained by moisture and carbon dioxide emissions.

A total of around 397800 m^3 of compost is generated by composting facilities. Around 63% of this compost is used in agriculture, 30% in horticulture and 7% for private purposes (Mandaliev, 2016). The mass of generated compost can be approximated using the measured densities of compost from the samples taken at the AD facility. The amount of waste removed from the inflowing organic waste and sent to incineration varies according to the organic waste quality and the plant's own protocol. Not all plants have a screening step before composting and foreign materials may be manually collected. Based on personal information obtained from several composting plants, a total amount of 2% foreign material was chosen as the maximum amount of foreign materials removed at this stage. For the modelling, an average of 2 ± 1 % was used. The fermentation process also generates water and carbon dioxide, which are calculated as the missing mass.

A total of 141000 m^3 of solid digestate are generated through AD, of which a certain fraction is further composted (Mandaliev, 2016). 59% of the compost produced from AD facilities is applied in agriculture, 34% in horticulture and 7% is used for private purposes (Mandaliev, 2016). The total volume of digestate generated can be converted using the density of the sampled digestate. In the absence of information on the use of non-composted solid digestate, we assume that both compost and solid digestate follow the mentioned applications. Similarly, in the case of composting plants, a certain amount of foreign material is removed from the incoming organic waste, which depends on the organic waste quality and the operating plant. Based on personal information received from several AD plants, the amount of foreign materials removed by sieving and delivered to incineration is between 2 to 10% of the incoming material. For the modelling, an average of 6 ± 6 % is used. Additional products of the AD process are gas and liquid digestate, which are calculated to be the remaining fraction.

Codigestion facilities process organic waste together with agricultural waste and mostly produce digested manure and liquid digestate. They also produce 8000 m^3 of solid digestate, which can be converted to mass units using the densities of the sampled solid digestate as presented earlier. 11% of the produced organic matter is used in agriculture, 82% in horticulture and 7% for private purposes (Mandaliev, 2016). We further assume that 2 ± 1 % foreign matter are removed.

Around 84000 m^3 of compost are produced on windrows, of which 90% are reused in agriculture, 9% in horticulture and around 1% for private purposes (Mandaliev, 2016). This volume of compost can be converted to the mass of compost generated using the samples from the AD facility. Wood is removed from the compost before processing, but the amount of wood contained in this organic waste stream is unknown. A distinction between foreign materials and gas and water can therefore not be made. We further assume that 2 ± 1 % foreign bodies are removed.

Parameters for the static MFA of plastic

The amount of plastic entering the system with the organic waste is estimated using the samples taken from the AD facility (Table 1). Variability can be expected in the plastic content in incoming organic waste, as organic waste coming from industry may have a greater plastic content depending on its origin and organic waste coming from horticulture and landscaping may be cleaner depending on the season. Nevertheless, as no quantitative information on the contamination of the specific streams is available, no distinction can be made between the different organic matter sources.

The amount of plastic pieces larger than 1 mm in processed organic waste was investigated in a series of measurements conducted in 2017 (Schleiss, 2017). A total of 139 samples were taken from 115 facilities in Switzerland between January and June 2017. Of these 139 samples, 48 were fermentation products, 51 were compost produced for agriculture and 40 were compost intended for horticulture and landscaping. The mass of plastic larger than 1 mm per dry mass of compost or solid digestate was reported, along with the percentage of dry mass per sample. Combining both variables for each sample, the mass fraction of plastic per moist mass of compost or solid digestate can be obtained and combined with the results from the organic matter MFA. Similar measurements conducted in 2015 showed that the contamination of liquid digestate was very low (Verein Inspektorat, 2015). Liquid digestate is therefore not considered as a pathway for the plastic MFA.

The transfer coefficients out of organic matter collection are identical for plastic and organic matter, except that no losses during transfers are modelled. It is assumed that all losses correspond to moisture and gas emissions and are therefore not relevant for plastic flows. The sorting residues of plastic are calculated in STAN based on the masses entering and leaving the system.

Parameters for the organic matter DPMFA

A time series of the amount of organic waste collected in Switzerland could be combined from the statistics of the Swiss Federal Office for the Environment (FOEN) (Table S3). The earliest estimate found was for year 1985, which was as a result chosen as starting year for the DPMFA. In some cases, the data reported for one year was identical to the data reported from the previous year, which can happen when a previous estimate is reused in official statistics for the next year. In such cases, the later identical data were ignored and replaced with an interpolated value between remaining estimates.

The transfer coefficients of the DPMFA were based on the MFA performed in STAN for the year 2013 and kept constant throughout the modelled time frame. No stocks are modelled within the system, as the processing time is typically below one year.

Parameters for the plastic DPMFA

The plastic inflow $I_{P,i}$ in year i is modelled using the organic matter input $I_{OM,i}$ known from literature and the concentration of plastic in the incoming organic matter C_i for year i:

$$I_{P,i} = I_{OM,i} \cdot C_i \text{ ,}$$

where C_i is calculated using the ratio of plastic concentration in year 2013 C_{2013} known from measurements with the amount of plastic used in Switzerland in 2013 U_{2013} and the amount of plastic used U_i in year i:

$$C_i = U_i \cdot \frac{C_{2013}}{U_{2013}}.$$

The amount of plastic used in Switzerland in year i is calculated knowing that 1 million tonnes of plastic were used in 2010[12] combined with GDP PPP (Gross Domestic Product- purchasing power parity) values from the World Bank database (data.worldbank.org) or GDP values for the years where GDP PPP was not available. Similarly as for the organic matter DPMFA, the transfer coefficients were based on the MFA performed in STAN for year 2013 and kept constant throughout the modelled time frame.

Results

Sampling of organic waste at the biogas plant

Table 1 presents the characteristics of the samples taken at the AD plant from the incoming organic waste at the conveyor belt, the final compost and the sieving residues. The average plastic concentration decreased by a factor of around 4 between the incoming organic waste and the final product. The plastic content in the incoming organic waste was between 0.05 and 1.18%. After the processing steps, only 0.03-0.31% plastic was found in the compost. The highest average concentration of plastic was observed in the sieving residues, as is to be expected for a process removing foreign bodies from the organic matter.

Table 1: Data collected at the anaerobic digestion plant, grouped by processing stage. The plastic fraction corresponds to the mass of plastic divided by the wet mass of organic matter.

Sampling location	Date	Sample wet mass (g)	Sample density (g/L)	Plastic mass (g)	Plastic fraction (%)			
						Average	Median	Std. Dev.
Conveyor belt (incoming organic waste)	19.07.2017	1165	259	0.57	0.05	0.50	0.48	0.46
	29.06.2017	1159	258	13.7	1.18			
	26.07.2017	1000	222	6.85	0.69			
	18.08.2017	1168	260	5.6	0.48			
	15.06.2017	1800	400	2	0.11			
Final product	19.07.2017	1905	423	0.61	0.03	0.12	0.04	0.12
	29.06.2017	1938	431	0.8	0.04			
	26.07.2017	1450	322	4.48	0.31			
	18.08.2017	1257	279	0.54	0.04			
	15.06.2017	1300	289	2.5	0.19			
Sieving residues	19.07.2017	680	151	30	4.41	2.07	0.81	1.84
	29.06.2017	1250	278	10.1	0.81			
	26.07.2017	995	221	7.17	0.72			
	18.08.2017	455	101	17	3.74			
	15.06.2017	880	196	6	0.68			

Many different types of plastic objects were found in the organic waste entering and leaving the plant (Figure 1). Most items were plastic bags, either shopping bags or lightweight plastic bags. Together, they accounted for 40% of all plastic items found in the incoming organic waste and 86% of the items found in processed organic waste. This difference may suggest a worse sorting efficiency of plastic bags compared to other items. More samples would be more representative of all collected organic waste and permit to answer this question.

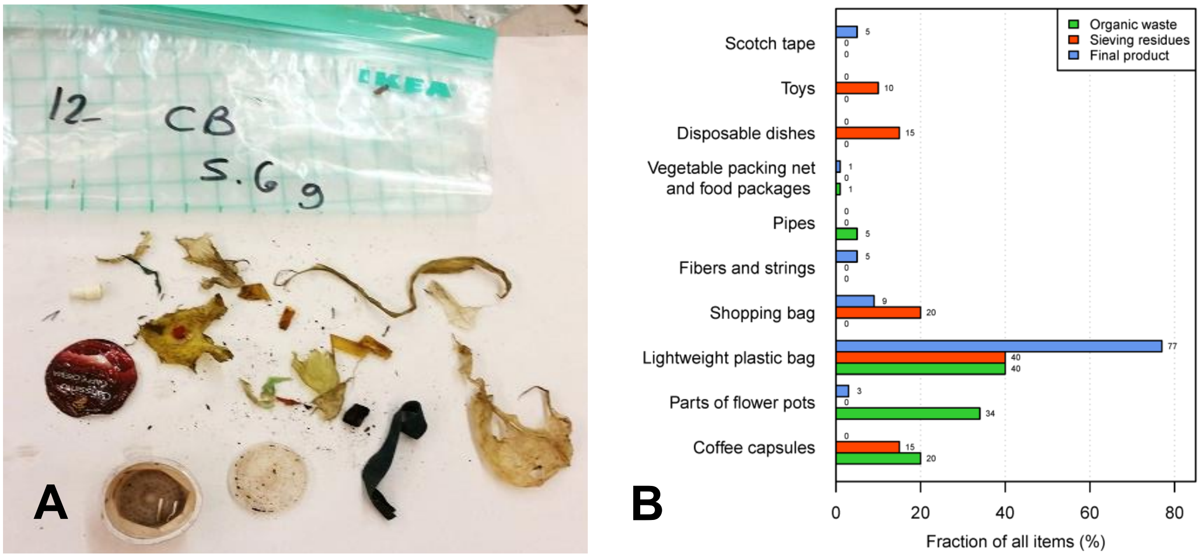


Figure 1: (A) Photo of plastic found in the organic waste entering the plant and in the final compost after sieving and (B) relative distribution of occurrence of various plastic items found at the different locations within the biogas plant.

Static MFA of organic waste and plastic in Switzerland for 2013

Based on the literature data given in the methods section, the material flow diagram of organic waste in Switzerland was obtained. This analysis involved converting volume and mass units and calculating mass losses during composting originating from gas and water emissions. Composting facilities and AD plants treat most of the organic waste. A large part of the processed waste exits the system as liquids, gas and sorting residues. Around two thirds of the produced compost and solid digestate is reused in agriculture, one fourth in horticulture, and the rest for private gardens. The final compost flows to agriculture, horticulture and gardening could be calculated using density measurements performed on three samples of compost and three samples of solid digestate. The three samples of compost yielded densities of 610, 656 and 684 g/L with an average of 650 g/L and a standard deviation of 30 g/L. The three solid digestate samples yielded 419, 424 and 580 g/L with an average density of 474 g/L and a standard deviation of 74 g/L.

Figure 2 presents the flowchart obtained from the static MFA for organic matter. Most of the collected organic matter is treated in composting facilities and AD plants, but large amounts are as well treated in codigestion plants. Most of the compost and solid digestate is used in agriculture at 252000 ± 36000 t, followed by horticulture at 108000 ± 17000 t. Finally, only 23600 ± 4000 t are used by private customers for gardening.

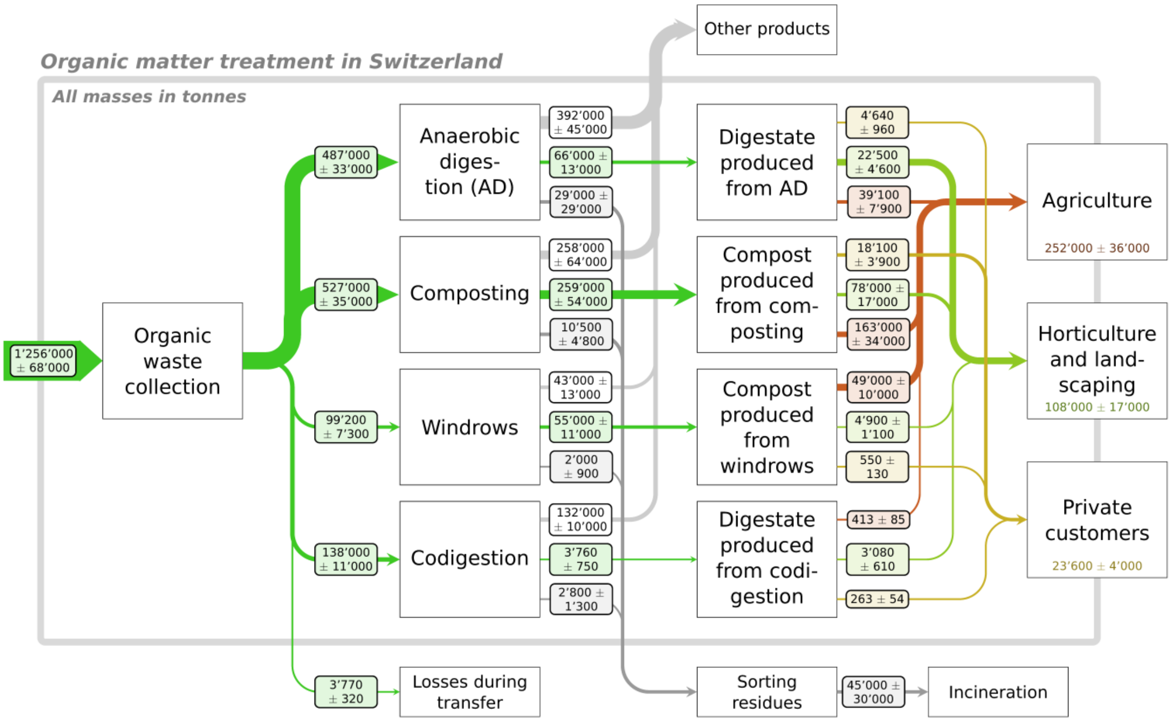


Figure 2: MFA of organic waste matter through the treatment systems and to the environment. All masses are in tonnes per year and rounded to the second digit of the standard deviation.

The probability distribution of the plastic content in compost and digestate in Switzerland resembles a slightly skewed normal distribution centered at about 0.025% for compost for agriculture, 0.01% for compost for gardening and horticulture and 0.05% for solid digestate (Figure 3).

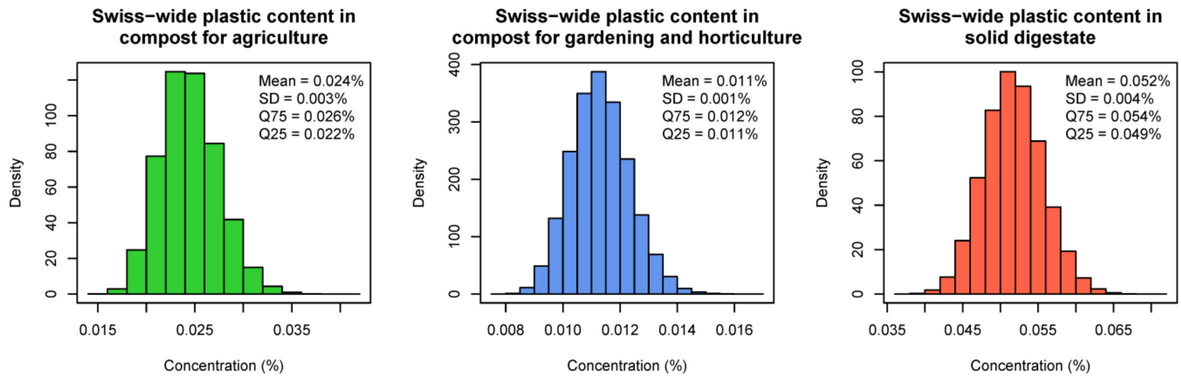


Figure 3: Plastic content distributions for all of Switzerland for the three types of treated organic matter derived from data by (Schleiss, 2017) using Eq. [2].

Combined with the organic waste MFA shown in Figure, the plastic MFA for organic waste was obtained and is presented in Figure 4. In 2013, a total of 98 ± 15 t of plastic were emitted to soils through compost and solid digestate. For a Swiss population of 8.1 million inhabitants in 2013 (FSO, 2018), this is equivalent to 12 grams/capita/year. 71 ± 11 t were emitted to agricultural soil, 22.4 ± 3.3 t to soil used for horticulture and landscaping and 4.60 ± 0.71 t to private gardens.

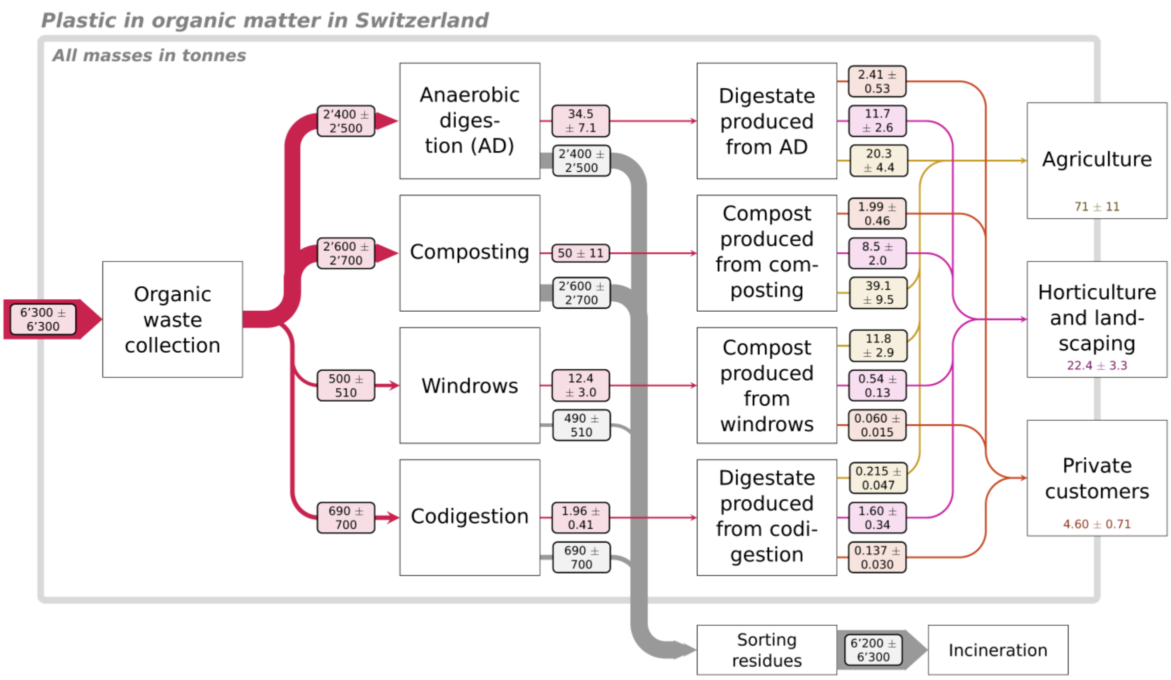


Figure 4: MFA of plastic through the same system. All masses are in tonnes per year and are rounded to the second digit of the standard deviation.

Dynamic material flow analysis of plastic and organic waste from 1985 to 2017

Around 200000 t of organic matter was collected in 1985, at the beginning of the time range considered in our model. In 2017, this amount reached around 1300000 t (Figure 5 and Table S3). The modelled plastic amount in the collected organic waste increased from close to 0 in 1985 to reach around 7300 t in 2017 (Figure and Table S5).

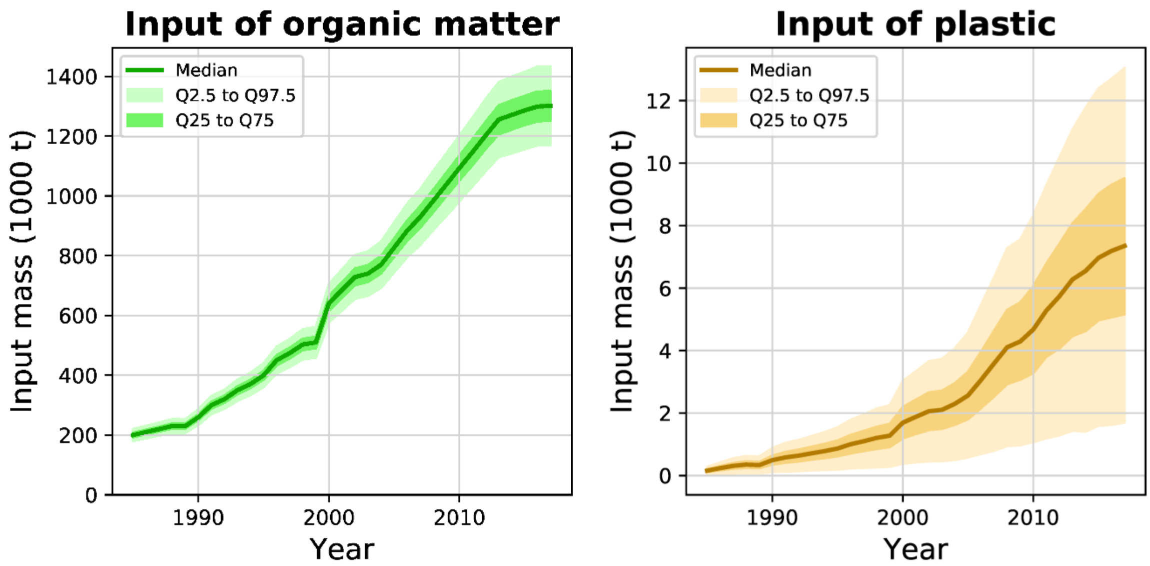
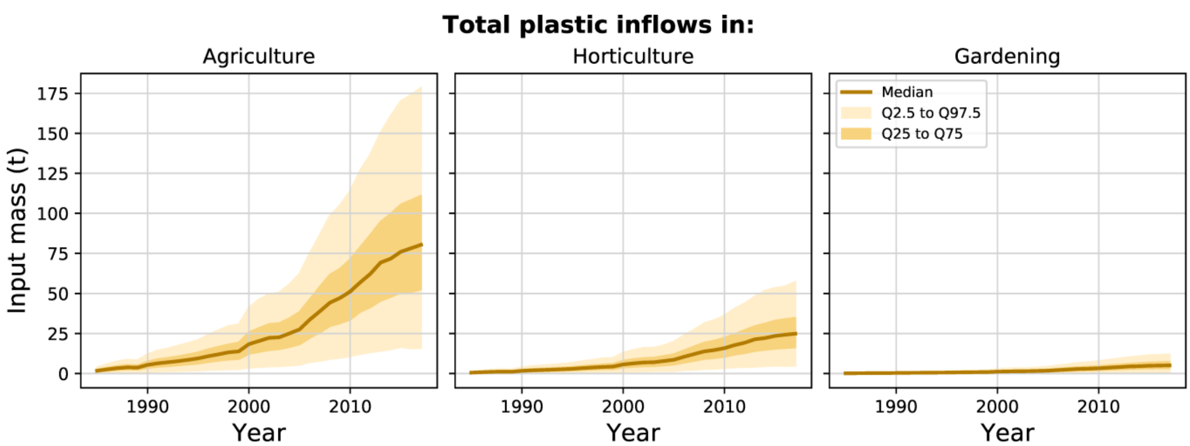


Figure 5: Overview of the inputs of organic matter and plastic into organic waste collection in Switzerland.

A total amount of 1390 ± 390 tonnes of plastic was modelled to have accumulated on soils through compost and solid digestate application onto soil (Figure 6). Of this total, 1010 ± 290 tonnes were applied to agricultural soil, 315 ± 95 tonnes through horticulture and 65 ± 21 tonnes in private gardens.



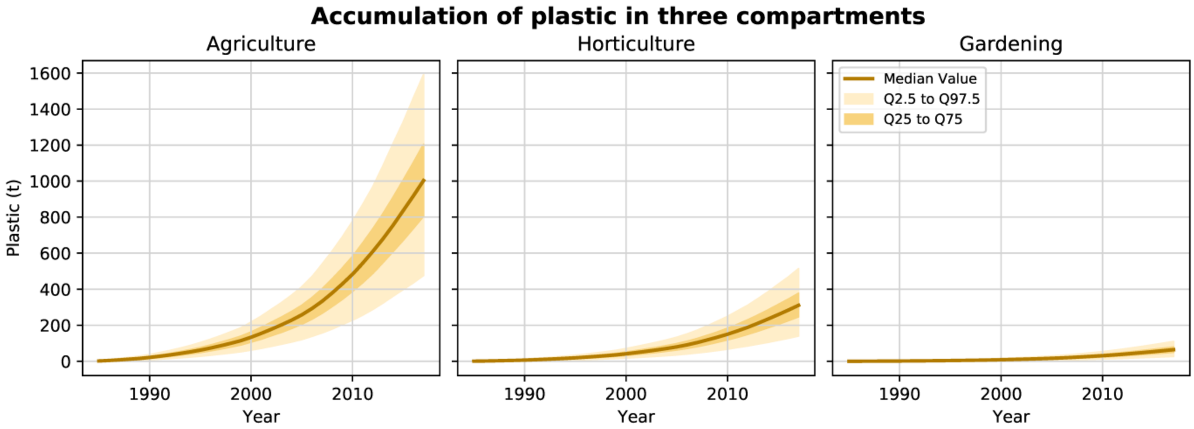


Figure 6: Accumulated amounts of plastic released to soil, as applied through agriculture, horticulture or private gardening.

Discussion

This work provides a first systematic modelling of the plastic emissions onto soils by compost and digestate. The modelling has been performed for Switzerland as many of the data needed for a quantitative assessment are available, e.g. the evolution of the amount of organic waste collection over time, the amount of organic waste collected and used in different applications and the plastic content in final compost or digestate. In order to fully model the system, also information of the plastic content in the raw organic waste is needed. Because this data was missing, we performed samplings at one co-digestion plant and interviewed persons at several composting plants to get a better understanding on the amount of plastic removed during the process. As the measurements show, the major part of plastic initially present in the organic waste is removed during the process, either during the shredding before the treatment, or after treatment before the compost or solid digestate is further used. There were differences in the lower particle size that was collected through sieving (6 mm for the raw organic waste, 1 mm for the finished compost). Because the plastic content in the finished product is calculated based on available data on 139 samples of processed compost and solid digestate, the total mass of plastic transferred to soil is not affected by the large uncertainty of the inflow of plastic into composting. However, more data is clearly needed on the plastic content of the raw organic waste in order to obtain a full picture of the magnitude of the plastic flows into organic waste.

The amount of plastic transferred to compost-treated soils is modelled to be 98 ± 15 t/y based on the year 2013. This amounts to 12 g/capita/year. This value can be compared to the total amount of plastic transferred to Swiss soils of 5000 t/y (combined macro- and microplastic)

(Kawecki and Nowack, 2019) that are mainly caused by littering. Compost is therefore responsible for less than 2% of the total amount of plastics released onto Swiss soils. We can also compare this value to the amount of rubber released from tires that end up in road-side soils and agricultural/forest soils. For Switzerland, it was estimated that 6310 tons (750 g/capita) of rubber are transfered to soils per year (Sieber et al., 2020). The absolute amount of plastic originating from compost is therefore small compared to other sources but both littering and release by tires is a much more diffuse source that affects a much larger area compared to the small area of compost-treated agricultural land.

Using the dynamic model, we can estimate that since 1985 in total 1390 ± 390 tonnes of plastic have been transferred onto soils. The use of compost is restricted to a relatively small area of soil. The application rate of compost on agricultural land varies according to the soil type and area, but an approximation of 30-35 tonnes per hectare of compost annually may be used for soils (WRAP, 2015). Based on the plastic flows to agricultural land, we can calculate the concentration of plastic in soils assuming a ploughed depth of 30 cm and a dry bulk density of soil of 1.5 g/cm^3. The plastic content added is then between 7.2 and 8.4 kg/ha or 1.6 – 1.8 mg/kg of soil.

The number of 1390 tonnes of plastic accumulated in Swiss soils since 1985 does not take into account any degradation or fragmentation processes of plastic. The plastic concentrations in compost used as basis for this work corresponds to all plastic pieces down to a size of 1 mm, so a large range of microplastic sizes are not considered in this number. We can expect that at least part of the macroplastic in the soil has broken down into microplastics. However, while the total mass of plastic remains the same, the number of particles increases. To this day, only few impact studies of microplastics on the soil ecosystem have been conducted (Chae and An, 2018). Some consequences of the presence of microplastic in soil were demonstrated, for example s change in soil properties (de Souza Machado et al., 2018b; Lwanga et al., 2017a), oxidative stress and metabolism change in earthworms (Rodriguez-Seijo et al., 2018), trophic transfer of microplastic from earthworms to chickens (Lwanga et al., 2017b) and accumulation of plastic additives in soil organisms (Gaylor et al., 2013), to name a few. The transport of microplastic to lower soil layers was also shown in several instances (Lwanga et al., 2017a; Rillig et al., 2017b). If the introduction of plastic contaminants into soil is not mitigated, negative effects on soil dwelling organisms, soil fertility and human health are therefore possible.

Conclusions

This work provides a first full picture of the flows of plastic in organic waste in Switzerland. Within the ongoing discussion on plastic waste in the environment, data about the magnitude of the flows to the environment originating from different applications are important for stakeholders to identify the most important flows and to design measures to reduce them. Compost is a valuable resource for soils and is an important part of a circular economy, but at the same time its quality needs to be ensured. Whereas the metal content of compost has received a lot of attention, it is now the plastic content that limits its acceptability by farmers. For the quantification of the flows of plastic to soils, not only the plastic content of compost is relevant, but also the different agricultural uses of compost, e.g. in agriculture or horticulture, and especially the total amount that has accumulated over the last years. The dynamic model applied in our work allowed us to get a first estimate of the total amount of plastic added by compost to soils in the last decades. Together with a solid knowledge on the current flows, the information on the plastic stocks already accumulated in soils will provide the necessary information to stakeholders to put the issue of plastic in compost into the full picture of plastic pollution in the environment.

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Data availability

The R-scripts used for the calculation of the plastic content in compost are available at DOI: 10.5281/zenodo.3973496.

Supporting Information

Document with details about the parameters used for the static and dynamic MFA.

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