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029

Early Warning, Emerging Issues and Futures

Plastics in agriculture – an environmental challenge

Background

The Foresight Briefs are published by the United Nations Environment Programme to highlight a hotspot of environmental change, feature an emerging science topic, or discuss a contemporary environmental issue. The public is provided with the opportunity to find out what is happening to their changing environment and the consequences of everyday choices, and to think about future directions for policy. The 29th edition of UNEP's Foresight Brief explores the use of plastic in agriculture and the significant waste problem this entails which impacts on soil health, biodiversity, productivity and food security.

Abstract

Plastics are used extensively in farming, from plastic coated seeds to mulch film. They also make their way into biosolid fertilizer which is spread on fields. All these products have helped increase crop yields, but there is increasing evidence that degraded plastics are contaminating the soil and impacting biodiversity and soil health. This can lead to reduced productivity and could threaten long-term food security. As a finite resource which is under pressure, agricultural soil needs to be safeguarded from further degradation. Steps are being taken to improve the production and management of agricultural products containing plastics but there is also a need to look at a more holistic approach to food production, including nature-based solutions.

Introduction

The low cost and vast range of available plastic products has changed agricultural production from a traditionally low-waste activity to an industry with a significant waste problem. The manufacture and marketing of new plastic products has increased plastic use. This has helped farmers increase yields and reduce food waste, but it has outpaced the development of systems and processes to reuse, recycle, effectively biodegrade, or adequately dispose of many agricultural plastics (**Figure 1**). And now there is increasing evidence that these plastics are polluting soils (Rillig 2012). Agricultural plastics are part of the broader, global problem of plastic pollution, including in the marine environment, analysed in detail in From Pollution to Solution: A Global Assessment of Marine Litter and Plastic Pollution (UNEP 2021).

Plastic particles found in the soil can come from the breakdown of plastic products (such as containers, mulch film, plastic silage wrap, greenhouse tunnels, etc.) or from the use of products contaminated with plastic particles (such as compost or sewage sludge which contains microplastics that enter wastewater treatment plants e.g., from washing of clothing and abrasion of tyres). Plastic that ends up in soil varies in size from macroplastics (>5 mm) to microplastics (<5 mm) and nanoplastics (<1 µm) (Joint Group of Experts on the Scientific Aspects of Marine Pollution [GESAMP] 2019).

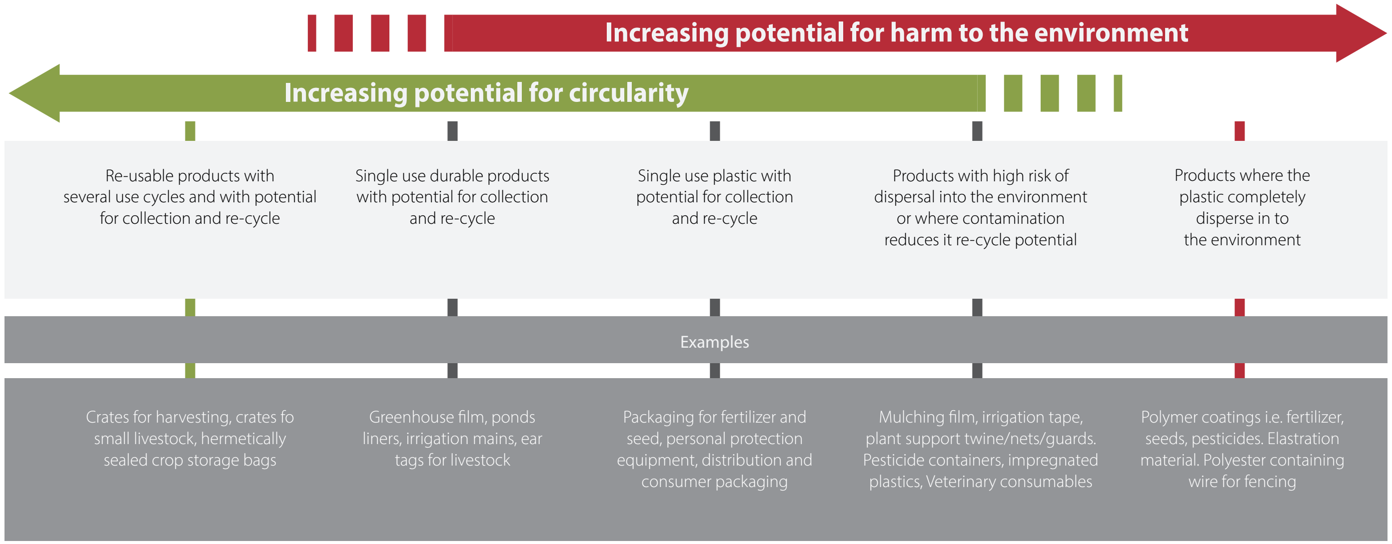

Figure 1: The potential for circularity or harm to the environment of some plastic products used in agriculture (FAO, 2021)
Source: Modified from FAO, 2021

Why is this issue important?

Healthy soil is more productive

Productive agricultural soil is a finite resource that is easily degraded. It is under pressure from multiple sources, including over-use and contamination (Food and Agriculture Organization of the United Nations [FAO] 2021 and Intergovernmental Technical Panel on Soils [ITPS] 2015) and its degradation is exacerbated by climate change. There is increasing evidence that plastics could be adding to this burden. Research indicates that a build-up of plastic can have wide ranging impacts on soil health, biodiversity, and productivity (de Souza Machado *et al*. 2019; Rillig *et al*. 2019; Liao *et al*. 2019). Maintaining healthy and productive soil is a critical aspect of food security (UNEP 2019).

Plastics in soil can be an important source of microplastics to other parts of the environment, as surface run-off and erosion can transport these small particles from fields onto waterways (**Figure 2**). Microplastics may also migrate from soil surface layers deeper into the soil profile. However, currently the fate of microplastics in soil is poorly understood (Rillig and Lehmann 2020). One study suggests that there is significant movement of the microplastics in biosolid fertilizer from the field into waterways (Crossman *et al*. 2020).

Photo credit: © Kristina Thygesen

Degrading plastic mulch film that can be a source of microplastic pollution that potentially ends up in the soil and waterways
Photo credits: CSIRO Australia

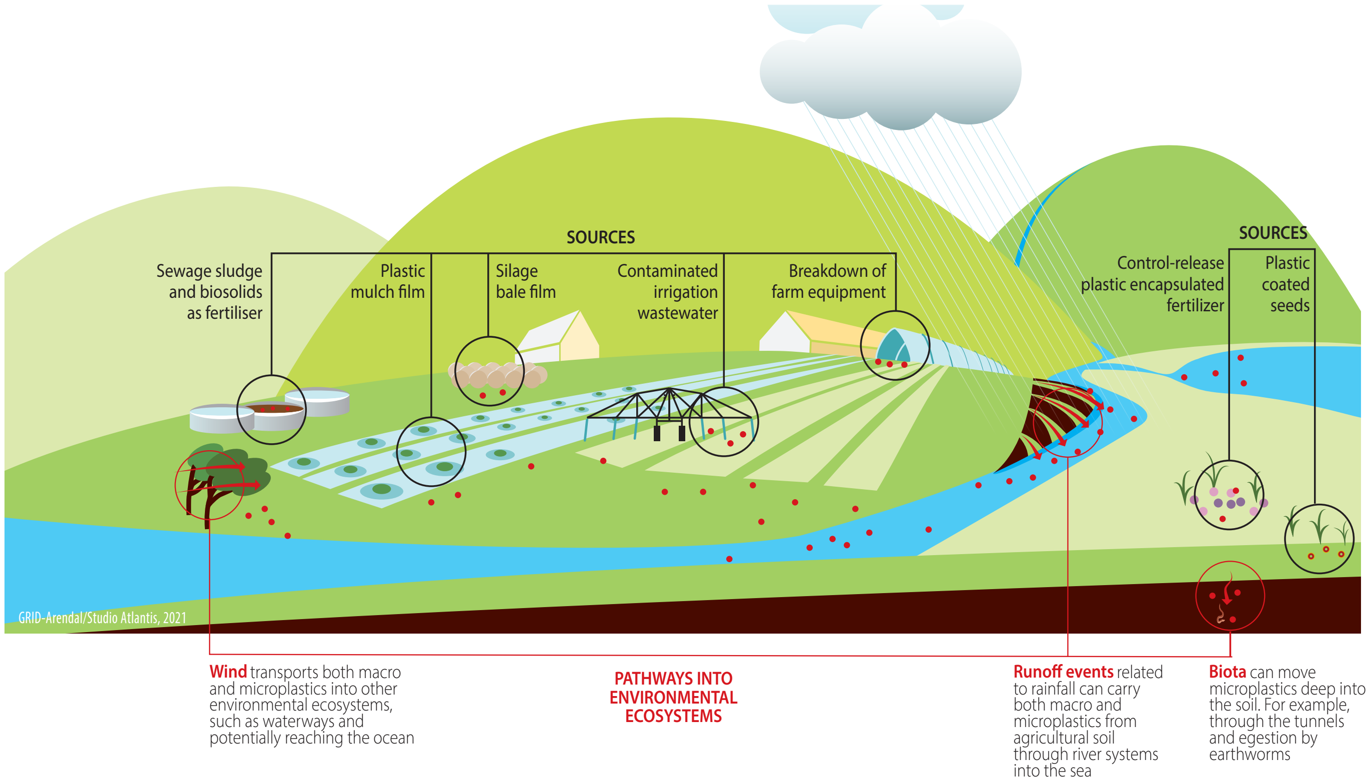

Figure 2. *Examples of the sources and transport of plastics and co-contaminants from agriculture production to the environment*
Source: UNEP (2021)

Main findings

Microplastics change soil properties

The ecotoxicology of soil microplastics is an expanding field. There is evidence that microplastics can have variable impacts (both positive and negative) on microbial communities, soil invertebrates and soil physio-chemical properties, depending on the size of the particles and the exposure level (e.g., Okoffo *et al.* 2021; Yu *et al.* 2020; Ganesh Kumar *et al.* 2019; Zhu *et al.* 2019).

Most studies are laboratory based and the conditions and methodology can vary greatly, making it difficult to compare results and quantify impacts. Investigations have found that the presence of microplastics can decrease the number, diversity, movement, and rate of reproduction of soil biota, decrease biomass of soil fauna, increase the biomass of microbes, and increase microbial activity (e.g., Zhu *et al.* 2019 and refs. therein).

While there are a limited number of studies, it appears that microplastics can effect changes in soil physio-chemical properties (structure, water holding capacity, density etc.) at environmentally relevant concentrations (de Souza Machado *et al.* 2018). Rillig *et al.* (2019) list potential impacts that changes in soil physio-chemical properties could have on plants, including reduced root growth and nutrient uptake.

As microplastics in the soil age, they experience changes in physical and chemical properties including colour, texture, chemical composition, surface characteristics and sorption capacity (Ren *et al.* 2021). Some of these changes make the microplastics more efficient at absorbing other soil contaminants that may be present, such as heavy metals and organic pollutants (Ren *et al.* 2021). This may make contaminants less available to soil biota and plants (Rillig *et al.* 2019).

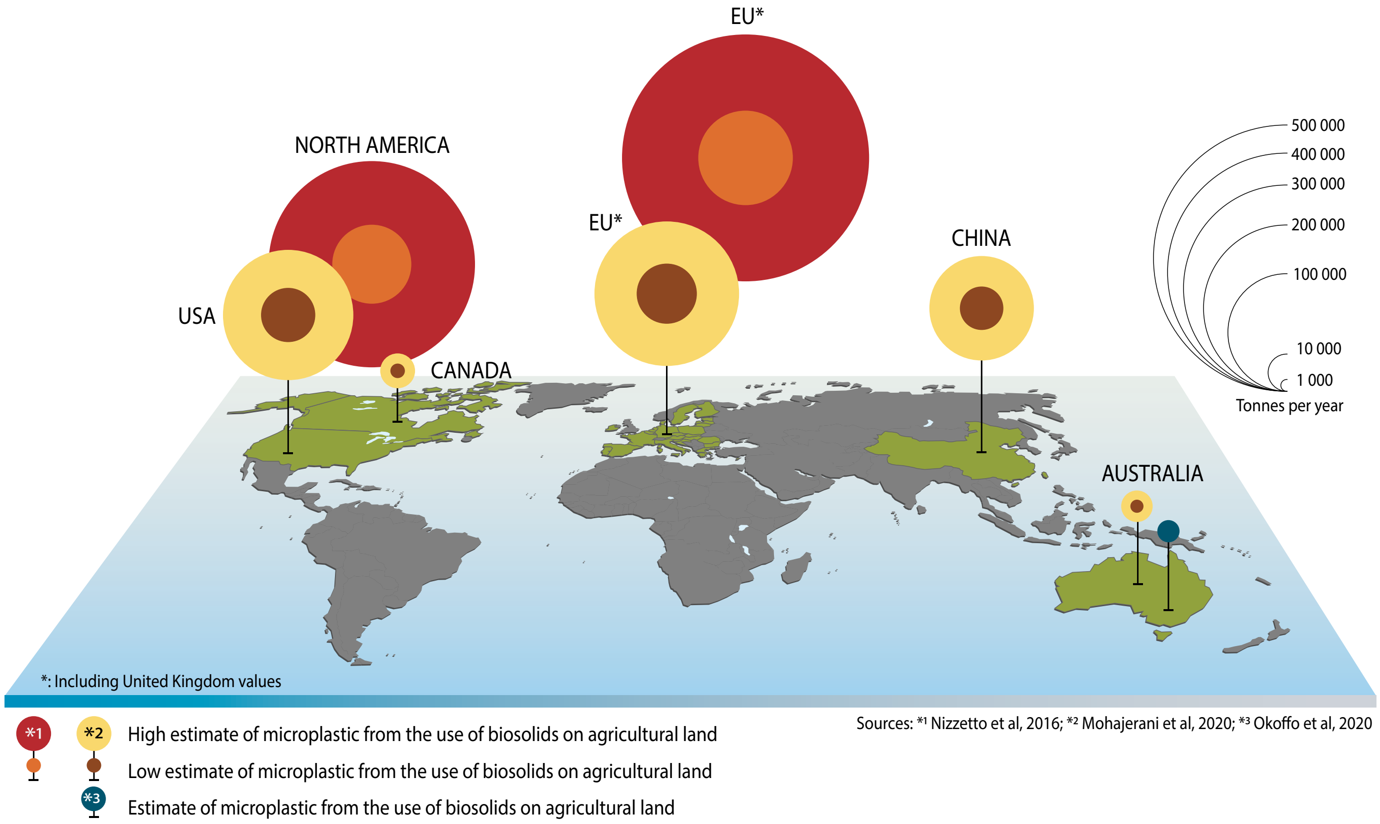

Figure 3. *The estimated contribution of microplastics to agricultural land through biosolids in tonnes per year in selected countries (Orange and Red circles Nizzetto, Futter and Langaas 2016; Yellow and brown circles Mohajerani and Karabatak 2020; Blue circle Okoffo et al. 2020).*

Biosolids - an important resource in the circular economy

Sewage sludge, a high-nutrient by-product from wastewater treatment plants (WWTPs), can be processed into biosolids (a treatment that removes pathogens and volatile organics) and used as fertilizer. The use of the biosolids in agriculture is seen as beneficial as it offers a relatively inexpensive, low energy alternative to manufactured fertilizers, while reducing the volume of waste requiring disposal. However, biosolids have been identified as the biggest contributor to soil microplastics (Corradini *et al.* 2019; **Figure 3**).

The number of microplastic particles entering WWTPs varies but has been found to decrease significantly in the wastewater with each treatment stage (primary, secondary, tertiary) as the microplastics are concentrated in the sludge (Lares *et al.* 2018; Hidayaturrahman and Lee 2019). With tertiary treatment, almost all microplastics can be removed from the wastewater and concentrated in the sludge (Carr, Liu and Tesoro 2016).

However, the process for turning sewage sludge into biosolids does not remove microplastics (microplastic particle concentrations of up to 1.4 x104 kg−1 have been found in biosolids; Crossman *et al*. 2020). In many countries, biosolids are used on agricultural land. For example, in Australia, the EU, Great Britain, and North America, 40–75 per cent of biosolids are used as fertilizer (Okoffo *et al*. 2021). It has been suggested that the annual input of microplastics to agricultural land in Europe and North America (a combined maximum total of more than 650,000 tonnes) could exceed the amount of microplastics estimated to be in the surface waters of the global ocean (a maximum of 214,000 tonnes; Nizzetto, Futter and Langaas 2016). A recent study in Germany estimated that the majority of the 13,000 tonnes of plastic entering the environment each year comes from sewage sludge (Istel and Jedelhauser 2021).

Table 1. The use and benefit of some agricultural products that contribute to soil microplastic pollution

Product	Use	Benefit
Biodegradable mulch (BDM)	Designed to be tilled into the soil and broken down by microorganisms.	Helps control soil microclimate, preserves moisture, and supresses weeds. Replaces commonly used LDPE non-biodegradable mulch, which is a major source of poorly recycled agricultural plastic waste.
Polymer encapsulated fertilizer	Fertilizer encapsulated in a variety of polymers that ideally break down and release fertilizer in sync with growth requirements - a few days to up to two years (Lawrencia *et al.* 2021; European Chemicals Agency [ECHA] 2019).	More efficient use of fertilizer, which results in less fertilizer loss from fields into waterways.
Polymer coated seeds	Designed to assist germination as they can contain fungicides, pesticides, hydrogels, nutrients, and symbionts. The coating polymers are designed to degrade as the seeds germinate.	Increase germination and seedling vigour. Reduces use of seed chemicals as controlled amount in each seed.

Biodegradable plastics

Agriculture products that intentionally introduce plastic into the soil include plastic mulch, coated seeds, and polymer encapsulated fertilizer (**Table 1**). Biodegradable mulch and coated seeds are available and biodegradable encapsulated fertilizer is being developed. Unlike the polymers in conventional agri-plastics, biodegradable polymers are designed to completely break down. However, because of the conditions required for complete breakdown (light, oxygen, soil temperature, pH, moisture, and microorganisms) influence the process and the rate of degradation, there is evidence that they can contribute microplastics to the soil (Wei *et al*. 2022; van der Zee 2021; Accinelli *et al*. 2019; Bläsing and Amelung 2018).

A recent study by Yu *et al.* (2021) acknowledged the formation of micro and nano-plastics from biodegradable mulch but found that, if the material is disposed of in soil or compost, the micro and nano particles do not persist for extended periods. However, if the mulch is left on the soil surface, the micro and nano plastics that form can be transported by wind or surface runoff. The process of biodegradation is slowed in atmospheric or aquatic environments and the authors suggest that, under these conditions, biodegradable plastics are likely to have similar environmental impacts to non-biodegradable plastics. A recent review of the impact of biodegradable plastics on soil ecosystems (Fan *et al.* 2022) found that, while biodegradable plastics are important in combating plastic pollution, the decomposition rates, the non-biodegradable components such as dyes, plasticizers etc, and the potential adsorption of other pollutants need further investigation before biodegradable plastics can be considered a successful non-polluting alternative to conventional plastics.

What is being done?

Plastic-free biosolids?

A recent review found 29 different polymers in WWTP influent, with polyester (PES) the most reported, followed by polyethene (PE) (Liu *et al.* 2021). The PES originates primarily from synthetic textiles and the PE comes from the breakdown of plastic packaging. Effort has been focused on removing microplastics for the wastewater that is discharged into the aquatic environment (tertiary treatment can remove more than 90% of microplastics, e.g., Iyare, Ouki and Bond 2020). However, successfully removing microplastics from the effluent concentrates the microplastics in the sludge (effectively cleaning one product by polluting another). Once the microplastics are in the sludge they are extremely difficult to remove, and current treatment practices do not include microplastics removal (sludge not used to make biosolids can be incinerated to produce energy, which eliminates the microplastics but depending on the system, may release other pollutants).

There has been some effort to decrease the number of microplastics particles entering WWTPs (e.g., bans in some countries on plastic microspheres in personal care products; Anagnosti *et al.* 2021). Microplastic fibres (PES and other polymers) from textiles and clothing are often the biggest contributors. There are commercial filters available that can be fitted on washing machines to trap microplastics (efficiency is largely untested; Browne, Ros and Johnston 2020) but at present washing machine manufacturers have not adopted this technology as standard.

The broad range of composition and size of microplastics increases the difficulty in finding a method to remove the particles once they are in the sewage sludge. There is some evidence that anaerobic digestion can reduce the number of microplastics in sewage sludge, and some treatment methods can fragment the microplastics, increasing the number of particles (Mahon *et al.* 2017). However, there is little targeted research investigating the removal of microplastics from sewage sludge. Amongst the small amount of research occurring in this area, there are some investigations into the use of ultrasound. This technique is used to remove organic compounds such as polycyclic aromatic hydrocarbons from wastewater (Ghasemi *et al.* 2020). Ultrasound has also been effectively tested (but not operationalised due to cost) to reduce the volume of sludge - the treatment causes cell lysis (breakdown of cell walls and the consequent release of fluid) (Romero-Pareja *et al.* 2017; Li *et al.* 2018). Recently, Alvim *et al.* (2021) demonstrated in the laboratory that ultrasound caused polyethylene microspheres to move into the liquid phase where they could be filtered out. The treatment removed nearly 40 per cent of microspheres from activated sludge and, importantly, did not appear to fragment the microspheres into nano-sized particles. However, it does not appear that ultrasound treatment has been tested to remove microplastic fibres (the most abundant plastic particles found in sludge).

Improved polymers

There is considerable research being undertaken to improve the biodegradability of polymers used in agricultural products. Most of these are being developed from starch.

Biodegradable mulch

- Mulch films are now being marketed as fully biodegradable and compostable (the standards for testing biodegradability and compossibility of mulch films under a variety of environmental conditions are still evolving). They are generally made from starch and polyesters (they may contain biodegradable hydrocarbon-based polymers).
- Research is ongoing into the development of sprayable biodegradable polymer membrane (SBPM) mulch (e.g., CSIRO's TranspiratiONal- SBM; Filipović *et al*. 2020). SBPM is a water-based polyurethane. Researchers are investigating formulating it from natural materials such as seaweed, sugar cane, wood-cellulose microfibers, lignin, gum, and leather (ibid.). A recent evaluation of SBPM (Braunack *et al*. 2021) found that development still needs to address sprayability, durability, biodegradability, and cost-effectiveness.


Trials with SBPM on tomato seedlings
Photo credits: CSIRO

Seed coatings

- To reduce the reliance on hydrocarbon-based polymers, the use of bio-based polymers is expanding. However not all bio-based polymers are biodegradable, despite being produced from corn, sugar cane, and waste fat/oil, so focus should be on polymers that are bio-based and biodegradable (Pirzada *et al.* 2020). Bio-based polymers are still more expensive to produce, but the increase in the price of fossil fuels may improve profitability.
- Research is being undertaken into using waste products from the timber and agriculture industries to produce bio-based polymers, replacing the use of food resources (Brodin *et al.* 2017).
- Incorporating selected microbial strains into polymer seed coatings is being trialled to enhance biodegradation times (Accinelli *et al.* 2019).

Polymer encapsulated fertilizers (controlled release fertilizers, CRF)

- Increasing research into biodegradable coatings made from polylactic acid (PLA), okara (soy pulp), linseed, polyurea and corn starch hydrogel (Lawrencia *et al.* 2021).
- Development of superhydrophobic CRFs that overcome the hydrophilic problems associated with many biodegradable bio-based CRF coatings and improve nutrient release (Zhang *et al.* 2017).
- The use of nanotechnology is being explored for the development of fertilizer coatings made of nanoporous material, the nano forms of the nutrients, and the development of nanocarriers that can better control the timing of nutrient release (Rakhimol *et al.* 2021). However, the toxicity of nano particles to plants and people is a concern and studies on potential impacts are limited (Ibid.).

Nature-positive solutions

Steps are being taken to improve the manufacture and management of agricultural products containing plastic and replace non-biodegradable plastics with biodegradables (and enhance their biodegradability). However, there has been limited research on assessing nature-positive approaches. There are also some farming practices that are being revisited, such as natural mulch cover crops. A cover crop such as cereal rye or hairy vetch can be planted during winter and then removed prior to sowing or planting. Living cover crops of legumes, such as peas, vetches, clovers, and beans, are also an option. These have the added benefit of providing nitrogen to the main crop, as legumes fix nitrogen and therefore increase soil fertility and reduce the cost of nitrogen fertilizer. However, due to the lack of context-specific information and appropriate education and training, there are significant barriers to the widespread roll-out of agricultural nature-positive approaches like cover crops. Key factors include concerns around potential reduction in yields and increased cost.

While many aspects of agricultural nature-positive food systems can be cost-efficient, such as a reduction in pesticide use potentially offsetting increased labour costs, plastic remains an inexpensive and easy-to-work-with material, making alternative options a hard sell. Increasing uptake could require policy instruments, capacity-building, and the involvement of interdisciplinary actors, including government, the private sector, academia, and civil society. To increase nature-positive production, governments need to consider financial incentives that compensate for reduction in yield and changes to subsidies that favour export-oriented intensive monoculture and chemical use. Policies also need to disincentivise unsustainable products or practices with, for example, levies on non-biodegradable and fossil fuel-based plastics.

The United Nations Food Systems Summit (2021) acknowledged the importance of a holistic approach to food production that values the conservation of ecosystem services:

> *Nature-positive food production systems recognize that biodiversity underpins the delivery of all ecosystem services on which humanity depends and that these are critical for the delivery of the Sustainable Development Goals, the Convention on Biological Diversity, and the Paris Agreement. Nature-positive food production is characterized by a regenerative, non-depleting and non-destructive use of natural resources. It is based on stewardship of the environment and biodiversity as the foundation of critical ecosystem services, including soil, water, and climate regulation.*

What are the implications/links for policy?

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Maintaining soil and water health is vital for food security and regulation of the global carbon cycle. Increasing the input of microplastics to agricultural soil could potentially result in severe impacts, including decrease in soil productivity and transport of microplastics into the aquatic environment (where negative impacts are well documented). Some of the policy implications include:

- Biosolids formulated from sewage sludge are an important source of nutrients. However, concentrating all the microplastics and associated toxics from wastewater and sewage into the sludge, which is spread on the crops we eat and washed back into waterways, is not a sustainable model for continued use. Uniform standards need to be developed and implemented in the use of biosolids.
- Stopping the introduction of microplastics into wastewater influent is difficult. Changes to product design and manufacture, improved solid waste management, and the elimination of unnecessary plastics (such as plastic microbeads) is required.
- Consumers need to be aware of the role that product choice (especially clothing) makes in the volume of microplastics entering WWTPs. To inform consumers, a rating system could be developed to indicate the potential of a piece of clothing or fabric to shed microplastics during washing. A tax could be levied on the sale of clothes that produce microplastics.
- Commercial and household washing machines should be manufactured with a filter capable of removing microplastics during washing.
- Governments need to improve regulations and standards on the biodegradable mulches, seed and fertilizer coatings and other agri-products. An example includes the European Union Regulation (EU) 2019/1009 that restricts polymers added to fertilizer. By 2026, all added polymers will have to meet new biodegradability criteria (currently being developed; Della Pietra 2019).
- Policies are required to encourage the improved collection and recycling of non-biodegradable agri-plastics.
- Research is required to develop products, such as alternative textiles, that do not shed microplastics during use.
- NGOs and other multi-stakeholder forums can continue to educate consumers and encourage manufacturers (like fast fashion producers) to reduce plastic pollution.

Conclusion

While there is still only limited research on the impacts of plastics in soil, there is evidence of negative effects on soil health and productivity, as well as the potential uptake of microplastics by crops (Rillig *et al.* 2019). Now is the time to adopt the precautionary principle and develop targeted solutions for stopping the flow of microplastics into the environment. Preventing microplastics from entering WWTPs and developing and implementing cost-effective mechanisms for removing the microplastics from sewage sludge or during the biosolid processing would be a major step in reducing soil contamination. In addition, accelerating the manufacture of zero-residue biodegradable plastics that are affordable (at present non-biodegradable products like LDPE mulch are considerably cheaper than the biodegradable alternatives), would give farmers better options for maintaining soil health. Finally, it's time to revisit farming practices that work with nature. A better understanding and quantifying of the environmental benefits of nature-based solutions is needed. A true comparison of the costs and benefits of different approaches can only be made if the full range of ecosystem services is assessed, and the full life cycle of each approach or product is analysed.

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This Foresight brief is based on the working paper, Plastics in Agriculture: Sources and Impacts (UNEP 2021). The paper focuses primarily on identifying sources of plastics and examining the fate of plastic residue in agricultural soil. It is expected to be the first in a series, which will also explore the movement of agricultural plastics from source to sea. At the recent United Nations Environment Assembly, a resolution was adopted to address plastic pollution - End plastic pollution: Towards a legally binding instrument. Negotiations are currently underway to develop a new treaty by the end of 2024 (UNEP 2022).

United Nations Environment Programme (2022).
Plastics in agriculture – an environmental challenge
https://wedocs.unep.org/bitstream/handle/20.500.11822/40403/Plastics_Agriculture.pdf

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