# iMPASSE

## Impacts of MicroPlastic in Agrosystems and Stream Environments

Results from an international research project on sources, behaviour and ecological impacts of microplastics from sewage sludge application to agricultural soils

NIVA
Norwegian Institute for Water Research

*“We found that the application of biosolids from sewage sludge represents an important source of microplastics (MPs) to agricultural soils. Soils that received more biosolid treatments in the past exhibit higher levels of MPs, demonstrating progressively increasing pollution. Soil organisms underpinning important ecological and agricultural functions interact with these MPs, experiencing sublethal health effects at realistic environmental concentrations. Soil is a non-renewable resource and soil MP pollution is irreversible. To enable sustainable and circular use of sewage sludge, measures that prevent MPs from accumulating in it, or that remove them prior to use are necessary”.*

*— IMPASSE team*

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# Note from the Coordinator

**Luca Nizzetto**

Luca Nizzetto is a Lead Scientist at the Norwegian Institute for Water Research (NIVA), where he conduct research on anthropogenic pressure and impacts on the natural environment and ecosystem services, including research on chemical and plastic pollution. Dr Nizzetto is the funder of the International Knowledge Hub against Plastic Pollution (IKHAPP) and the coordinator of the EU-funded international project PAPILLONS (Plastics in Agricultural Production: Impacts, Life-cycles and Long-term Sustainability). NIVA is a leading International research institute devoted to multidisciplinary environmental research, covering the areas of biodiversity, climate, pollution, sustainability and green transition.

NIVA

In 2016, a group of scientists from the Norwegian Institute of Water Research and the Swedish University of Agriculture (that later seeded the formation of the IMPASSE consortium) published a seminal perspective paper on the pages of Environmental Science & Technology.[1] That short article drew theoretical considerations on the role of sewage sludge application as soil amendment in agriculture (a common practice in Europe and North America) as a potential major source of plastic pollution to the environment. At that time, only fragmentary data were available on the loads of MPs in sewage sludge. No validated method was in place to accurately measure microscopic plastic fragments in complex environmental matrices such as sludge, soils and sediments, and no scientific peer-reviewed studies had directly addressed or highlighted this potential environmental problem. Using life-cycle-derived indirect estimates of sources of MPs to wastewater and the knowledge that most of these MPs are retained in sewage sludge during wastewater treatment, the authors conducted an initial estimate of the expected loads of MPs potentially reaching agricultural soils. Through these calculations, it was estimated that between 63 000–430 000 tons and 44 000–300 000 tons MPs are added yearly to European and North American farmlands, respectively. This would be an alarmingly high input.

This paper had a considerable resonance amongst academics, stakeholder groups and the general public. It contributed to initiate several international research programs focused on assessing the sources and impacts of MPs in terrestrial environments, which was previously overlooked in plastic pollution research (a discipline that emerged from the area of marine sciences). The provided estimates shed a first light on the perspective that some terrestrial environments could be significant hotspots of this pollution, and thus, potential sources of MPs to freshwater and marine environments. At that time, empirical evidences capable of confirming or rejecting those theoretical estimates were limited and hindered by the lacking capacity to measure MPs in complex solid environmental media. Similarly, at that stage, only a few experimental assessments of the effects of MPs on soil and freshwater organisms were available, generally reporting results for unrealistically high exposure levels. As a consequence of this lack of empirically grounded awareness on the pressure and impacts of MP pollution in soil, the policy debate on the safe use of biosolids in agriculture has been, up to now, mainly based on narratives and positions that could be easily affected by insufficient evidence.

The project IMPASSE (Impacts of MPs in AgroSystems and Stream Environments) was conceived to fill these knowledge gaps through a rigorous empiricist approach. This research was enabled by significant efforts to consolidate methodology[2] and developing an objective and a reliable quantitative analysis of MP occurrence in biosolids, soils and sediments. Similarly, we designed new sets of reference materials for toxicological testing. We deployed these through a comprehensive array of toxicological tests (covering a broad spectrum of terrestrial and aquatic organisms with key ecological and agricultural functions) to investigate the direct and indirect effects of MPs including realistic concentrations.

IMPASSE is an initiative of six research institutes in Europe and Canada and was supported under the framework of the EU ERA-NET scheme through WaterWorks2015 call financed by national agencies in Norway, Sweden, Spain, Canada, the Netherlands and Slovenia. It was one of the first internationally funded projects to tackle sources, behaviour and impacts of MPs in terrestrial environments. Results from IMPASSE are described in detail in several peer-reviewed publications available in top international scientific journals (the complete bibliography is included at the end of the document). This report, mainly dedicated to dissemination towards societal actors, summarizes in clear terms (we hope) these results and provides recommendations that can contribute to consolidate the ongoing policy debate on the safe use of biosolids from sewage sludge in the context of a circular economy.


1. Nizzetto, L.; Futter, M.; Langaas, S. Are Agricultural Soils Dumps for Microplastics of Urban Origin? Environ. Sci. Technol. 2016, 50 (20), 10777–10779. https://doi.org/10.1021/acs.est.6b04140
2. Hurley, R. R.; Lusher, A. L.; Olsen, M.; Nizzetto, L. Validation of a Method for Extracting Microplastics from Complex, Organic-Rich, Environmental Matrices. Environ. Sci. Technol. 2018, 52 (13), 7409–7417. https://doi.org/10.1021/acs.est.8b01517.

# Executive Summary

Microplastics (MPs) are increasingly seen as an environmental problem of global proportions. The concern of MPs in soils has largely been overlooked; There is a lack of knowledge regarding the consequences of MP pollution for agricultural landscapes and freshwaters, especially in relation to the application of sewage sludge as a soil amending agent in farming. Wastewater Treatment Plants (WWTPs) receive large amounts of MPs emitted from households, industry and surface/road run-off in urban areas. Most of these MPs are retained in the sewage sludge. In many countries, WWTP sludge is converted into biosolids and applied to agricultural fields as a supplement to traditional fertilizers. Currently, MPs presence in sewage sludge is not on the regulatory agenda. IMPASSE was one of the first research projects to deal with this issue internationally. The project's overall objective was to investigate the loads, fluxes and potential ecological impacts of MPs in farming case studies in Europe and Canada and it dedicated laboratory experiments to provide farmers, the water industry and regulators with scientifically informed perspectives on the environmental implications of MP contamination from biosolid use in farming.

# Ecosystem Exposure

We delivered the first validated method for the analyses of MPs in complex, organic matter-rich media (e.g., sludge, soils and sediments). Validation showed the ability of a quantitative (70-98%) recovery of MPs from these media. Linked to this validation work, we developed methods for producing and characterizing new reference materials using a cocktail of MPs similar to that found in sewage samples to support ecotoxicological testing and quality assurance in MP analyses. The newly developed analytical method was applied to analyse the samples from case study locations in Spain and Canada with contrasting climatic conditions, in which agricultural soils are treated with biosolids. In all cases, sludge samples contained large amounts of MPs (Average MP concentrations of between 8,700 MP $kg^{-1}$ and >14,000 MP $kg^{-1}$ of dry sludge), reinforcing results from earlier assessments and theoretical expectations. **The application of biosolids represents an important source of MPs to agricultural soils.**

De-watering of sewage sludge during production of biosolids for agricultural use appears to reduce MP content. MPs were found in control soils where there was no record of biosolids application, which shows that other MP sources exist. However, in all analysed scenarios, MP concentrations were considerably higher in soils with a history of biosolid applications. Results from both case studies show that MPs are more abundant in soils that have received more biosolids treatments, indicating **effective storage and the tendency of MP level to increase over time in these soils.** During drought or normal precipitation events very small releases of MPs from soils to water ecosystems were observed in a runoff experiment conducted in Spain (e.g. < 0.1% of the total MP content in soil were released in one year). While these trends were clear, data on mass budget closure were still affected by a level of uncertainty. In contrast, in the Canadian scenario evidence showed that even a few extreme precipitations can mobilize a substantial fraction of the MPs present in soil.

MPs loads were analysed in different sections of the rivers draining the catchments where experimental fields were located. Polyethylene and polypropylene fragments and polyester fibers were predominant in these samples, roughly reflecting (in qualitative terms) the contamination profile of wastewater and sludge.

MP concentrations in river sediments were strongly dependent on catchment land-use, with pollution levels increasing significantly downstream of urban and industrial areas and with higher concentrations observed in sediments collected from areas with low water flow.

In the Spanish case study, it was estimated that around 10 billions MPs are discharged annually via wastewater effluents alone, which represent about 50% of the MPs river discharge under baseline conditions. Hence, under the conditions of this case study, agricultural sources from the use of sludge appeared not to be dominant. A similar finding was obtained in Canada where a model-based mass balance approach showed that agricultural sources of MPs to water ecosystems are expected to become dominant when biosolids are applied to 34% of the total agricultural land (currently, biosolids are applied to only 2%).

# Impacts on soil and water organisms

Effects of different types of MPs (Polyester fibers and car tyre scrub) were assessed on a range of soil organisms (enchytraeid worms, earthworms, isopods and springtails) and freshwater organisms (planktonic and benthic crustaceans and benthic worms). At environmentally relevant concentrations, effects are minimal; effects on survival were negligible in all cases, however evidence of interactions between organisms and MP particles (e.g., ingestion or entrainment on the external part of the body) and a range of sublethal effects on reproduction, mass allocation, energy storage and levels of biomarkers linked to immune response were observed in soil organisms even at environmentally representative concentrations (e.g., of highly contaminated soils and sediments). This implies that while the acute risk posed by MPs to soil and water invertebrates at environmentally relevant levels is low, **prolonged exposure holds the potential to negatively affect a broad spectrum of organisms with different ecology and functions, some of which are key for sustaining agriculture.**

Enchytraeid worms, earthworms, isopods and woodlouses ingested polyester fibers. Fibers extracted from the earthworms and from earthworm faeces were shorter than the ones extracted from the spiked food, which suggests that **earthworm activity in soil can transform polyester fibers to smaller sizes and thus increase the risk for their uptake by invertebrates**. Bioconcentration experiments were performed on fish (*Danio rerio*) using polyethylene MPs spiked with organic chemicals with different physical-chemical properties (hexachlorobenzene and chlorpyrifos) in order to study the influence of MPs on their uptake and bioconcentration. The level of the chemical pollutants measured in fish tissues slightly decreased in the presence of MPs, indicating that MPs can modulate exposure and chemical risk, potentially decreasing it. In a separate set of experiments, MPs were also found to modulate the effects of the pesticide chlorpyrifos on isopods and springtails. However, while some parameters indicated that MPs reduced the bioavailability of chlorpyrifos, some other parameters indicated increased toxicity of the pesticide. **Microfiber addition to a soil mesocosm to simulate sewage sludge application did not seem to affect plant growth and earthworm abundance at fiber application rates up to 32 kg $ha^{-1}$.**

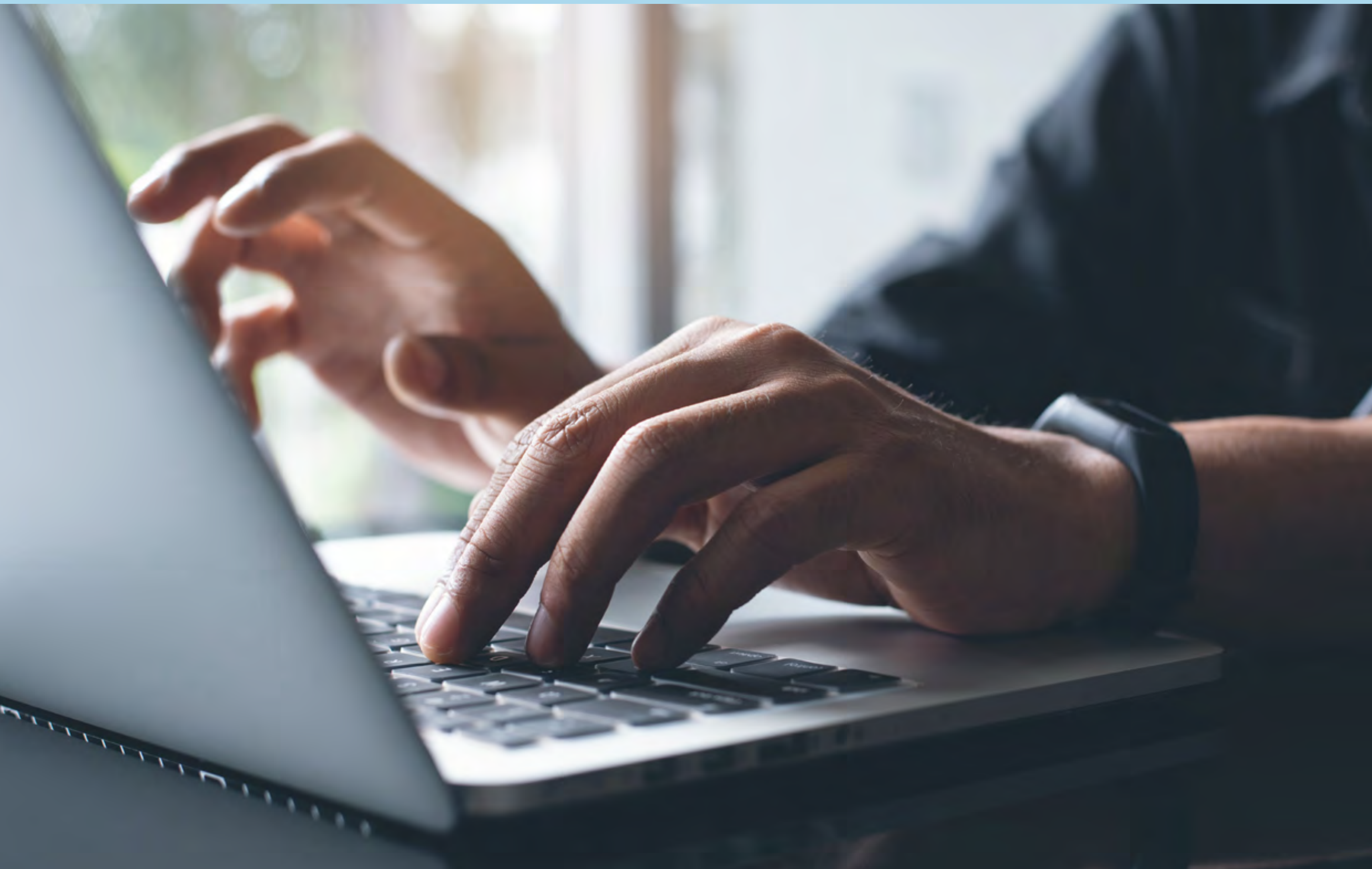
Experiments with polystyrene nanoplastics (with the major dimension ranging between 20 and 100 nm) were carried out with *Daphnia* (a freshwater crustacean). Nanoplastics are orders of magnitude smaller than the MPs studied in the previously described tests and hold the potential to migrate across biological membranes and accumulate inside cells. **In this study, no significant effects were observed on zooplankton viability. Nanoplastics were, however, ingested and transported in the digestive tract and the outside of the carapace, suggesting the bulk of these materials did not enter the organisms' cells.** Elimination of nanoplastics was observed after 3 days.

# Decision support tool

**We developed a new mathematical model of physical transport of MPs in the soil and freshwater at the watershed scale (INCA-MP).** The model is the first and only of its kind to simultaneously account for the budget of MPs in terrestrial and river environments as a function of their physical characteristics. An existing prototype was completely recoded and several new functions describing the physical transport of MPs as dependent on their size, shape and density were added. In addition processes such as fragmentations of MPs and heteroaggregation in soil and water were included.

The model was successfully applied to both case studies (in Canada and Spain). **Both observed and modelled data demonstrated significantly higher MP concentrations of agricultural soils where biosolids had been previously applied, compared to agricultural soils with no history of biosolids application.** The model successfully predicted the order of magnitude of MPs in river sediments and the release of MPs from soil following extreme rain events.

The model was finally applied to analyse viability of management scenarios in Canada for reducing ecosystem exposure to MPs. These scenarios were drawn based on inputs and perspectives from farmers, municipalities and the government sector, based on a multi-actor research approach. In the Spanish scenario, the model was applied to evaluate prediction performance and run a thorough analysis of parameter sensitivity and long term, basin-scale exposure. INCA-MP is available as an executable computer program with a full graphical interface. In addition it is developed in a programming environment (MOBIUS, developed by NIVA) that offers simplified access to the part of the model encoding the biogeochemical processes, facilitating future scientific developments of the model also by non-professional programmers.

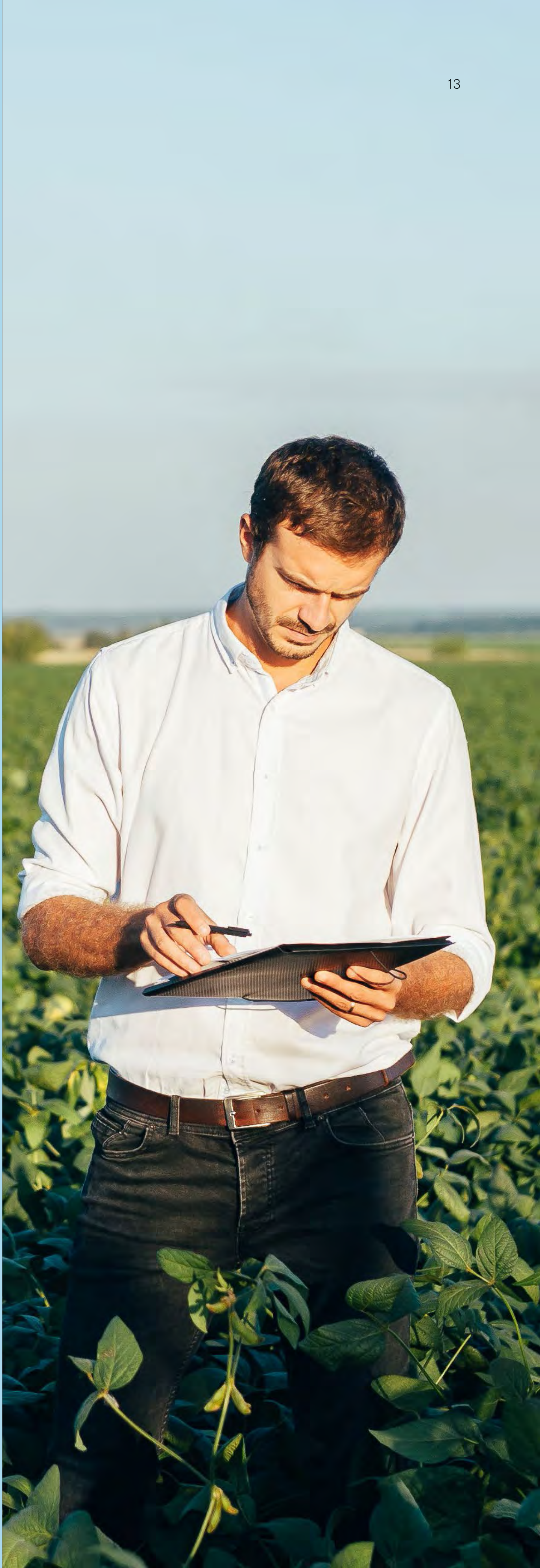


# Multi-actor approach

Stakeholder interaction took place under a multi-actor approach, whereby stakeholders (especially in the farming and water industry sectors) served both as recipients of dissemination and providers of information to enable research. Routine meetings (both during workshops and face to face meetings) with stakeholders were carried out at both national and international levels.

As part of this interaction, a stakeholder scoping study was conducted in Sweden to document knowledge and attitudes towards microplastics in sludge applied to agricultural soils. This analysis included interviews with 33 actors (politicians, government workers, water industry professionals and researchers). It emerged that the discussion, policy debate and positioning of stakeholders in the context of the problem of plastic pollution in biosolids has until now been largely based on few sources and uncertain data. **The results from the scoping analysis shows that stakeholders do not believe they are sufficiently well informed about the issue**, highlighting the need for further research and communication.

Stakeholders from Canada and Norway have also provided their perspectives on the usefulness and economic viability of using sewage sludge-derived biosolid for improving agricultural performance. Stakeholders suggested that the use of biosolids is likely to increase in the future, as it embodies a circularity approach. Unfortunatley, this may collide with the need to protect the environment from plastic pollution. Hence, knowledge and models delivered by IMPASSE were used to frame and investigate economically viable, yet environmentally and socially sustainable management of biosolids from sewage sludge.



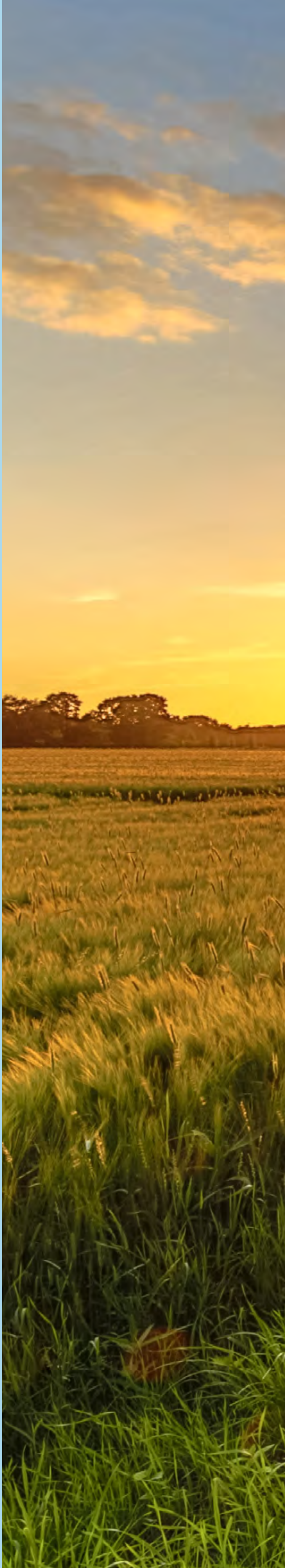
# Assessment of initial measures for MP pollution reduction

The evaluation of strategies for minimizing MP release to agricultural fields and freshwater environments was conducted considering perspectives and inputs from farmers and wastewater managers. Stakeholders identified that with an increasing population (generating excess waste), and a subsequent increase in food requirements, the 2% rate of land application of biosolids will likely increase over time. Two possible management scenarios were identified in relation to the Canadian case study and simulated with the use of the new INCA-MP model. These were conceived to assess possibility of achieving MP releases reduction under: i) a changing climate and ii) changes in landuse.

Within the first scenario, IMPASSE researchers were asked by stakeholders to assess whether applying sludge during dry periods would reduce the release of MPs to water environments (a practice adopted for example, for reducing runoff of fertilizers). Model simulations revealed that during drier years, agricultural soils can act as a MP accumulator; however, sufficiently high rainfall events can mobilize the MPs stored even years after the biosolids were first applied. **Climate change will result in increased frequency of extreme rainfall events. Storage of MPs within all land uses is therefore likely to become less effective. Management solutions designed around meteorological events can therefore serve to delay, but not reduce, MP export to the environment.**

In the second scenario we assessed that biosolids are not currently the primary source of MPs to the environment, although they are clearly a critical pathway. Stakeholders have indicated a future need to increase biosolids application rates, hence model scenarios were run to ascertain the threshold of land area (in percentage of the catchment area) at which biosolids can be applied before they become the dominant source to water ecosystems. It was found that the threshold is 34%. Currently only 2% of the agricultural land is treated in Canada. A similar figure applies to Europe. Hence, it was recommended that effective policies and instruments to reduce plastic pollution should initially focus on other and more relevant sources. In this context, a **comprehensive policy could indirectly lower the loads of MPs reaching wastewater at source, with benefits for biosolid quality and their applicability in farming.**

An initial economic viability analysis performed within IMPASSE suggested that options of increasing the use of biosolids in agriculture are economically advantageous for both farmers and municipalities (citizens). This however, largely depends on the possibility of reducing the amount of MPs in biosolids at zero (or low cost) and on the non-verified assumptions that the cost of loosing environmental capital and agricultural performance due to the impact of MPs are negligible. At present, zero-cost instruments for preventing plastic from reaching wastewater are not known, and agricultural and environmental externalities of plastic pollution are little understood. Research into these zero-cost solutions for biosolids MP management is currently being funded by the Canadian Federal Government, though more research will be needed to identify viable policies and management to protect the environment from MPs and preserving circularity in the use of sewage sludge.



# Recommendations

We found that the application of biosolids from sewage sludge represents an important source of MPs to agricultural soils. Soils that received more biosolid treatments in the past exhibit higher levels of MPs, demonstrating progressively increasing pollution. Soil organisms underpinning essential ecological and agricultural functions interact with these MPs and experience sub-lethal health effects at realistic environmental concentrations.

The policy debate on the sewage sludge management should assimilate these findings as rapidly as possible. Continuous addition of MPs to agricultural soils will result, over time, in increasing pressure and risks for the soil ecosystem. The safety threshold to prevent abrupt and irreversible damage on soil ecological and agricultural services is unfortunately not known. Soil is a non-renewable resource and MP pollution in soil is likely irreversible.

The following recommendations are given::

- Regulation on sewage sludge use in agriculture should include legal thresholds for MPs.
- In order to safeguard circularity in the use of sewage sludge, cost-effective measures that can reduce or, better, remove MPs completely from sewage sludge should be strongly endorsed.
- Economic cost-benefit analysis of sewage sludge use in agriculture should include sound estimations of environmental externalities for both present day and future scenarios of MP contamination in soils and freshwater environments.

# Detailed Report of Results

Microplastics (MP) are increasingly seen as an environmental problem of global concern. MPs in soils have largely been overlooked, while a lack of knowledge of their impacts on agricultural landscapes and freshwater from the application of sewage sludge has prevented the definition of measures for the safeguarding of agriculture and the environment. Wastewater Treatment Plants (WWTPs) receive large amounts of MPs emitted from households, industry and surface run-off in urban areas. Most of these MPs accumulate in the sewage sludge. In many countries sludge from municipal WWTPs is converted into biosolids and applied to agricultural fields as a supplement to traditional fertilizers. Currently MPs are not in the regulatory agenda for the use of sludge. Knowledge and awareness of their amounts and impacts have been missing. IMPASSE was one of the first research projects to deal with this issue internationally. It investigated, for the first time, the loads, fluxes and potential ecological impacts of MPs in farming case studies and conducted laboratory experiments in Europe and Canada.

# Exposure

Inputs, levels and behavior of MPs from sewage sludge in agricultural soils and in downstream environments.

## Analytical method development

A first important task of IMPASSE was to develop and validate a method for the analysis of MPs in soil and sludge samples. This was achieved through a method based on both microscopy and automated micro-Fourier Transform InfraRed Spectroscopy (the "golden standard" for the analysis of MPs in environmental samples). An initial step of the sample preparation included removal of interfering natural organic matter. We achieved removal through basic digestion without altering the properties of MPs in the samples.

We provided a validated method showing recoveries of spiked reference MPs (fibers and fragments) ranging between 70 and 98%. This resulted in a seminal publication which has received a high number of citations.

A set of MP reference materials was developed, and batches were produced to be used in validation exercises and toxicological testing. MP reference materials of environmental relevance were not available on the market. The production of MP reference material batches was launched for commercialization. These products have been distributed internationally to support quality assurance and control, method validations and water treatment efficiency assessments.

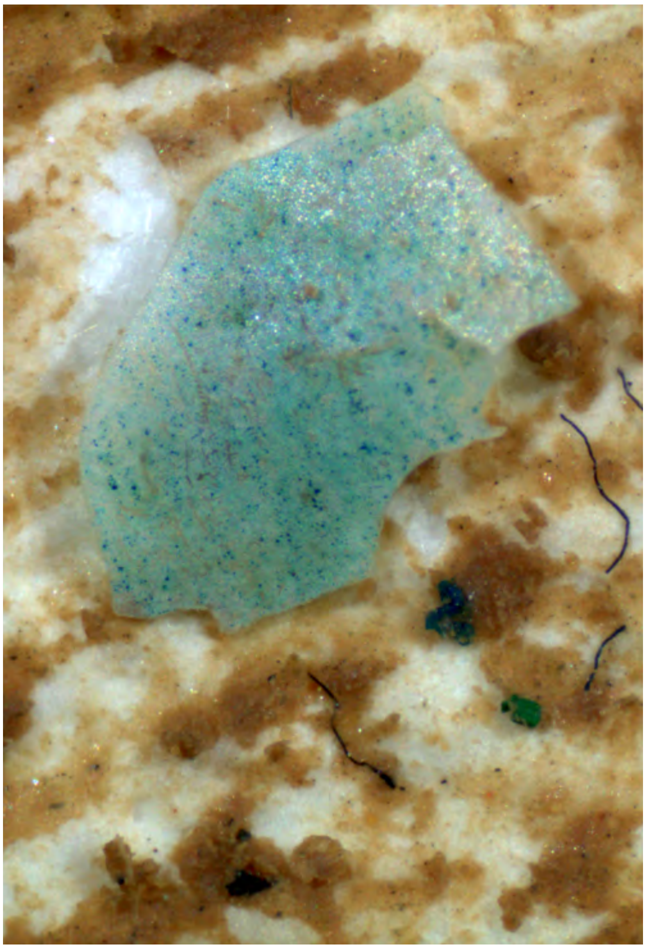
## Monitoring and MP budget assessments

The new validated analytical method was applied to analyse the samples from scenarios (Spain and Canada), with contrasting climatic conditions where agricultural soils are treated with biosolids. We have conducted comprehensive monitoring campaigns in agricultural catchments covering fields with different history of biosolid treatment and fields that were never treated (as a reference). We collected samples of sludge, sludge-based fertilizers, agricultural soils, surface runoff, river sediments, stream water and wastewater from WWTP effluents.

**In Canada**, MP monitoring was undertaken in three catchments within the Lake Simcoe region of Ontario with either a substantial history of biosolids applications on agricultural lands, or with no previous biosolid application (control). The region is characterized by a boreal climate with wet and temperate summers. Samples of agricultural soil were taken before, during and after the application of biosolids to attempt a dynamic mass budget of MPs at field level. Soil samples were taken at multiple soil depths to assess any vertical movement of MPs, and over a range of transects across different slope inclines. Table 1 summarizes results of MP masses in solid and liquid samples collected in the Canadian study.

| Sample | kg of MPs per squared kilometer” | Sample | MP concentration (mg of plastic per liter of sample) |
|---|---|---|---|
| Soil with biosolid treatment | 37.7 | Biosolids | 6.1 |
| Soil with no history of bio-solid treatment | 5.97 | Agricultural runoff | $7.1x10^{-3}$ |
| River bed sediments | 0.01 | Urban stormwater flow | $2.2X10^{-4}$ |
| | | Wastewater treatment outflow | $1.2X10^{-6}$ |
| | | Water column | $3.6x10^{-7}$ |

Results indicate that sludge samples contained large amounts of MPs (Average MP concentrations of between 8,700 MP and >14,000 MP kg of dry sludge (Figure 1)) confirming theoretical expectations that the application of biosolids represents a predominant source of MPs to agricultural soils. Treatment of biosolids prior to use in agriculture appears to result in different MPs content, with de-watering process during storage possibly providing a means to reduce MP content. MPs were found in control soils where there was no record of biosolids application (Figure 2), however MP concentrations were considerably higher in soils with a history of biosolids applications, empirically confirming that biosolid treatment is a predominant source of MPs to agricultural soils in these fields (Figure 2). Shortly following biosolids application, soils exhibited significant increases in MP levels, predominantly in the form of microfibers. The movement of MPs between soil layers differed between sites reflecting different soil conditions and structure. When comparing soil data to the MP mass applied in 2017, evidence from all cases showed a considerable loss of MPs from the soils in relation to intense precipitations. In several instances a greater number of MPs were lost in 2017 than were applied. This is interpreted to be a result of runoff driven by the intense precipitation recorded during the study. This evidence indicates that soil MPs can mobilize and contaminate  freshwater ecosystems.



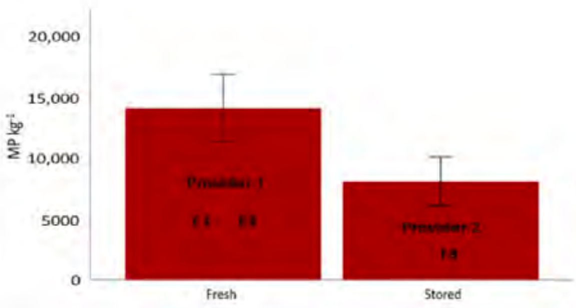



Figure 1: Concentration of MPs within stored and fresh biosolids, as measured within haulage companies operating within the Lake Simcoe region, Ontario

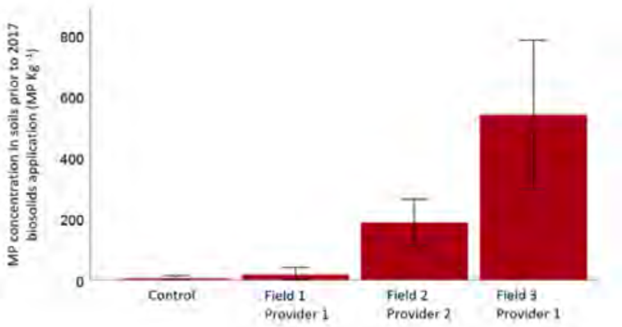



Figure 2 Total MP concentrations in soils prior to 2017 biosolids application. Field 1, Field 2, and Field 3 were historically treated with sewage sludge-derived biosolids at progressively increasing frequencies

**In Spain** the study was conducted in the Henares River watershed, which is located in the upper Tagus River Basin (Central Spain). The area is subjected to a continental Mediterranean climate, characterized by hot and dry summers and mild-to-cold dry winters. While the upper part of this watershed is mostly characterized by forest areas or extensive agriculture, the lower part is influenced by industrial and urban areas and frequent municipal wastewater discharges. Here, we studied MP concentrations in soil samples with different histories of biosolid applications, in agricultural runoff, in river sediments and in stream water. Also in this case, wastewater effluents were analysed to assess the contribution of agricultural runoff compared to wastewater effluents in supplying MPs to the river. MPs were identified in all river sites, with water and sediment concentrations ranging between 1-227 MP/L and 0-2630 MP/kg of sediment dry weight, respectively. These MPs were predominantly polyethylene and polypropylene fragments. MP concentrations in river sediments were found to strongly depend on landuse in the catchment, with pollution levels increasing significantly downstream of urban and industrial areas and being larger in the sediments in areas with low water flow. We estimated that around 10 billion MPs are discharged into the Henares watershed via wastewater effluents annually, constituting about 50% of the total MPs river outflow. Agricultural runoff must therefore be a relatively small source being included (among other sources such as road runoff, atmospheric drift and deposition,

fragmentation of litter, etc.) in the remaining 50%. It has to be highlighted, however, that unlike in Canada, during the study in Spain no major precipitation events occurred which may hinder a more complete understanding of the role of agricultural runoff as a source of freshwater MP pollution.

In order to directly assess levels of MPs in agricultural soils and the possibility of their release through runoff, we set three experimental plots in the same catchment equipped with runoff collection devices (Figure 3). The treatments were as follows: (1) a control with no sludge application; (2) historical sludge application five years prior to the start of the experiment; and (3) first sludge application at the beginning of the experiment. MPs were analyzed in soil before and after the sludge application and during the study duration (3 months). We also measured MPs in collected runoff samples. Like observed in Canada, sludge application significantly increased MP concentrations in soils (Figure 4). The soil MP concentrations remained stable for one year. Surface water runoff under normal (low-intensity) precipitation had a negligible influence on the export of MPs from soil, mobilizing only 0.02-0.04% of the MPs added. Thus, we conclude that, under the conditions of this study, agricultural soils behaved as long-term accumulators of MPs. However even background leaching of MPs can contribute, over time, to deliver large amounts of MPs to aquatic ecosystems. Despite the low background runoff, after upscaling to the area of soils treated with sludge in dry environments (such as Spain or more generally Southern Europe) it is estimated that tens of tonnes of MPs are released every year to aquatic ecosystems from farmlands. It is suggested that the figure will be considerably higher in wetter environments.

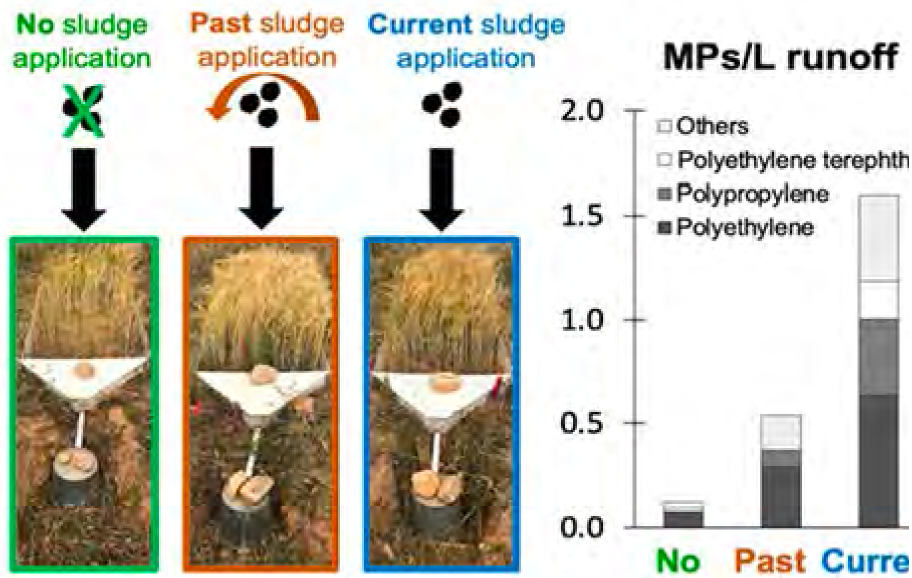



Figure 3 Experimental set-up with field plots and runoff analysis conducted in the Spanish case study

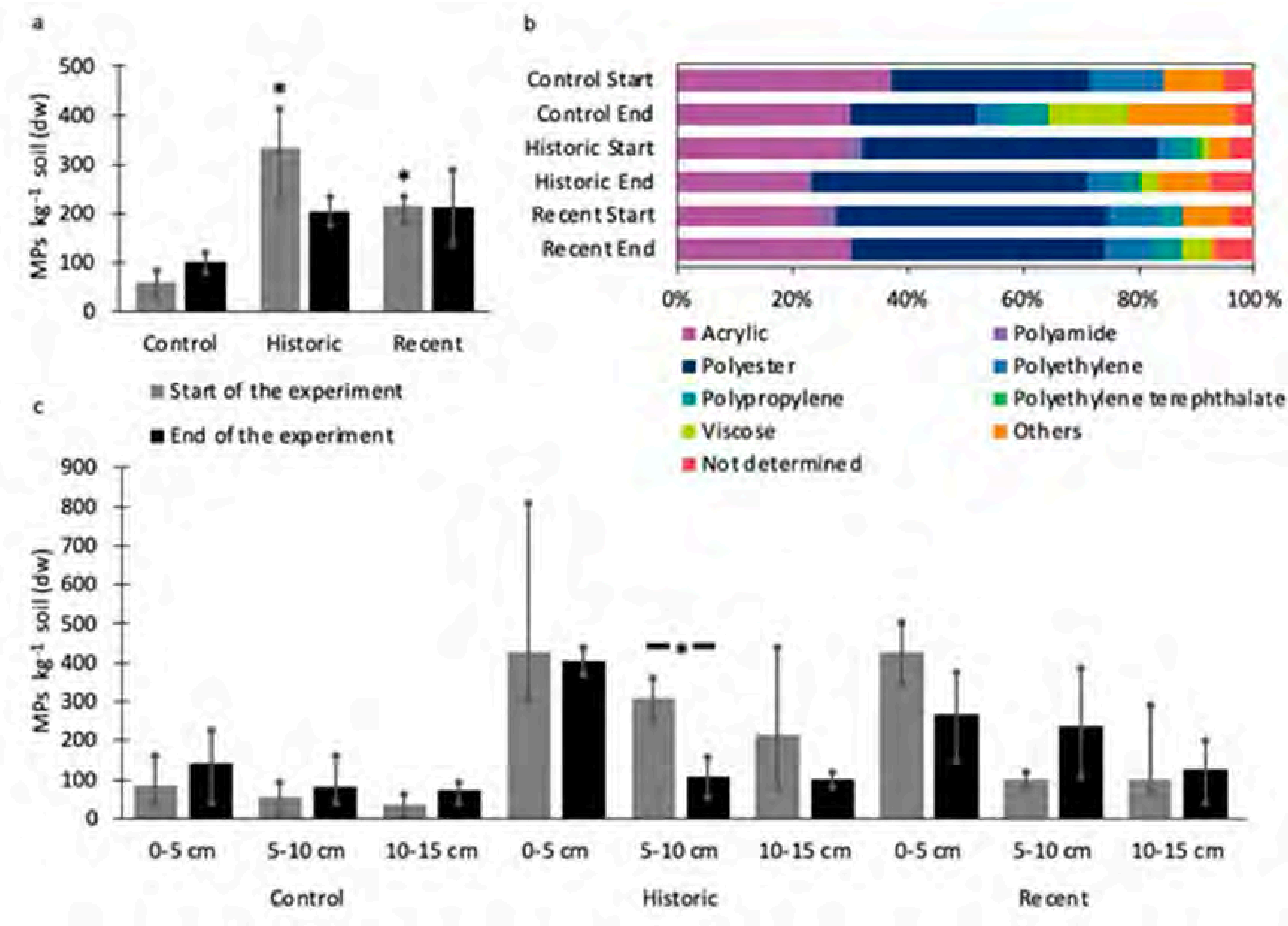



**Figure 4**
MPs detected in soils of the Spanish case study, subjected to different sludge treatments, at the start and the end of the experiment reported by a) mean, min and max (error bars) concentration (MP $kg^{-1}$) per experimental plot; b) polymer type observed at the start of the experiment (Start) and the end of the experiment (End) ; and c) mean, min and max (error bars) concentration (MP $kg^{-1}$) according to different sample depth. Statistically significant differences compared to the control are indicated by asterisks (*), while significant differences between the start and the end of the experiment are indicated by asterisks in between dashes (-*-).

# Impacts

Effects of MPs were assessed on the health and viability of several freshwater and soil organisms considering realistic exposure scenarios.

### Impacts on soil organisms

Polyester fibers had only slight effects on soil invertebrates. Survival and reproduction of springtails and earthworms were not affected by polyester fibers, whilst energy reserves of the isopods were slightly affected when exposed to short (12 mm–2.87 mm) and long (4–24 mm) fibers. Reproduction of enchytraeids also decreased up to 30% with increasing fiber concentration, but only for long fibers in soil (Figure 5). Only a few fibers were ingested by enchytraeids in the case of longer fibers, which suggests that the fibers posed physical harm outside the organism rather than hazards due to fiber ingestion.

Worms and isopods ingested polyester fibers too. The rate of ingestion of earthworms increased with increasing concentration in soil (Figure 6 and Figure 7 ), showing the increased risk of synthetic fibers to enter the food web when the number of fibers in the soil is high. The fibers extracted from the earthworms and from earthworm faeces were shorter than the ones extracted from the spiked food, which suggests that earthworm activity in soil can transform polyester fibers to smaller sizes and thus increase the risk for their uptake by (other) soil invertebrates (Figure 8).

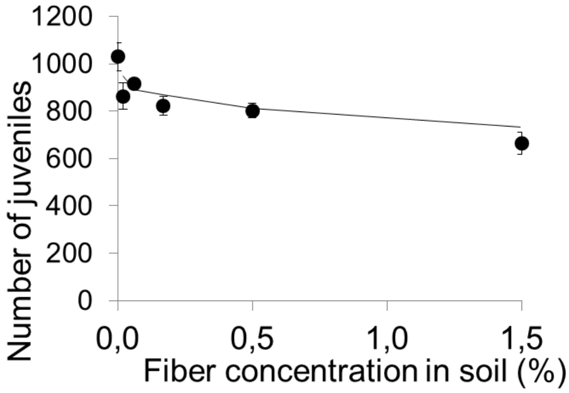



Figure 5. Relation between the % of long (4-24 mm) polyester microfibers in soil and number of enchytraeids worms juveniles showing a statistically significant (p<0.05) reduction in the ability of producing offsprings above 0.2%.

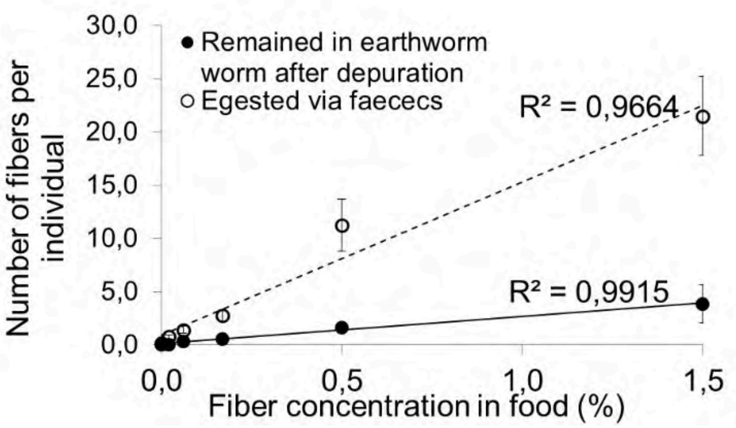



Figure 6. Left, relation between the % of polyester microfibers dispensed in food and the number of fibers accumulated in earthworms or found in egested faeces. Right. Pictures of egested earthworm faeces

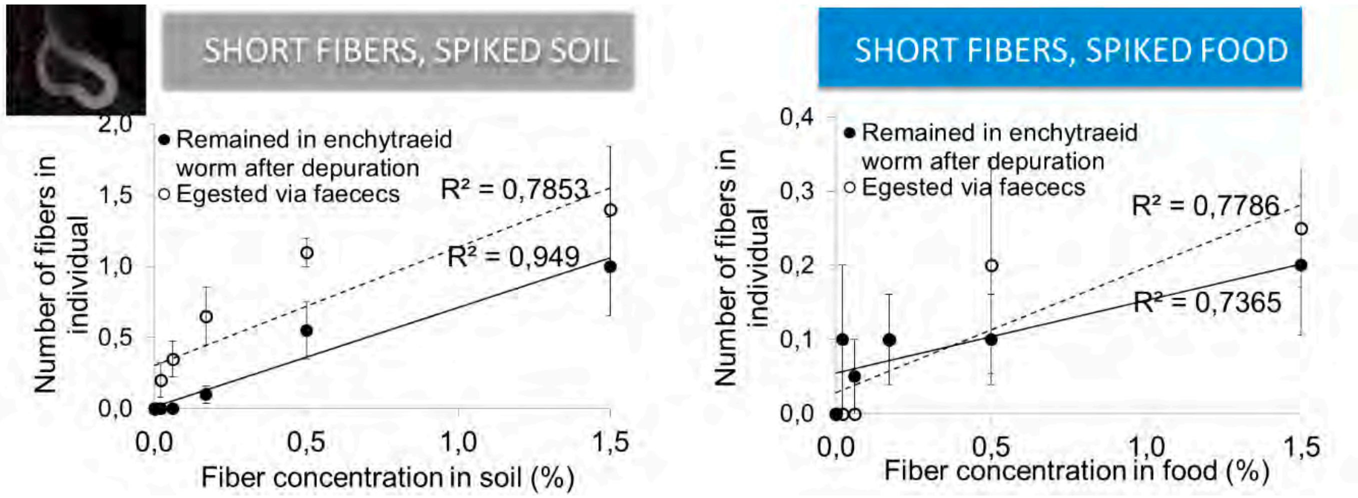



Figure 7. Relation between the % of polyester microfibers in soil (left) and dispensed food (right) and the number of fibers accumulated in enchytraeids worms or found in their egested faeces.

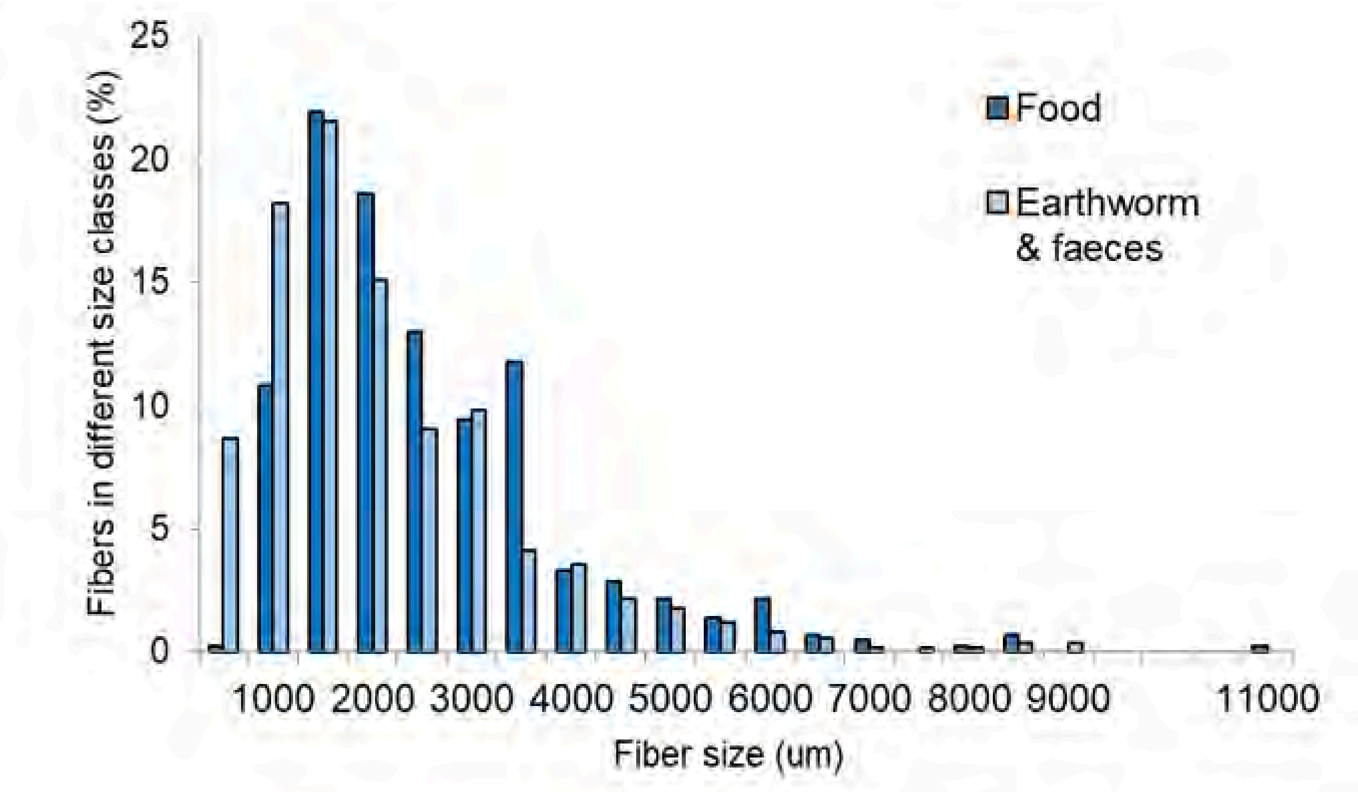



Figure 8. The size distribution of fibers extracted from earthworms and earthworm faeces (light blue) and from the food of earthworm (dark blue).

Also tire particles (i.e. crumb rubber, <180 μm) had only slight effects on soil invertebrates. For enchytraeids, the slight decrease in reproduction was not dose-dependent. On the contrary, crumb rubber induced changes in glutathione-S-transferase and catalase activity in earthworms at moderate concentrations, indicating oxidative stress. In springtails, the highest test concentration of crumb rubber (1.5%) decreased the reproduction by 38% and survival by 24% when spiked in soil, and survival by 38% when spiked in food. Acetylcholinesterase (AChE) activity of isopods was decreased by 65% at the highest test concentration in soil, indicating neurotoxicity of the material. Crumb rubber contained a variety of potentially harmful substances. Zinc (21 900 mg $kg^{-1}$) was the dominant trace element, whilst the highest concentration of the measured organic compounds was detected for benzothiazole (89.2 mg $kg^{-1}$). These results suggest that micro-sized particles from tire wear can affect soil invertebrates at concentrations found at road sides, whilst short-term impacts at concentrations found further from the roadsides are unlikely.

Tire crumb rubber decreased the toxicity of chlorpyrifos on the reproduction of the springtail *F. candida*, whilst polyester fibers did not remarkably affect the chlorpyrifos toxicity. These findings indicate that the effects of microplastics on the toxicity of the pesticide chlorpyrifos depend on the type and concentration of microplastics.

Furthermore, the effects on energy reserves and immune response of the crustacean *Porcellio scaber* was analysed in relation to MP size distribution and shape. The results show that after 3 weeks of exposure the overall hazard of tested microplastics to *P. scaber* was low, however a shift in energy allocation and induction of immune response were evident. We also showed that microplastics may alter the effects of other pollutants which may be present as mixtures with microplastics.

In summary, while the risk posed by MPs to soil invertebrates at environmnentally relevant levels are low, the occurrence of sublethal effects even at environmentally realistic concentrations imply that prolonged exposure can potentially induce negative effects on soil biota.

## Impacts on water organisms

Single species toxicological tests were performed on zooplankton (*Daphnia*) and zoobenthos (*Asellus*, *Hyalella*, and *Lumbriculus*) to assess ingestion and potential effects of two types of MPs (fibres and tire crumb) on different short-term and long-term toxicity endpoints. MP ingestion depended on MP type, exposure pathway (water or sediment) and feeding strategy or habitat of the species. Survival and reproduction of zoobenthos species were not affected at the tested MP concentrations (up to 0.15 g/L water or 2 g/kg sediment). However, while *Daphnia* survival was also not affected during short term exposure, reproduction and long-term survival significantly decreased in chronic exposure test in the presence of both MP types. In both cases concentration of MPs in the range of 0.015 g/L produced significant effects(Figure 9 and 10). In case of Fibers this was apparently caused by impeded movement due to entanglement of *Daphnia* in agglomerates formed by fibers and algae provided as food (Figure 9 Upper panel).

In case of car tire crumb particles ingestion by Daphnia increased proportionately to exposure concentration. Reproduction of *Daphnia* was negatively influenced between 0.015 and 0.15 g/L (Figure 10).

**A study on the effects and bioaccumulation of nano-sized plastic particles was also conducted with *Daphnia***

Experiments were conducted with three different polystyrene nanoplastics (20 and 100 nm FITC labelled, and 100 nm Rhodamine labelled). Acute immobilisation tests showed that smaller nanoplastics did not cause significant effects. Uptake of nanoplastics was proven for Rhodamine labelled nanoplastics using fluorescence microscopy. Fluorescence was only observed in the digestive tract and the outside of the carapace, which suggests that the majority of particles have not left the digestive tract and have therefore not entered the cells. Elimination of nanoplastics was observed 3 days after the transfer of *Daphnia* into clean water.

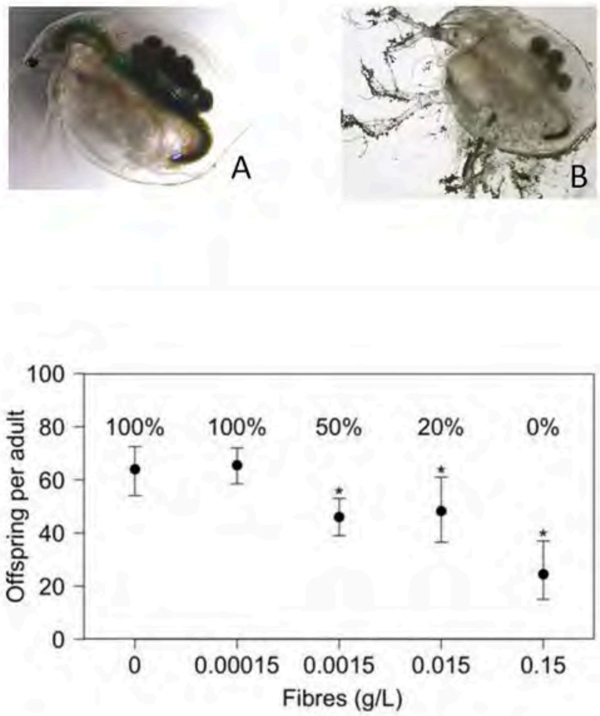



Figure 9. Upper: *Daphnia magna* exposed for 21 d to (A) control (B) 0.015 g fibers/L. Lowe: Reproduction displayed as median number of offspring per adult (± 95% CI, n=10) after 21 day of exposure to increasing fiber concentrations. The percentage of surviving adults is

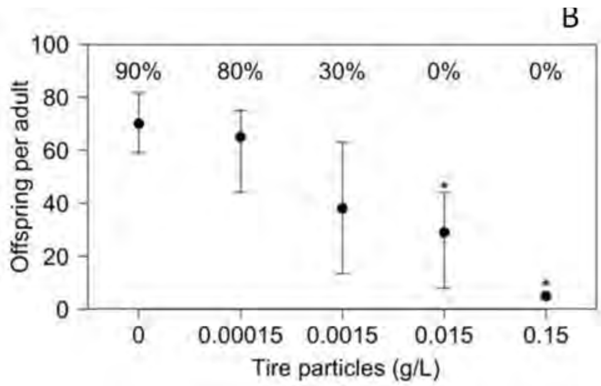



Figure 10. Reproduction rate of *Daphnia magna* displayed as median number of offspring per adult (± 95% CI, n=10) after 21 day of exposure to increasing car tire crumb concentration. The percentage of surviving adults is shown above the respective treatment.

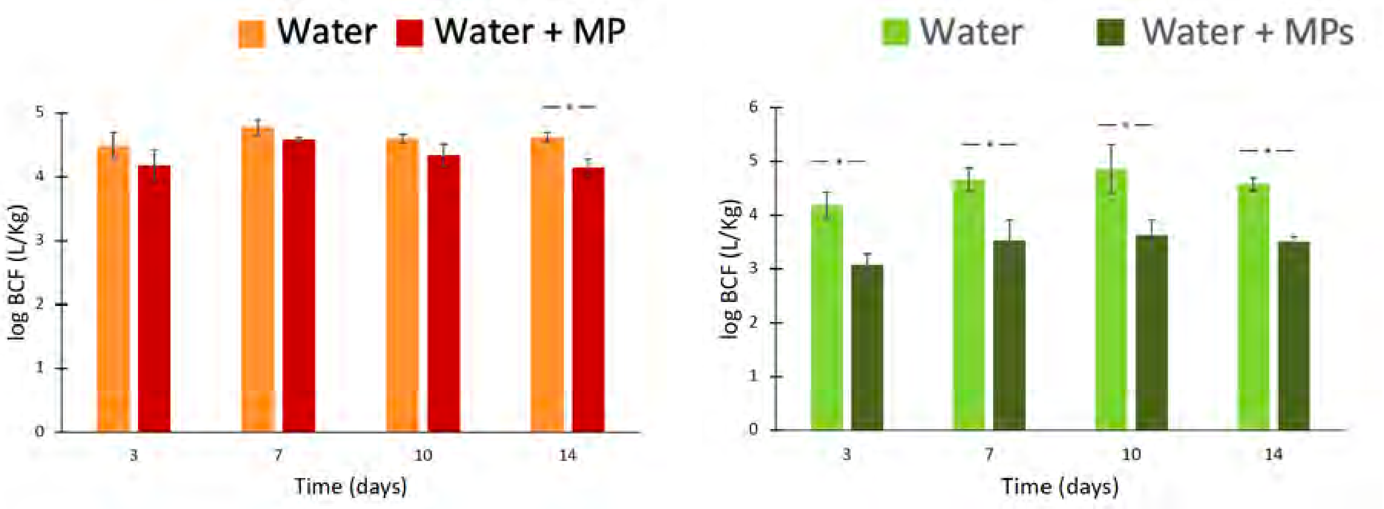



Figure 11. Effect of MPs on the bioconcentration of pesticides (Chlorpyrifos (left) and Hexachlorobenzene (right) in fish (Danio rerio), showing the presence of MPs lowered exposure.

# Decision support tool

We developed a new mathematical model of physical transport of MPs in the soil and freshwater at the watershed scale (INCA-MP).

The model is the first of its kind. We completely recoded an existing prototype and added several new functions describing size/shape/MP density-dependent transport of MPs, as well as fragmentation and heteroaggregation processes in soil and water. The model was applied to the data of the case studies successfully. Figure 12 and Figure 13 show results of model performance for the Canadian scenario. Both observed and modelled data demonstrated significantly higher MP concentrations of agricultural soils where biosolids had been previously applied, compared to agricultural soils with no history of biosolids application. The model is available in an executable and fully graphically interfaced version. Furthermore, it is also available in a development platform (MOBIUS) operating in the C++ programming language developed by NIVA that enables easy modification of the model frame by future users (even with limited technical programming skills). This was conceived to enable users in the environmental research area to continue the development of the model within and outside this project consortium. Finally, the modelling work included the provision of an interface with the programming language PYTHON that enables rapid automatization for controlling the runs of the model executable version to facilitate, for example, calibration/validation exercises and development of sensitivity analyses. The model was used for the scenario assessment in the Canadian case study.

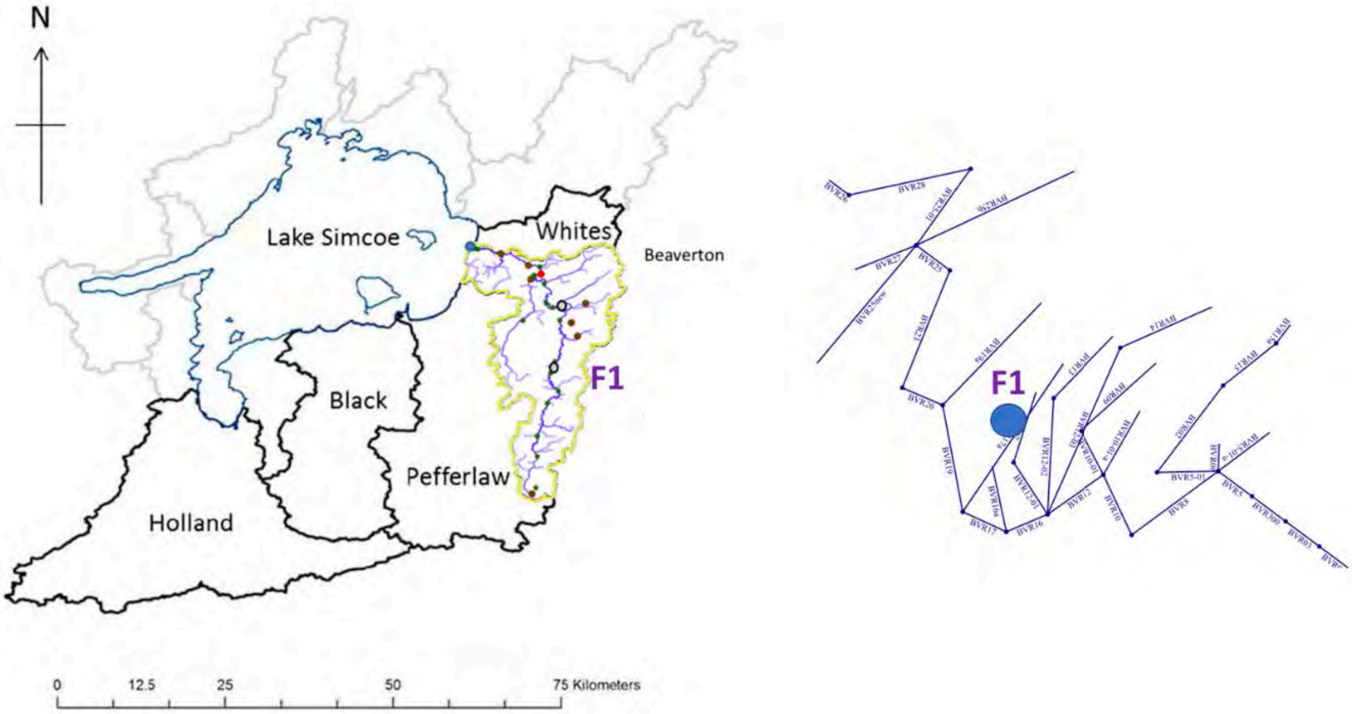



Figure 12. Model application to the Canadian case study. Left: Geographic information system layer depicting catchment boundaries of the study area (Lake Simcoe region). The yellow boundaries show the catchment specifically selected for the model simulation. Dots represent sampling locations where MP measurements were conducted in water or sediments. Right: INCA-MP discretization of the river network.

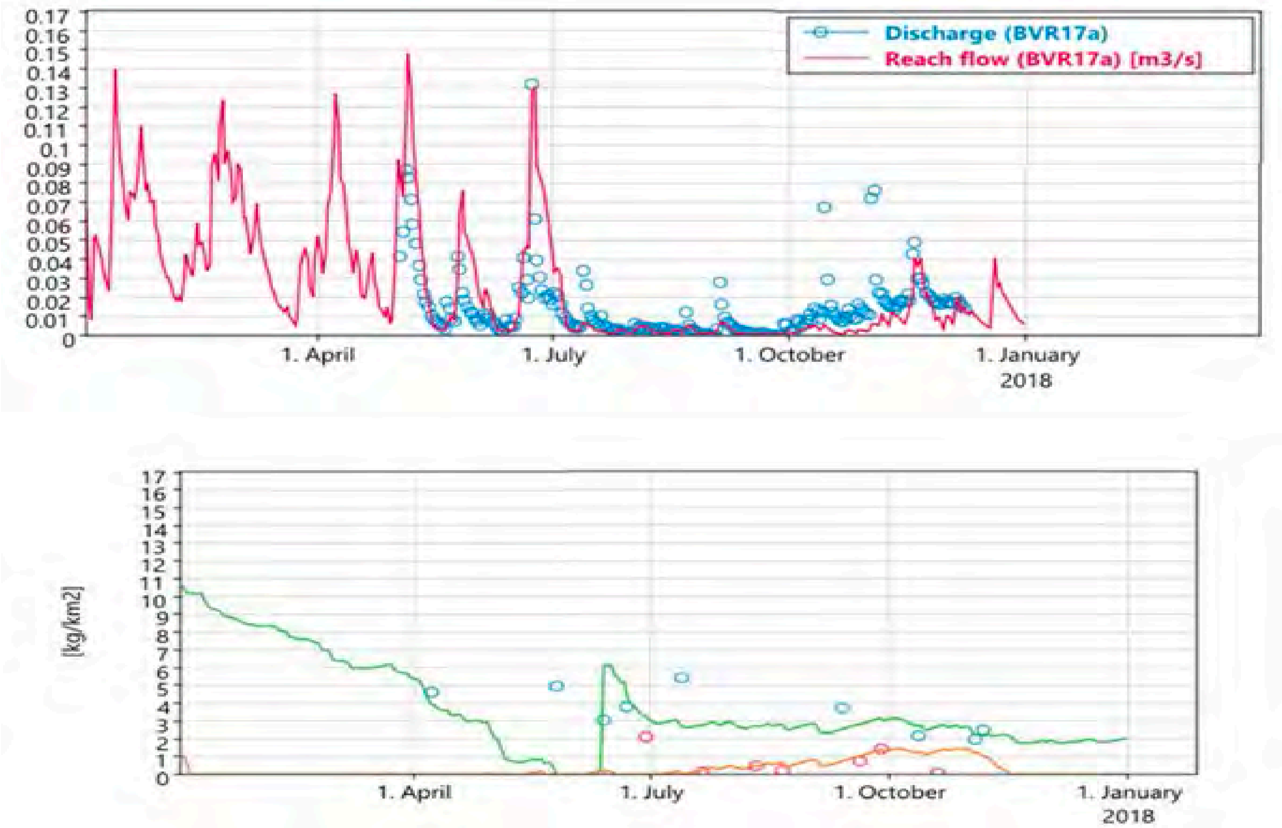



Figure 13. Model application to the Canadian case study. Upper panel shows the fit between modelled (red line) and observed (blue dots) river water discharges (driven in the model by an underlying hydrological module). The lower panel shows predicted (green and red lines) vs observed (blue and red dots, respectively) masses of MPs in the catchment soils over time. (green shows results for soils with applied sludge while red represents control soils).

# Stakeholders

Stakeholder interaction took place through a multi-actor approach, whereby stakeholders (especially in the farming and water industry sectors) served both as recipient of dissemination and providers of data.

**Multi-Actor approach:** Routine interaction took place at regional, national and international levels. Stakeholders in the farming, water industry and governance were asked to provide perspectives and ideas on practices that can lower MP pollution to soils and water environments. These inputs were used to assess management scenarios through the knowledge and decision support tools developed during IMPASSE. This activity involved in particular farmers and water industry in Canada, Norway and Sweden.

**Stakeholder scoping analysis in Sweden:** In December 2020, IMPASSE attempted a first documentation of stakeholder knowledge and attitudes towards MPs in sludge applied to agricultural soils. In Sweden, we conducted interviews with 33 actors including politicians, government workers, water industry professionals and researchers. Our results suggest that stakeholders do not believe they are sufficiently well informed about the issue, highlighting the need for further research and communication. Results will be submitted to the peer-reviewed literature.

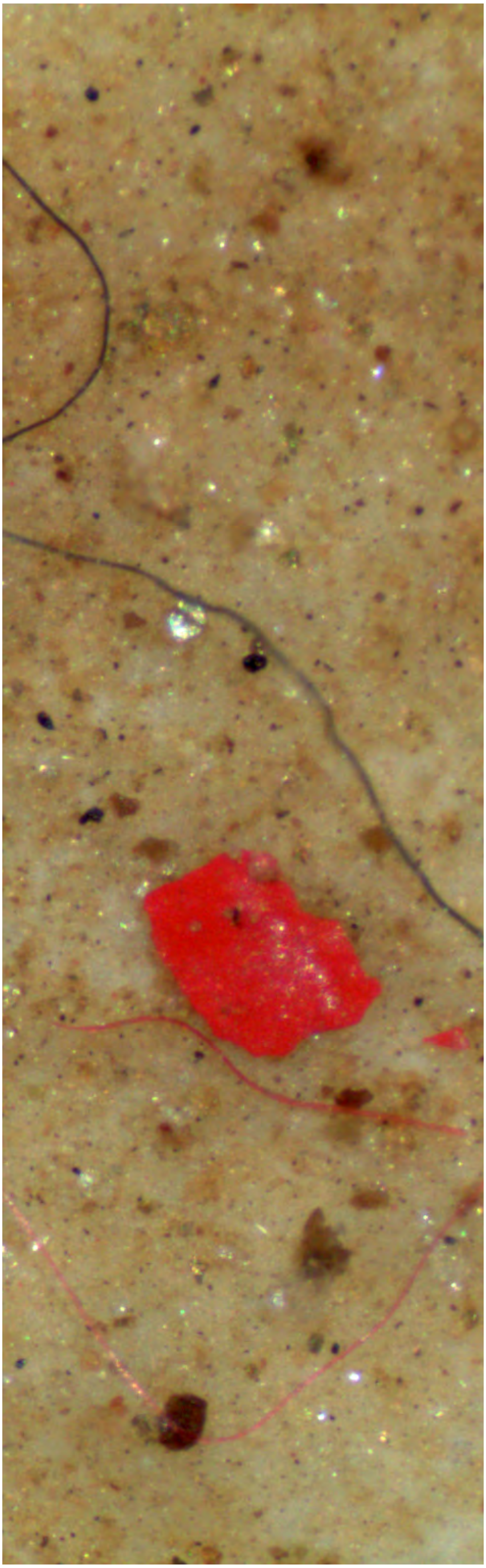
**Final stakeholder conference:** We held a final virtual stakeholder conference on the 2nd December 2020, which attracted 60+ registrants from Sweden, Norway, Germany, Lithuania, Spain and Canada (www.impassesverige.weebly.com). The event featured summary presentations about research conducted during the project and a panel discussion about microplastics in sludge applied to agricultural soils. In this context, stakeholders from governance (Swedish Environmental Protection Agency) and Water industry (International Water Association) presented their position and data. During the event, an open discussion was held on comparing perspectives and positions in light of the results achieved by IMPASSE. In particular, we found that most of the discussion and policy debate on MPs in biosolids carried out among societal actors and groups of interests was until now largely based on limited and uncertain preliminary data. IMPASSE has therefore provided a new scientific basis to continue such a debate towards effective policies and instruments for preventing plastics from contaminating wastewater resources.

**Between June and July 2020** we held a series of virtual meetings with stakeholders including representatives of plastics and bioplastics industries and international governance. In these meetings, we provided direct information on some of the key findings from IMPASSE and obtained a direct enrolment of these stakeholders in a new research planning initiative that resulted, in September 2020, in the successful application to a European Commission H2020 grant. The project PAPILLONS focusing on sources, behaviour and impact of plastics in agricultural systems is the result of such an initiative. PAPILLONS is built using the IMPASSE consortium as a core and further expanding it to 20 European and Chinese research partners and a list of 20 Stakeholders in the governance, industry and farming sectors. PAPILLONS is due to start in May 2021.

**European Chemical Agency (ECHA).** IMPASSE researchers have undertaken important interactions with stakeholders at European level. We were invited by the European Chemical Agency (ECHA) to attend the workshop on the Restriction of Intentionally-Added Microplastics under REACH on the 30-31st May 2018. There we gave a presentation on IMPASSE to the plenary group. Within that meeting we presented and participated in the discussion in the Agriculture sub-group, providing an overview on existing works related to MPs in agricultural systems.

**British Royal Society.** We were invited to collaborate with the British Royal Society during the preparation of a synthesis document (Living Landscapes) on MPs for policy makers in UK. This document will feed into the UK government strategy on MPs.

**International Water Association (IWA) (Water Industry)** We have actively participated to the IWA world congress in Tokyo in September 2018. There we organized two workshops on MPs. We presented our preliminary results and provided our perspective over the future and needs of research in this field.



# Scenario assesment

## A series of possible practices for reducing MP addition to soils were proposed by farmer and wastewater stakeholders and assessed by IMPASSE

Stakeholders have identified that with increasing population (generating excess waste), and a subsequent increase in food requirements, the 2% rate of land application of biosolids will likely increase over time. Two possible management scenarios were identified and disclosed to stakeholders during the final stakeholder meeting.

### 1.MP reduction under a changing climate:

Scenarios were run using the INCA-MP model to test the hypothesis that storage of MPs in soils occurs in dryer years. The 2017 precipitation was reduced by 50%, and the model re-run for the 2017 period. Relative storage and transport amounts were compared for all land-uses, between the 'wet year' (observed 2017 rainfall scenario), and the dry year (50% precipitation scenario) (Figure 14).

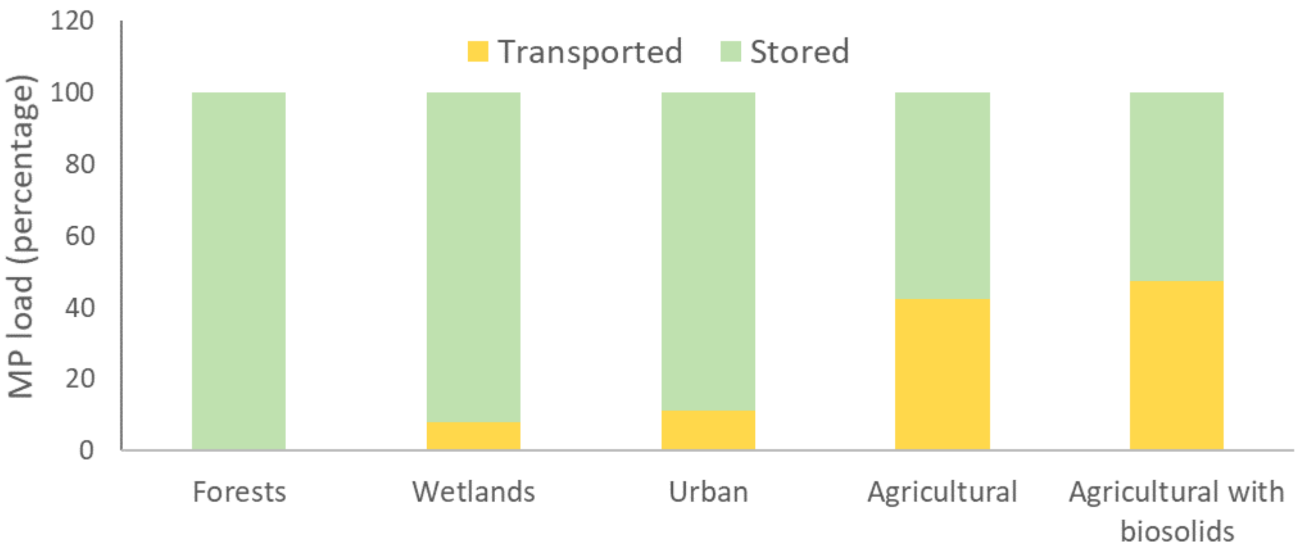



Figure 14: Proportion of MPs stored and transported during a dry year, assessed through an INCA-MP model application

The meteorological simulation revealed that during drier years, agricultural soils can act as effective stores; This explains how the 'residual' MP soil stores are generated. While the ability of soils to store MPs might at first appear to be a potential management solution, sufficiently high rainfall events subsequently mobilize these stores, even years after the biosolids were first applied. Climate change will result in an increased frequency of extreme rainfall events. Storage of MPs within all land-uses is therefore likely to become less effective. Management solutions designed around meteorological events (e.g. application of biosolids in dry periods) will serve only to delay, but not reduce, MP export to the environment.

**2.Changes in MP inputs with changes in land-use**

Although biosolids are not currently the primary source of MPs to the environment, they are clearly a critical pathway. Stakeholders in Canada have indicated a future need to increase biosolids application rates, hence model scenarios were run to ascertain the threshold of land area (in % of the catchment area) at which biosolids can be applied before they become the dominant source of MPs. At a critical threshold of 34% of agricultural land, biosolids are estimated to become the dominant source of MPs to the catchment. Currently only 2% of the agricultural land is treated with biosolids. Our results highlighted that given the current relatively low rates of biosolid applications to fields, effective policies for protecting water ecosystems from MPs should initially focus on reducing sources other than biosolids, while measures to reduce releases of MPs at sources and their input to wastewater treatment plants will be necessary in the future to guarantee circularity in the use of sludge.

**Economic effectiveness of identified MP management strategies.**

Economic effectiveness of identified management strategies was analyzed considering the Canadian scenario (scaled to Ontario Province). Such analysis is bound within the contest of the costs that could be accurately estimated given current knowledge and data.

**Hence, this analysis does not include the assessment of the possible negative economic impacts posed by plastic pollution onto environmental or agricultural ecological services. These externalities cannot be estimated based on the knowledge produced within this novel area of research. Resolving this gap was beyond the scope of this project and will be a core scientific challenge for the incoming years.**

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The economic efficiency of four management options were explored, based upon observations and input from stakeholders (Figure 14 ).

- Option 1: to reduce the % of biosolids applied and reduce land coverage to 1%;
- Option 2: to maintain current coverage, and apply biosolids during drier periods;
- Option 3: to increase the % of biosolids applied, and increase land coverage to 4% (assuming MPs were removed from biosolids at net zero cost);
- Option 4: to increase the % of biosolids applied, and increase land coverage to 5% (assuming MPs were removed from biosolids at net zero cost).

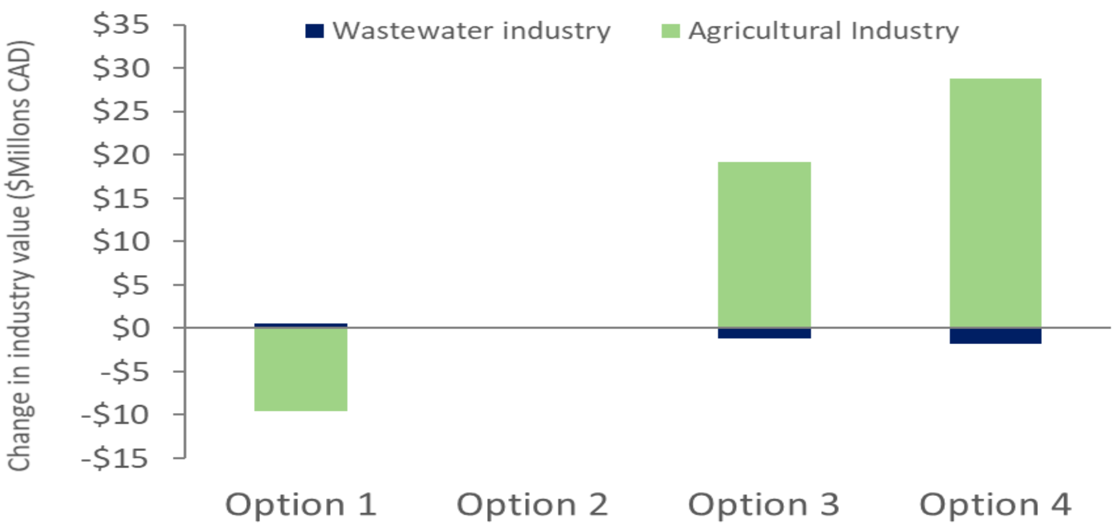


Figure 15: Estimated change in industry value ($Million CAD) under each management option evaluated

In all these scenarios, it was assumed that zero cost methods to reduce MPs from biosolids could be achieved. Options 1 and 2 maintaining or reducing rates of sludge application appear to be economically inefficient. They enable minor savings in transport costs to the WWTP industry, and cause increased expenditure for farmers due to purchasing of chemical fertilisers as replacement. Economically, the greatest value is in increasing the rate of agricultural application of biosolids. By association this requires increasing the proportion of land to which they are applied. Because scenarios 4 and 5 are both economically convenient and assimilate circularity-thinking, they will most likely be core pillars of policy addresses and management in the coming years. Unfortunately, reducing the amount of MPs in biosolids may not be cost free. Restrictions of MP use in personal care products (a relatively low cost measure, affecting however, assets in the industrial manufacturing sector) only result in a partial reduction of plastic inputs to the sewage. Similarly, passive biosolid treatment (e.g. dewatering) can possibly remove only a fraction of the MPs. Solutions that will enable a bulk removal of MPs from biosolids include incineration with recovery of mineral nutrients, or infrastructural solutions to limit transfer of MP from laundry effluents (carrying microfibers) or urban runoff. It is therefore unlikely that MPs could be completely removed from biosolids at zero-costs. A more detailed analysis remains for future studies, where also possible costs of long term agricultural and environmental impacts of MPs should be estimated and assimilated.

# Conclusions & Recommendations

IMPASSE provided seminal knowledge of the role of sewage sludge application to agricultural soil as source of MPs. The project has provided seminal data on the effects of selected types of MPs (common in sludge) on a broad range of soil and water organisms. Main conclusions are:

- Biosolids from sewage sludge are vectors of large amounts of MPs. It is estimated that in mass units, dry biosolids contain on average between 400 and 800 mg of MPs per kg of dry weight, prevalently in the form of fibers and fragments. It is important to note that these figures are based on experimental assessments performed on biosolids produced in a semirural context and analyzed with a method validated for MPs with a minimum size of 50 micrometer (in their larger dimension). The adopted method is not optimized and validated to detect black rubber particles (e.g., from car tire debris). Because of this, the figures reported here are to be considered as underestimations of the real level of MP contamination in biosolids.

- Application of biosolids from sewage sludge is a dominant source of MPs to treated agricultural soils.

- Soils with longer history of treatments with biosolids are more contaminated than soils with only recent treatments or soils that were never treated. Hence agricultural soils behave as long-term accumulators of MPs.

- MPs from soils treated with biosolids from sewage sludge can undergo remobilization driven by water runoff. While baseline low-intensity precipitation appears to mobilize only a minimal fraction of MPs from the soil, our evidence suggests that extreme precipitation events can instead release a large amount of MPs to downstream environments.

- In dry environments, in years without flooding, MPs leached by agricultural soils are likely to represent a minor fraction of the total load of MPs reaching rivers (from all other sources). While this could not be assessed directly in experimental terms, a mass balance analysis at the field scale highlighted that during flooding, MP releases from treated agricultural soils may represent an important source of MPs to downstream water ecosystems.

- At environmentally relevant concentrations, effects of MPs on soil and water macroinvertebrates and zooplankton were very small, but in some cases detectable and significant. Organisms were observed to interact with MPs in their environment. MPs were ingested or entrained on the external parts of the organisms’ body.



- While survival effects were negligible, a range of sublethal effects on reproduction, mass allocation, energy storage and biomarker responses linked to the immune system were observed in soil organisms at concentrations representative of highly contaminated soils (possible in real environmental conditions). Upon ingestion, earthworms were found to modify the properties (i.e., length) of microfibers, indicating that organisms can affect behavior and bioavailability of MPs.

- While the acute risk posed by MPs to soil and water invertebrates at environmentally relevant levels is low, prolonged exposure holds the potential to negatively affect a broad spectrum of organisms with different ecology and functions, some of which are key for sustaining agriculture.

- Co-occurrence of MPs and organic contaminants in soil and water can affect the bioconcentration of these contaminants in biota. In experiments with fish, we observed that MPs can lower the bioconcentration of pollutants.

- After dialoguing with stakeholders in the farming and wastewater industry sector, it emerged they expect that the use of biosolids in agriculture will increase due to the needs of enabling a cost-effective disposal of produced WWTP solid waste, increasing economic efficiency of agricultural production (e.g., by reducing the use of artificial fertilizers), and acknowledging adoption of circularity in agriculture and waste management. It emerged however, that the understanding and the adopted narratives amongst these actors with regards to MP contamination and their ecological and agricultural impacts were (necessarily at this stage) based on insufficient data.

**Our recommendation are the following;**

- The policy debate on sewage sludge management should assimilate the new data and knowledge emerging from IMPASSE and other research initiatives as rapidly as possible.

- Regulation on sewage sludge use in agriculture should include legal thresholds for MPs.

- As MPs are not easily dissipated by soils and persist in the environment, regulation should acknowledge that continuous addition of MPs to agricultural soils will result in increasing pressure and risk to soil organisms.

Soil is a non-renewable resource and MP pollution in soil is likely irreversible. Under natural processes, MPs can only be released from soils at the cost of contaminating downstream environments. Under current treatment scenarios or possible future scenarios with increased use of biosolids from sewage sludge in agriculture, pollution levels will tend to increase. Regulators should consider that while sublethal effects on soil biota are possible already at present day levels (in case of highly polluted ecosystems), the safety threshold to prevent abrupt and irreversible damage of MPs on soil ecological and agricultural services is not known.

**We furthermore recommend that:**

- in order to safeguard circularity in the use of sewage sludge, policies, management approaches and technologies that cost-effectively reduce or, better, remove completely MPs from sewage sludge are strongly endorsed.

- economic cost-benefits analysis of sewage sludge use in agriculture should include sound estimations of environmental externalities for both present day and future scenarios of MP contamination in soils and freshwater ecosystems.

# Publications

## Published

1. Dolar, A., Selonen, S., van Gestel, C.A.M., Perc, V., Drobne, D., Jemec Kokalj, A. 2021. Microplastics, chlorpyrifos and their mixtures modulate immune processes in the terrestrial crustacean Porcellio scaber. Science of the Total Environment 772, 144900. https://doi.org/10.1016/j.scitotenv.2020.144900
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3. Selonen, S., Dolar, A., Jemec Kokalj, A., Skalar, T., Parramon Dolcet, L., Hurley, R., van Gestel, C.A.M. 2020. Exploring the impacts of plastics in soil – The effects of polyester textile fibers on soil invertebrates. Science of the Total Environment 700:134451. https://doi.org/10.1016/j.scitotenv.2019.134451
4. Galafassi, S., Nizzetto, L., Volta, P., Plastic sources: A survey across scientific and grey literature for their inventory and relative contribution to microplastics pollution in natural environments, with an emphasis on surface water, 2019, Science of the Total Environment 693, 133499. https://www.sciencedirect.com/science/article/piiS0048969719334199?via%3Dihub
5. Schell, T., Rico, A., Vighi, M., Occurrence, fate and fluxes of plastics and microplastics in terrestrial and freshwater ecosystems. 2019 Reviews of Environmental Contamination and Toxicology, DOI 10.1007/398_2019_40. https://link.springer.com/chapter/10.1007%2F398_2019_40
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7. Hurley, R. R. Lusher A. L, Olsen, M., Nizzetto, L. Validation of a Method for Extracting Microplastics from Complex, Organic-Rich, Environmental Matrices, 2018, Environ. Sci. Technol., 2018, 52 (13), pp 7409–7417 https://pubs.acs.org/doi/10.1021/acs.est.8b01517
8. Hurley, R.R, Nizzetto, L. Fate and occurrence of micro (nano) plastics in soils: Knowledge gaps and possible risks, 2018, Current Opinion in Environmental Science & Health, Pages 6-11 https://www.sciencedirect.com/science/article/pii/S2468584417300466 Van Gestel, C.A.M & Selonen, S. 2018. Ecotoxicological effects of microplastics in soil: New
9. research themes should not ignore basic rules and theories. Comments on the paper by Zhu et al. (2018) "Exposure of soil collembolans to microplastics perturbs their gut microbiota and alters their isotopic composition". Soil Biology and Biochemistry 116:302-310. https://doi.org/10.1016/j.soilbio.2018.05.032
10. Crossman, J., and Weisener, C (eds). 2020. Contaminants of the Great Lakes Handbook of Environmental Chemistry DOI 10.10.1007/698_2020_592. https://www.springer.com/gp/book/9783030578732

## In review

10. Baho, D, M Bundschuh, MN Futter, under review. Microplastics in terrestrial ecosystems: moving beyond the state of the art to minimize the risk of ecological surprise. Global Change Biology
11. Schell, T., Hurley, R., Buenaventura, N., Ablanque, P. V. M., Nizzetto, L., Rico, A., Vighi, M., Fate of microplastics in agricultural soils amended with sewage sludge: The importance of surface water runoff as an environmental pathway. Submitted to Environmental Science & Technology
12. Schell, T., Hurley, R., Nizzetto, L., Rico, A., Vighi, M., Spatio-temporal distribution of microplastics in a Mediterranean watershed: the importance of wastewater as an environmental pathway, Submitted to Environment International
13. Selonen, S., Dolar, A., Jemec Kokalj, A., Sackey, L.N.A., Skalar, T., Cruz Fernandes, V., Rede, D., Delerue-Matos, C., Hurley, R., Nizzetto, L., Van Gestel, C.A.M. Exploring the impacts of microplastics and associated chemicals in the terrestrial environment – exposure of soil invertebrates to tire particles. (submitted)

## In preparation

14. Lavoy, M*., and Crossman, J. In submission. A novel method for organic matter removal from soils and wastewater samples containing microplastics Journal of Environmental Pollution
15. Norling, M., Rico, A., Schell, T., Crossman, J., Futter, M., Nizzetto, L., Constraining uncertainties in MP fate and transport in catchment, (In preparation)
16. Schell, T., Rico, A., Cherta, L., Dafouz, R., Giacchini, R., Vighi, M., Bioconcentration of organic contaminants in fish in presence of microplastics: is the "Trojan horse" effect matter of concern? (in preparation)
17. Schell, T., Martinez, S., Dafouz, R., Hurley, R., Rico, A., Vighi, M., Acute and chronic effects of synthetic fibers and tire fragments for freshwater invertebrates (in preparation)
18. Žilinskaitė, E, D Collentine, MN Futter. in prep. Swedish stakeholder perspectives on microplastics (from sludge) to agricultural land
19. Materić, D, M Peacock, J Dean, M Futter, T Maximov, F Moldan, T Röckmann, R Holzinger. in prep. Local and regional sources drive the deposition of nanoplastics in lakes and streams
20. Selonen, S., Jemec Kokalj, A., Dolar A., Drobne, D., Van Gestel, C.A.M. et al. Microplastics as possible modifiers of pesticide effects in soil – the effects of polyester fibers and tire wear particles on the toxicity of chlorpyrifos to soil invertebrates

## List of conference presentations

1. Baho, D., Evidence for harmful effects of microplastics in soil, Swedish University of Agricultural Sciences, IMPASSE Final stakeholder meeting, Virtual workshop 2020.
2. Collentine, D., The precautionary principle and microplastics in sludge spread on agricultural soils, Swedish University of Agricultural Sciences, IMPASSE Final stakeholder meeting, Virtual workshop 2020.
3. Žilinskaitė, E., Swedish stakeholders perspectives on microplastics, Swedish University of Agricultural Sciences, IMPASSE Final stakeholder meeting, Virtual workshop 2020.
4. Crossman, J., and M.N. Futter. Transfer of microplastics through agricultural soils. No regrets? The accumulation of microplastics in agricultural soil. Swedish University of Agricultural Sciences, IMPASSE Final stakeholder meeting, Virtual workshop 2020.
5. Schell, T., Dafouz, R., Rico, A., Vighi, M. Acute and chronic effects of tire particles and microfibers on Daphnia magna, 30th SETAC Europe Annual Meeting. Dublin, May 2020
6. Rico, A., Schell, T., Hurley, R., Nizzetto, L., Vighi, M., Fate of microplastics in agricultural soils amended with sewage sludge, 30th SETAC Europe Annual Meeting. Dublin, May 2020
7. Crossman, J., Hurley, R*., Nizzetto, L., and Futter, M.N. Microplastics in biosolids and agricultural soils. SETAC North America, Toronto, 2019.
8. Koestel, J, E Bäckström, A Lehoux, N Gottselig, MN Futter. 2019. 3-dimensional imaging of nanoplastic transport through a sand column using magnetic resonance imaging. Poster presentation at SETAC Helsinki meeting,. Abstract M0281, May 2019
9. Lavoy, M*., and Crossman, J. Transport and fate of microplastics within wastewater treatment systems. International Association of Great Lakes Research . Brockport, NY, USA. 2019.
10. Nizzetto, L, M Norling, R Hurley, J Crossman, A Rico, JLJ Ledesma, TC Schell, MN Futter. 2019. A comprehensive model of macro-, micro- and nano-plastic fate and transport in catchment soils and surface waters Poster presentation 256 at SETAC Toronto meeting, November 2019
11. Schell, T., Martinez, S., Dafouz, R., Hurley, R., Rico, A., Vighi, M., Effects of microfibers and tyre debris on freshwater invertebrates, 29th SETAC Europe Annual Meeting. Helsinki, May 2019
12. Schell, T., Hurley, R., Rico, A., Nizzetto, L., Vighi, M., Assessing the relevance of wastewater and runoff as microplastic sources for aquatic environments: A case study incentral Spain, 29th SETAC Europe Annual Meeting. Helsinki, May 2019
13. Schell, T., Martinez, S., Quesada, M. M., Dafouz, R., Rico, A., Vighi, M., Ingestion and impacts of tire particles and synthetic fibers on freshwater invertebrates, SETAC North America 40th Annual Meeting. November 2019
14. Crossman, J., Futter, M.N., Hurley, R*., Vighi, M., Schell, T., Bundschuh, M., and Nizzetto, L. Impacts of microplastics in farmed soils and stream ecosystems. International Association of Great Lakes Research, 2018.
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# About the consortium

Norwegian Institute for Water Research

**Project coordinator**
The Norwegian Institute for Water Research is a leading environmental research centre in Norway with an internationally oriented research programme. NIVA has run research and development projects in over 70 countries. Since 2016 NIVA has pioneered research on fate and toxicity of micro and nanoplastics, hosting state-of-the-art facilities and infrastructures for analyses, monitoring, ecotoxicity tests and modelling of fate and distribution.

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IMDEA Water belongs to the IMDEA network of research institutes of the community of Madrid and conducts research on all aspects of integrated soil and water management and environmental sustainability. Since 2017 IMDEA Water has been involved in several research activities aimed at assessing the fate and effects of microplastics in agricultural and surface water environments.

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The Department of Biology of the Biotechnical Faculty at University of Ljubljana carries out international level education and research activities on different areas of natural resources protection and management (soil, physical space, flora, fauna and water). Since 2015 the department conducts research on micro and nanoplastic hazard in aquatic and terrestrial environments.

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The department of Aquatic Sciences and Assessment at the Swedish University of Agriculture in Uppsala focuses on research on environmental pollutants, biodiversity, and ecosystem services. Since 2016 the group has conducted seminal research on fate, distribution and impact of micro and nanoplastics in terrestrial and freshwater environments.

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The Department of Ecological Science of the Faculty of Science at Vrije Universiteit Amsterdam is at the international forefront of soil ecological and ecotoxicological research focusing on the effects of chemical and abiotic stressors (incl. climate change) at different levels of biological organization.

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The Department of Earth and Environmental Sciences at Windsor University develop world class research on geofluids, geochemistry, and environmental geoscience. Since 2016 The department has an active research programme on microplastics sources and transport in terrestrial and freshwater environments.

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## Additional partners

The Finnish Environment Institute (SYKE) is the leading Finnish institute working on the broader area of environmental research. SYKE has a strong background in MPs research, both in effects assessment, analytics, and monitoring. The research interests also include various topics related to plastics in circular economy

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# Credits


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**Summary**
We found that the application of biosolids from sewage sludge represents an important source of microplastics (MP) to agricultural soils. Soils that received more biosolid treatments in the past exhibit higher levels of MPs, demonstrating progressively increasing pollution. Soil organisms underpinning important ecological and agricultural functions interact with these MPs experiencing sublethal health effects at realistic environmental concentrations. Soil is a non-renewable resource and soil MP pollution is irreversible. To enable sustainable and circular use of sewage sludge, measures that prevent MPs accumulating in it, or that remove them prior to use are necessary".

| Four keywords | Fire emneord |
|---|---|
| • Microplastics<br>• Agriculture<br>• Sewage Sludge<br>• Soil | • Mikroplast<br>• Jorbruk<br>• Kloakkslam<br>• Kord |

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