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WORKING PAPER

Plastics in agriculture: sources and impacts

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Purpose and scope

This working paper is an initial assessment of the potential impact of plastics used in agriculture. 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. The aim of the series is to increase knowledge and awareness and to invite discussion and action among relevant stakeholders to reduce plastic contamination of soil and the movement of agricultural plastics into the broader environment.

Summary

- Modern agriculture relies heavily on products that contain plastic.
- There is evidence that plastics, including microplastics, are accumulating in agricultural soil. This can impact soil properties, which in turn can affect agricultural productivity.
- The business model for agricultural plastic products currently relies on many single-use plastic products.
- Some non-biodegradable plastic products are being replaced by biodegradable ones. However, there is concern regarding the time frame for degradation and the completeness of the process in the natural environment.
- The rate of biodegradation of plastic in soil is influenced by soil moisture, UV-light, temperature, pH and the type and size of the plastic.
- At present, there is limited evidence that microplastics can move through the soil into plants and into food consumed by humans.
- Microplastics can adsorb other soil contaminants such as heavy metals and toxic organics. However, this is considered a minor pathway for contaminant accumulation.
- As concentrations of microplastics in soil increase, they may influence carbon and nutrient cycling due to changes in soil structure and microbial and fungal abundance.
- Microplastics can be washed out of agricultural soil into other ecosystems, including inland waterways and the coastal and marine environment.
- Nature-based farming practices may be cost-effective, even on a large scale, if co-benefits are included in accounting.

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Recommendations

There is limited research on the impacts of plastic in soil, however there is extensive evidence that plastic pollution causes severe negative environmental, social, and economic impacts in freshwater and marine systems. Although less well established, this working paper has found some evidence of similar impacts in agricultural soil. Increased understanding of the drivers and impacts of agricultural practices will help develop targeted solutions and sustainable options.

1. Develop standardized methods of detecting microplastics in soil to better understand residence times and transformations.

2. Determine the impact of plastics in soil on crop yield and the nutritional value and safety of food.

3. Develop models and scenarios to predict the likely future concentrations of microplastics in soil and their impact on soil health, crop yield and global food security.

4. Develop mechanisms for removing microplastic particles and fibres from biosolids used as fertilizer.

5. Accelerate the use of environmentally safe biodegradable polymers for controlled-release fertilizer and seed coatings.

6. Improve understanding of the behaviour of biodegradable plastic products under conditions of normal use in agriculture.

7. Support research into the movement of microplastics in soil and the possible uptake by plants, and the potential impact of microplastics on soil temperature.

8. Accelerate research and development of cost-effective plastic alternatives, including nature-based solutions.

9. Investigate the contribution of transported agricultural plastic to waterways and the ocean.


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1. Introduction

Over the last decade, we have increasingly realized the additional environmental, social and economic price we pay for the convenience of plastic products. Photographs of plastic waste on beaches, plastic material in the stomachs of dead seabirds and whales, and turtles and seals choking on plastic have become familiar. However, there is a less well-known site for the accumulation of plastics – agricultural soil, as first identified nearly 10 years ago by Rillig (2012).

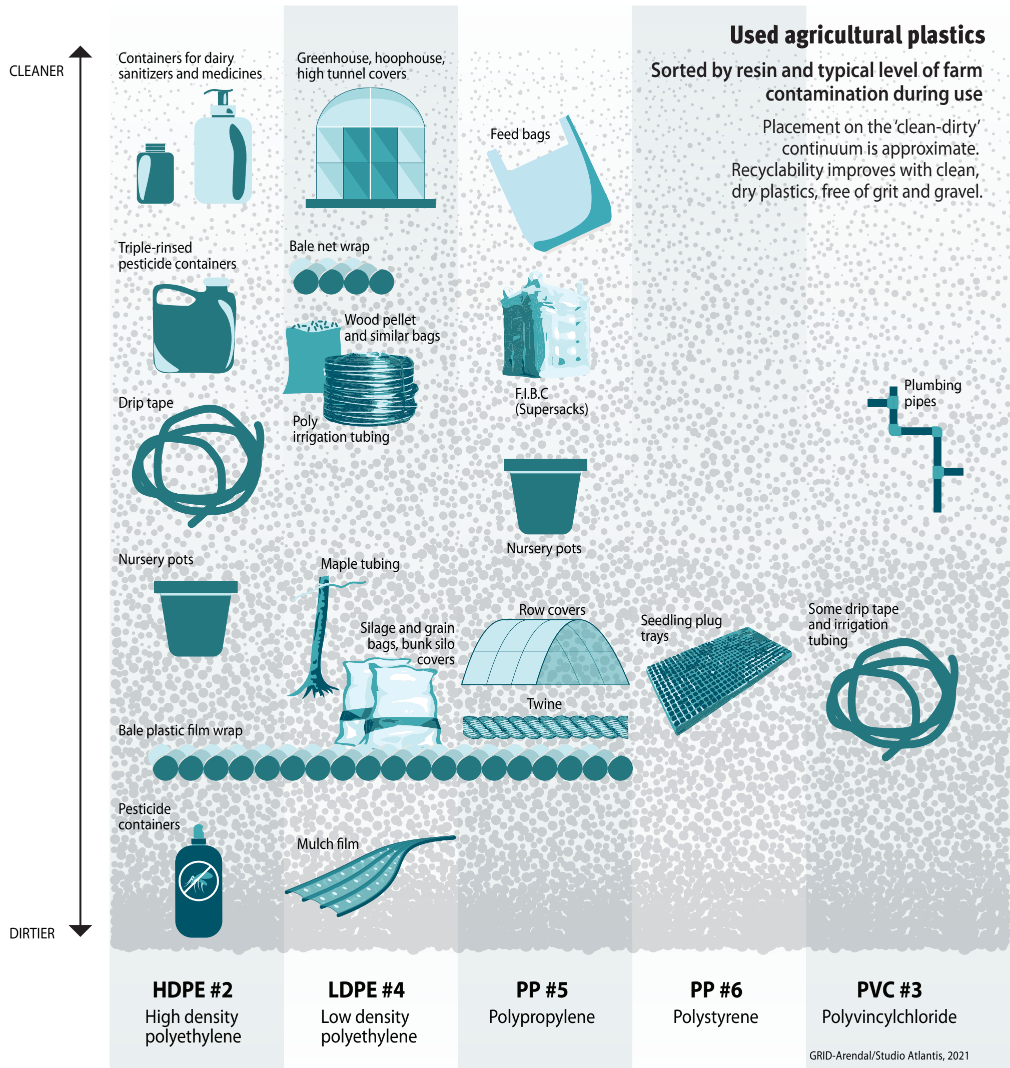
Laboratory studies indicate that the presence of plastic particles in soil can have wide-ranging impacts on soil health and biodiversity (de Souza Machado *et al.* 2019; Rillig *et al.* 2019). Currently, as there is no standard method for assessing concentrations of microplastic in soils, field studies are often difficult to compare or interpret. Since the 1950s, there has been a steady increase in the use of plastic in the agricultural sector (Orzolek 2017). Consequently, more plastic has found its way into soil, raising concerns that it could eventually impact soil health (Rillig, Leifheit and Lehmann 2021).

The most recent Global Environmental Outlook (United Nations Environment Programme [UNEP] 2019) indicates that feeding the global population in 2050 will require a 50 per cent increase in available food. While addressing food loss and waste will be important, using land more sustainably is necessary to increase or even to maintain current production levels. Soil health is critical for efficient food production and is essential to achieving many of the United Nations Sustainable Development Goals (Bouma, Montanarella and Evanylo 2019).

2. The source of plastic in soil

Farmers use products containing plastic to increase crop yields and improve the efficiency of water, agrochemical, and fertilizer use. These products include greenhouses, high and low tunnels, shade cloth, protective mesh, irrigation tape, drainage tubing, mulch, and silage films (Figures 1 and 2). Plastics are also used in containers for pesticides, seedlings, and post-harvesting operations such as feed storage for livestock (Scarascia-Mugnozza, Sica and Russo 2011; Vox *et al.* 2016; Table 1). Plastic particles found in soil can result from the breakdown of intentionally used plastic products (such as mulch film) or from the use of products unintentionally contaminated with plastic particles (such as compost or sewage sludge). Plastic products can be long-lasting, but the breakdown process starts on the surface of the plastic as soon as it is exposed to the environment. The breakdown is facilitated by the action of UV-light, water (weather and irrigation), wind, soil abrasion and mechanical handling. Plastic that ends up in the soil varies in size from macroplastics (>5 mm) to microplastics (<5 mm) and nanoplastics (<1 μm) (Kershawa, Turrab and Galganic 2019).

Figure 1. Examples of plastic products used in agriculture and the most common type of plastic used in their manufacture.



Note: The arrow indicates the product's degree of contamination at its end of life (usually soil or chemicals), which can impact the cost and/or effort required to recycle the product.

Figure 2. Examples of agricultural plastic use. From left to right: A tunnel made of thin film used to grow strawberries emerging through holes in protective black mulch; clear mulch employed in open field cultivation; and irrigation pipes feeding a field.

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Table 1. Types, uses and other information on agricultural plastics (Espí *et al.* 2006).

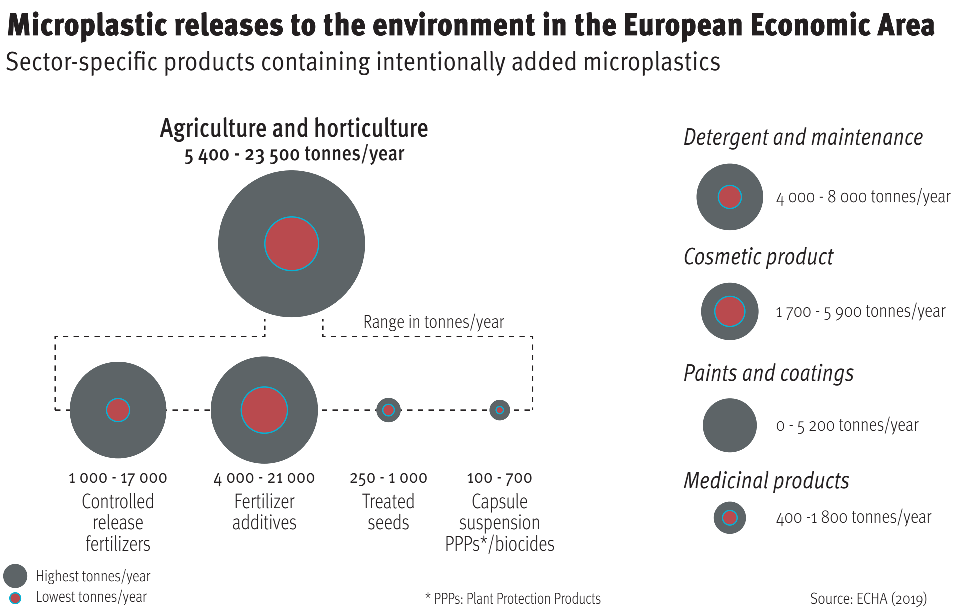
Examples of plastics used in the agricultural production of food and feed

Types of production	Groups of use	Types use	Application time *Single use*	Direct soil contact *Contamination, breakage*	Direct plant contact *Contamination, breakage*	Source of microplastic/fiber *Broken down by sun, wind, rain, mechanical*	Recycle potential *Commitment to clean, sort and return*
Horticulture *e.g.* *Vegetable (olericulture)* *Orchard* *Fruit and berries* **Agriculture crops** *e.g.* *Cereal* *Oil crops* *Hops* **Livestock** *e.g.* *Cows* *Sheep* *Poultry*	Protective cultivation films	Greenhouse Wind tunnel Low tunnel Mulching Nursery film Direct cover Non-woven floating cover	3-4 years 6-8 months 2-4 months	Low tunnel Mulching Nursery film Direct cover Non-woven floating cover	Low tunnel Mulching Nursery film Direct cover Non-woven floating cover	Greenhouse Wind tunnel Low tunnel Mulching Nursery film Direct cover Non-woven floating cover	Greenhouse Wind tunnel Low tunnel Mulching Nursery film Direct cover Non-woven floating cover
	Protective (conservation) films	Fumigation film Silage film Bale wrap film	Days to weeks 6-12 months 6-12 months	Fumigation film	Silage film Bale wrap film	Fumigation film Silage film Bale wrap film	Silage film Bale wrap film
	Nets	Anti-hail Anti-bird Wind breaking Shading Net for olives and nut picking		Net for olives and nut picking	Anti-hail Anti-bird Net for olives and nut picking	Anti-hail Anti-bird Wind breaking Shading Net for olives and nut picking	Anti-hail Anti-bird Wind breaking Shading Net for olives and nut picking
	Twine	Bale twine String Rope	6-12 months 4-6 months 4-6 months		Bale twine String Rope	Bale twine String Rope	Bale twine String Rope
	Piping, Irrigation, drainage	Water reservoir lining Channel lining Irrigation tape and pipes Drainage pipes	years years 8-24 months years	Water reservoir lining Channel lining Irrigation tape and pipes Drainage pipes	Irrigation tape and pipes	Water reservoir lining Channel lining Irrigation tape and pipes Drainage pipes	Water reservoir lining Channel lining Irrigation tape and pipes Drainage pipes
Used by all three sections	Direct addition of microplastics	Slow release fertilizer Polymer covered seeds Biosolids		Slow release fertilizer Polymer covered seeds Biosolids	Slow release fertilizer Polymer covered seeds Biosolids	Slow release fertilizer Polymer covered seeds Biosolids	
	Packaging (nonfood)	Fertilizer sacks Agrochemicals cans Nursery pots Tanks for liquid storage Crates		Nursery pots	Nursery pots	Fertilizer sacks Agrochemicals cans Nursery pots Tanks for liquid storage Crates	Fertilizer sacks Agrochemicals cans Nursery pots Tanks for liquid storage Crates

Sources: Espí et al. (2006)

Agriculture contributes to intentionally added microplastics that can enter the environment (Figure 3), as products used in agriculture can break down to form microplastics. Some will completely biodegrade, while more resistant plastics can accumulate in the soil. Determining the rate and completeness of biodegradation is difficult, as plastics can be labelled "biodegradable" with no information provided regarding the conditions required or the time frame of degradation. In some cases, they may not be degradable under natural environmental conditions (European Innovation Partnership for Agricultural productivity and Sustainability [EIP-AGRI] Focus Group 2021).

Figure 3. Intentionally added microplastics released into the environment in the European Economic Area from products used in agriculture and other manufacturing sectors (European Chemicals Agency [ECHA] 2019).



A recent review by Büks and Kaupenjohann (2020) of agricultural soils tested around the world found that microplastics are unevenly distributed (while plastic usage at the sites was variable, sewage sludge and mulch films had been used at the majority of test sites). For example, the European soils tested had an average of nearly 3,000 items kg^{-1}, which is twice the average amount found in Chinese test sites. In addition, sites closer to urban areas had consistently higher concentrations of microplastics than rural sites.

2.1 Sources of soil microplastic

Plastic mulch films

Plastic films, made from low-density polyethylene (LDPE, which is largely produced from petroleum), are widely used in agriculture for mulch. A mulch is a layer of material placed on top of the soil that changes the micro-environment around the crops. There are many different types of plastic mulch manufactured for different climates, soil types and purposes.

Although LDPE mulch is designed to be removed at the end of the harvesting season, often some is left and incorporated into the soil when preparing for the next crop (Kasirajan and Ngouajio 2012). The breakdown of the plastic is influenced by factors such as temperature, moisture, and solar radiation as well as the quality, thickness, and internal structure of the film. In areas where there is widespread and long-term use of LDPE plastic mulch, plastic mulch film residue can accumulate in soils (Huang *et al.* 2020). For example, Yan, He and Mei (2010)[1] found that in areas where mulch had been used for more than 10 years, residual plastic levels measured in topsoil were 50–260 kg per hectare. The plastic used to make mulch can also contain chemical additives that can further contaminate the soil (Wang *et al.* 2013).

While it is currently difficult to determine the amount of plastic mulch used globally, it appears to be rising. For instance, official figures from China show an increase

1 The original article in Chinese was unavailable but it is referenced in Lui *et al.* (2014).

from 2.173 million tonnes in 2010 to 2.408 million tonnes in 2019 (People's Republic of China, Ministry of Agriculture and Rural Affairs 2020). In addition, the estimated value of the global market for plastic mulch film and mulch handling equipment is projected to reach US$5.1 billion by 2027 (Global Industry Analysts Inc. 2021).

Box 1. Biodegradable plastic mulch – a better alternative?

Unlike the commonly used LDPE mulch, which is removed from the soil after harvest, biodegradable plastic mulch (BDM) – invented in the 1980s – is promoted as an environmentally sound product that can be tilled into the soil and broken down by microorganisms. While an appealing alternative to conventional mulch, there are still concerns over the length of time that some BDMs take to biodegrade, with some potentially never completely biodegrading (UNEP 2015). A review by van der Zee (2021) noted that at normal soil temperatures, not all material labelled "biodegradable" will biodegrade at a sufficient rate to avoid the accumulation of plastic residue in the soil. In Portugal, dry weather conditions slowed degradation and BDM debris was still present after two years (Rayns *et al.* 2021). Farmers in Spain also observed that while BDM fragments are breaking down, they can be blown across large distances (Ibid.). The BDM standards of the European Union (EU), EN 17033, specify that 90 per cent of organic carbon in BDMs must be converted into carbon dioxide (CO_2) within two years, with this being confirmed in laboratory tests with soil at 20–28°C (European Committee for Standardization 2018). Research by van der Zee (2021) concluded that mulches that meet EU standards do successfully break down in the field within the designated time frame.

A review by Hayes (2021) on the end-of-life performance of BDMs suggests that better understanding of the long-term soil impact of BDMs is required before there is widespread uptake by farmers. Although the evidence so far indicates that residual BDM fragments minimally impact soil health and microbial community structure, the behaviour of BDM derived micro and nanoplastics requires further investigation (Ibid.).

Most commercially available BDMs include a high percentage of fossil derived polymers (see, for example, United States of America, Department of Agriculture 2015). For this reason, they are not permitted by organic certifiers such as the United States National Organic Program, whereas conventional plastic mulch that is removed at the end of the growing season is allowed.

Polymer encapsulated fertilizer

Plastic polymer encapsulated controlled release fertilizers (CRF) are another potential source of soil contamination (Bläsing and Amelung 2018; Qi *et al.* 2020; Katsumi *et al.* 2021). The fertilizer can be coated with a variety of polymers that are designed to synchronize the release of the fertilizer with the plant's growth requirements, for a period of a few days to up to two years (Lawrencia *et al.* 2021; European Chemicals Agency [ECHA] 2019). Although the market for controlled release fertilizer is currently only a fraction of the global fertilizer market, it is growing rapidly (Markets and Markets 2020). At present they are mainly used in horticulture and tree nurseries and by home gardeners. However, these products are seen as having a major advantage over traditional soluble fertilizer, as they reduce the use of fertilizer and limit nutrient leaching from soil into waterways (Chandran and Mathew 2021).

There is considerable research into improving the efficiency of CRFs, including the use of more effective coatings. Many recent patents employ biodegradable coatings such as soy pulp, linseed, polyurea and corn starch hydrogel (Lawrencia *et al.* 2021). However, the commercial products that are currently available can leave plastic residue that can accumulate in soil. The time this takes to degrade varies and it can be washed out by surface run-off. For example, polyethylene fertilizer microcapsules used in irrigated paddy fields in Japan have been identified as a major source of microplastic in the adjacent coastal environment (Katsumi *et al.* 2021).

In an effort to reduce microplastics entering the environment, the European Chemicals Agency identified products that contain intentionally added microplastics (ECHA 2019). Their list included CRFs, as polymer coatings are considered microplastics due to the time required to degrade. The report concluded that the risks arising from the release of microplastics into the environment are not adequately controlled and therefore releases should be minimized. The ECHA estimated that restricting the use of microplastics in CRF and fertilizer additives over a 20-year period would reduce the amount of microplastic entering the environment by more than 250,000 tonnes, and potentially up to 442,500 tonnes (ECHA 2019, Table 1, p. 12). The report also noted that the economic impact of reformulating coatings to comply with EU biodegradability requirements could potentially be absorbed by consumers. The EU has specified that CRFs with non-biodegradable polymers cannot be manufactured after 16 July 2026, with the biodegradability criteria and compliance testing methods to be established by 2024 (European Union [EU] 2019).

Polymer-coated seeds

The use of coated seeds is increasing, with the market projected to grow to US$3 billion by 2025 (Markets and Markets 2020). However, coated seeds currently make up less than 3 per cent of the global seed market. Seed coatings, many of which currently contain plastic polymers, are designed to assist seed germination. In addition to polymers, they contain agrochemicals, such as fungicides, pesticides, hydrogels, nutrients and symbionts as well as fillers and dye. The coatings are generally very thin and designed to degrade relatively quickly. However, there is very little publicly available information on the composition and degradability of commercial coatings as most are proprietary formula polymers (Pedrini *et al.* 2017). Independent studies on the coatings are dominated by investigations into the dust produced during handling and planting, as this dust contains active ingredients such as pesticides that can impact non-target species such as bees. However, some of these studies have noted degradation times. Accinelli *et al.* (2019) found that the degradation times for seed coatings varied, with a non-commercial starch-based coating degrading completely within 32 days, while commercial polymer coatings took 48 days or longer to degrade.

Biosolids and organic waste used as a fertilizer

Sewage sludge is a high-nutrient by-product from wastewater treatment plants (WWTPs) that can be processed into biosolids for use as a fertilizer (Table 2). The amount of microplastics entering WWTPs varies (Hidayaturrahman and Lee 2019). When reviewing WWTP influent in developed countries, Gatidou, Arvaniti and Stasinakis (2019) found that microplastic particle numbers varied from negligible to over 7,000 per litre in the 69 WWTPs sampled. However, microplastic content has been found to decrease significantly with each treatment stage (Lares *et al.* 2018; Hidayaturrahman and Lee 2019). Gatidou, Arvaniti and Stasinakis (2019) found that 99 per cent of microplastics can be removed during treatment, with removed microplastic being concentrated in the sludge (Carr, Liu and Tesoro 2016).

The process for turning sewage sludge into biosolids used for fertilizer involves treatment to reduce disease-causing pathogens and volatile organic matter, however it does not specifically remove microplastic. In many countries, sewage sludge is converted to biosolids to be used on agricultural land, and in Australia, the EU, Great Britain, and North America, 40–75 per cent of biosolids are used as fertilizer (Okoffo *et al.* 2021; Figure 4. Corradini *et al.* (2019) proposed that biosolids are the main driver of soil microplastic pollution (Figure 5). A study by Zubris and Richards (2005) found that synthetic fibres were detectable in experimental soil columns five years after application of a variety of treated sludge products, including dewatered, composted, pelletized, and advanced alkaline stabilization. Zubris and Richards (2005) also found fibres in the soil of an orchard field site 15 years after the application of sludge products.

Table 2. Definitions of sewage sludge and biosolids.

Sludge	Biosolids
• Solids removed during sewage and wastewater treatment • Generally comprises around 1 per cent of the volume of the original wastewater stream • Consists of 2–3 per cent solids • Can have high levels of pathogens • In some countries, untreated sludge can be used in agriculture	• Sludge that has undergone treatment – aerobic or anerobic digestion, alkaline stabilization, composting • Consist of 15–90 per cent solids • Low/no pathogens • Reduced odour

Figure 4. The application or disposal method of sewage sludge and biosolids in selected countries (Christodoulou and Stamatelatou 2016).

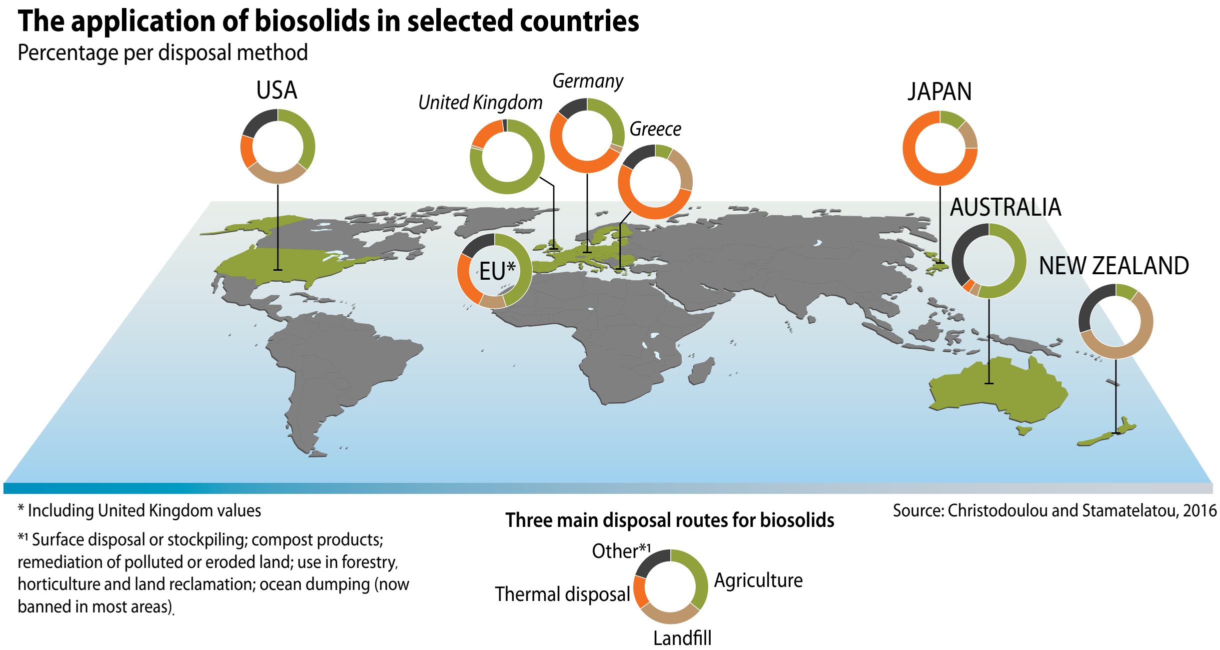
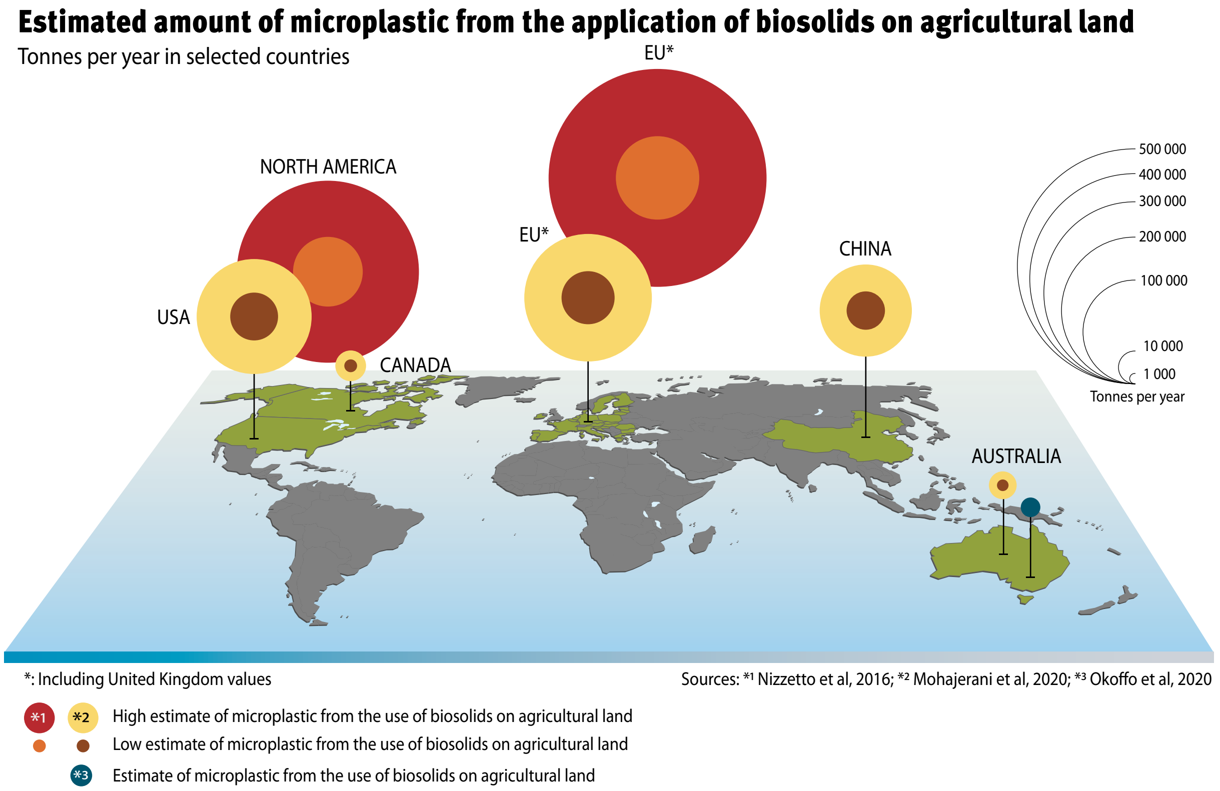


Figure 5. The estimated contribution of microplastics to agricultural land through biosolids in tonnes per year in selected countries (Nizzetto, Futter and Langaas 2016; Mohajerani and Karabatak 2020; Okoffo *et al.* 2020).



Organic fertilizers produced from commercial and household biowaste have been found to contain plastic particles (Weithmann *et al.* 2018). These fertilizers are more likely to be used by home gardeners than in commercial agriculture.

Fresh water, wastewater, and sediments used for irrigation and fertilization

Both fresh water and wastewater used for irrigation can contain microplastics. Microplastics have been observed in rivers, tap water and groundwater (McCormick *et al.* 2014; Bouwman *et al.* 2018; Weideman, Perold and Ryan 2020). Microplastic in fresh water can come from surface run-off, WWTP effluent, breakdown of plastic litter, and aerial deposition. Street run-off can be a major contributor as microplastics are released from tyres through abrasion (Sommer *et al.* 2018). Although WWTPs effectively remove most microplastics, some can remain in the treated wastewater released into waterways (Hidayaturrahman and Lee 2019) or used directly for irrigation.

Wastewater and sediment from terrestrial aquaculture ponds can also be used for crop irrigation and fertilization. While they are high in nutrients from fish waste, they can also contain microplastics (Wang *et al.* 2020). Microplastics may be introduced into the ponds through influent water, such as microplastics accumulating in ponds adjacent to the Pearl River in Guangzhou, China (Ma *et al.* 2020). They can also come from plastic products used in pond management (ropes, nets, floats, cages, etc.). In addition to microplastics, Cheng *et al.* (2019) also recorded high levels of phthalate esters in freshwater pond sediment in China. Phthalate esters, used in the production of industrial polymers, can leach from plastic products, and are associated with negative human health impacts.

2.2 Other sources of plastic to agricultural soils – unrelated to agricultural activity

Plastic contamination of agricultural soils from external sources is expected to be small compared to sources from farming. Nevertheless, open dumping, poorly managed landfills and littering can lead to windblown plastic. Studies on the atmospheric deposition of microplastic have been summarized in a review by Zhang *et al.* (2020), who noted that microplastics deposition from the atmosphere occurs in both urban (Cai *et al.* 2017; Zhou, Tian and Luo 2017) and remote areas (Allen *et al.* 2019; Brahney *et al.* 2020). Precipitation may act as a positive driver towards atmospheric microplastics deposition (Dris *et al.* 2015).

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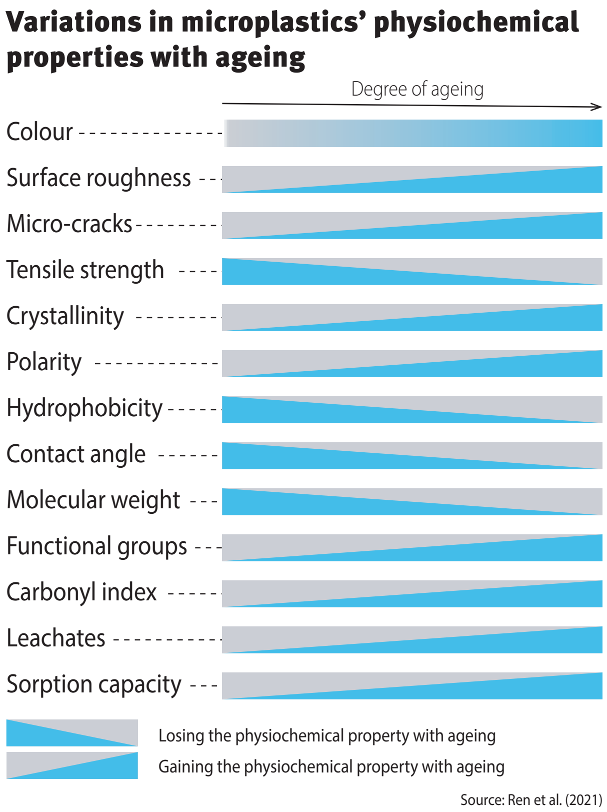
3. Adverse effects of microplastics

3.1 Soil and soil ecosystems

There is some evidence demonstrating that microplastics deposited on the soil surface can move down into the soil where they can interact with soil biota and plant roots (Rillig, Ziersch and Hempel 2017). Microplastics have been found to vertically migrate through the soil, with mobility influenced by changes in soil moisture content, such as the differences between seasonal wet and dry cycles (O'Connor *et al.* 2019). Earthworms, ants, termites, microarthropods and other soil dwellers have also been found to facilitate the movement of microplastic particles. In a laboratory experiment, Lwanga *et al.* (2017) found that earthworms (*Lumbricus terrestris*, a globally distributed species) incorporated microplastics into the long vertical burrow walls they constructed. As earthworm burrows facilitate water flow through the soil, they could therefore increase chemical leaching from plastic and move contaminants downward in the soil profile. If biota moves microplastic particles deeper into the soil, this is likely to slow the biodegradation process because of the lower number of microbes and cooler temperatures at depth (Fierer, Schimel and Holden 2003).

As microplastics in the soil age, they experience changes in their physical and chemical properties, including colour, texture, chemical composition, surface characteristics and sorption capacity (Ren *et al.* 2021; Figure 6). Some of these changes make the microplastics more efficient at adsorbing other soil contaminants that may be present, such as heavy metals and organic pollutants (Ren *et al.* 2021).

Figure 6. Variations in microplastics' physiochemical properties with ageing (Ren *et al.* 2021).



A number of authors have reviewed the potential impact of microplastics infiltrating soils (Okoffo *et al.* 2021; Ganesh Kumar *et al.* 2019; Zhu *et al.* 2019). There is evidence that microplastics can have both positive and negative impacts on microbial communities, soil invertebrates and soil physiochemical properties, depending on the size of the particles and the exposure level. While there are a limited number of studies, it appears that high concentrations of microplastics can impact plant growth, with changes observed in physiochemical properties, including soil structure, water holding capacity and density. However, the level of concentration of microplastics used in such research is generally greater than what has currently been observed in field studies (Rillig *et al.* 2019 and references therein).

3.2 Adverse effects of plastic on livestock and poultry

Livestock and poultry can ingest microplastics in fields and from prepared feed. The plastic in prepared feed can end up in the soil as a result of direct excretion or when the manure is used as fertilizer and compost (Wu *et al.* 2021). Plastic is increasingly being found in the intestines and manure of animals, especially in areas of intensive farming. For example, it has been found in the stomachs of farmed ducks in Indonesia (Susanti, Yuniastuti and Fibriana 2021), sheep manure in Spain (Beriot *et al.* 2021) and the manure of cows, pigs and chickens in China (Wu *et al.* 2021). However, there is currently no information on whether the ingestion of microplastic has an impact on the health of poultry and livestock.

Some animals such as cattle, pigs and goats will also ingest plastic waste – especially if there is a shortage of food – which can cause gastrointestinal problems that may result in weight loss or death. It has been suggested that indigestible plastic remaining in the rumen of cattle for long periods of time could potentially contaminate meat and milk with chemicals released from the plastic (Priyanka and Dey 2018).

3.3 Adverse effects of agricultural plastic on humans

There is growing research into the human health impacts of plastic (UNEP 2021) but there is still uncertainty regarding levels of exposure, especially to nanoplastics, and the potential of ingested particles to cause harm (Lehner et *al.* 2019). One of the ways people can ingest micro and nanoplastic particles is through agricultural produce, although studies detailing exposure are rare. However, relatively small concentrations of microplastics have been found in a range of fruit and vegetables. Conti *et al.* (2020) studied microplastic levels in store-bought carrots, lettuces, broccoli, apples, and pears. They found that the fruits had higher concentrations than the vegetables and theorized that this could be due to several factors, including the vascularity of the fruit pulp, the size of the root system and the age of the plants (several years for the fruit trees compared to months for the vegetables). It appears that microplastics can enter plants via cracks in the roots and then move into the shoots and leaves, as has been observed in lettuce and wheat (Li *et al.* 2019; Li *et al.* 2020). Microplastic particles can also be transported by the vascular system to the stems, fruit, and leaves (Conti *et al.* 2020).

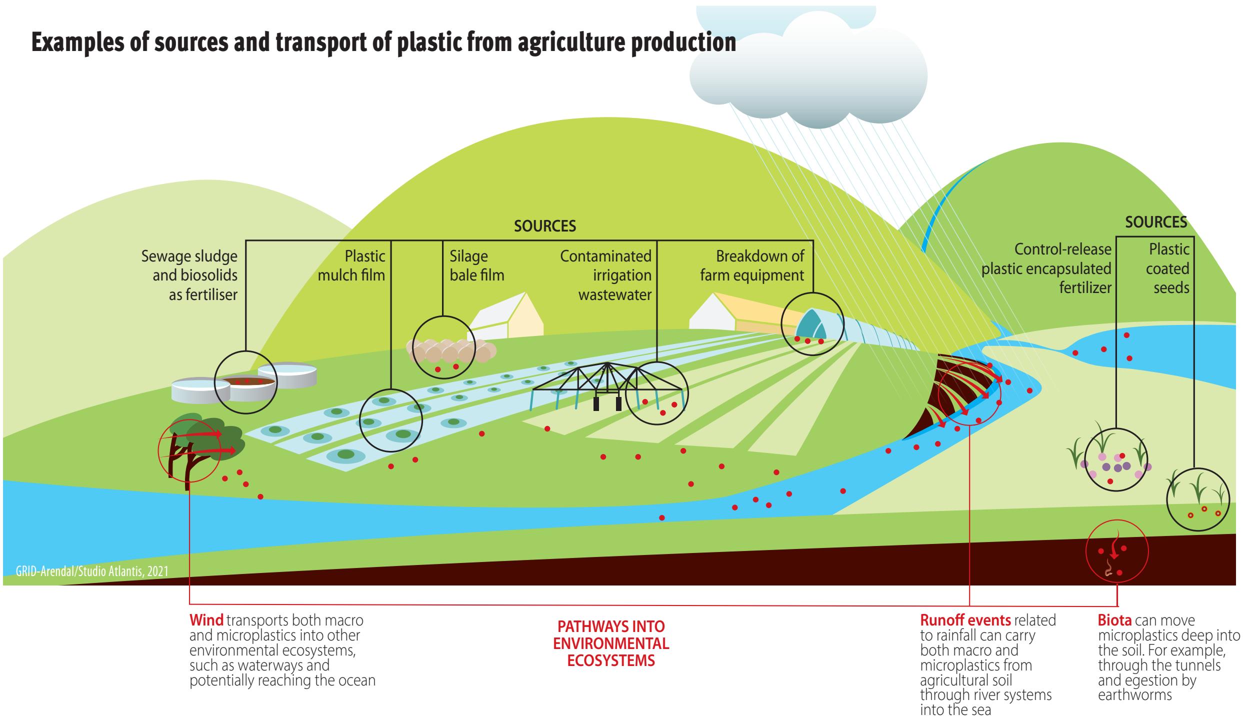
There has been considerable research on the toxicity of plastic additives such as bisphenol A (BPA), although there are still information gaps, including on less well-known additives and other chemicals associated with plastics. Some research has also shed light on the capacity for plastic particles to concentrate other environmental contaminants such as heavy metals and toxic organic molecules (Teuten *et al.* 2007, Lithner *et al.* 2009). It has been suggested that adults in the United States could be consuming more than 50,000 pieces of plastic a year from all sources including food, beverages, and inhaled particles (Cox *et al.* 2019). Due to the lack of information, microplastics from fruit and vegetables could be an underestimated dietary exposure source, albeit likely small.

4. The movement of microplastics from the soil to other ecosystems

The combination of microplastic from sewage sludge products and other known sources makes agricultural land an important sink for microplastic, and importantly, a potential major source of microplastic into other parts of the environment (Figure 7). Having calculated the rate of sewage sludge products used in fields, Nizzetto, Futter and Langaas (2016) suggested that the annual input of microplastic to agricultural land in Europe and North America (a combined maximum total of more than 650,000 tonnes) could exceed the accumulated amount of microplastic estimated to be in the surface waters of the global ocean (a maximum of 214,000 tonnes). As microplastic in sewage sludge comes primarily from urban areas, it represents a major movement of plastic pollution (Ibid.). A recent study estimated that the agriculture and horticulture sectors in Germany release more than 13,000 tonnes of plastic into the environment each year, the majority of which comes from sewage sludge (Istel and Jedelhauser 2021).

Surface run-off and erosion can transport microplastics from fields. The size and shape of the particles will influence their transport pathway and fate, but like leached nutrients, they are expected to end up in waterways. As mentioned in section 3.1, microplastics may also migrate from the surface deeper into the soil profile, facilitated by field preparation such as ploughing, as well as bioturbating organisms and drainage. There is little information on the properties of microplastics once they are in the soil, for instance their average residence time or turnover, so the exact fate of microplastics is poorly understood (Rillig and Lehmann 2020). However, it is likely that at least some microplastics will be able to infiltrate groundwater (O'Connor *et al.* 2019).

Figure 7. Examples of the sources and transport of plastic and co-contaminates from agriculture production to the environment (GRID-Arendal).



5. Can we use plastic more sustainably or replace it all together?

In recent decades, the world has been slow to recognize that the cost of environmental degradation needs to be included in the accounting system for food production. The emphasis on increasing yields fails to consider the long-term sustainability of food production systems. In addressing global food security, Scialabba and Obst (2021) question the current agricultural policies that prioritize "yield per hectare" and neglect long-term ecosystem health and other factors such as food wastage and the type of crops cultivated. A recent report (Food and Agriculture Organization of the United Nations [FAO] 2021) recommends repurposing global support for agriculture (estimated at US$540 billion per year) to phase out environmentally and socially harmful practices and in the process transform food systems to be more efficient and supportive of the Sustainable Development Goals.

5.1 Managing agricultural plastic waste

Most agricultural plastic ends its life on site, with high levels of contamination from pesticides, dirt, rocks, and plant material as well as physical wear. Plastic mulch removed from fields can have a 200 per cent weight increase due to contamination, with the most contaminated plastics being those in continuous close contact with soil (LeMoine *et al.* 2021; Figure 8; Figure 9), which makes recycling difficult. This combined with the fact that the majority of farms have poor access to recycling facilities, means that agricultural plastic wastes (APWs) have lower recycling rates than other plastics. For example, in Australia approximately 7 per cent of agricultural plastic is recycled compared with 28 per cent of consumer packaging (Australia, Department of Agriculture, Water and the Environment 2020, p. 53). Australia has not set a target for management of APW, although the national target of 80 per cent average resource recovery from all waste streams by 2030 should apply (Australia, Department of the Environment and Energy 2019, p. 41). Individual industries are also developing their own targets, for instance the dairy industry has a programme to recycle 100 per cent of plastic silage wrap by 2030 (Dairy Australia 2019, p. 111).

Figure 8. Increased weight of farm-contaminated agricultural plastic used in crop production in Europe (EIP-AGRI Focus Group 2021).

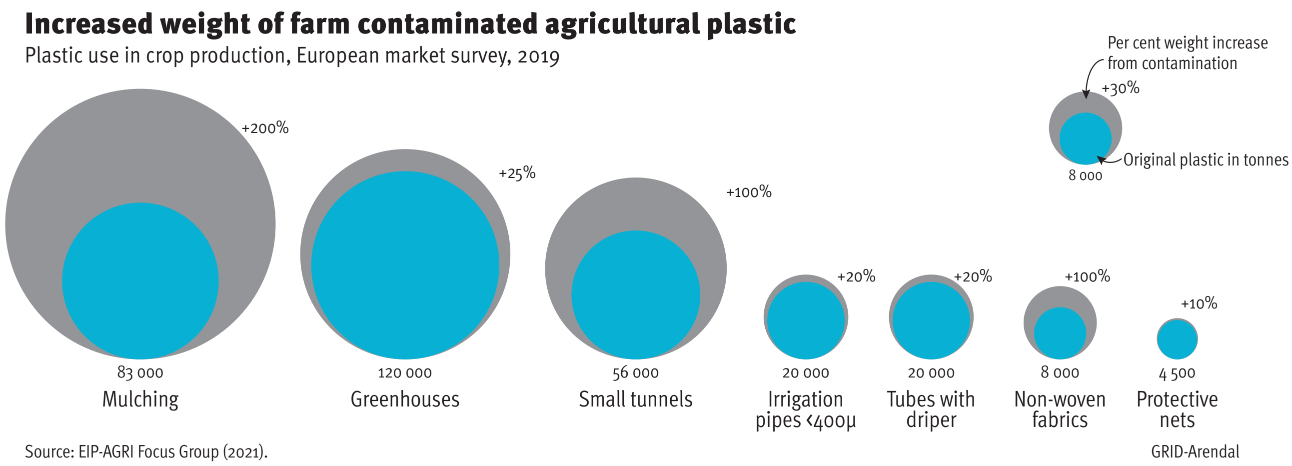
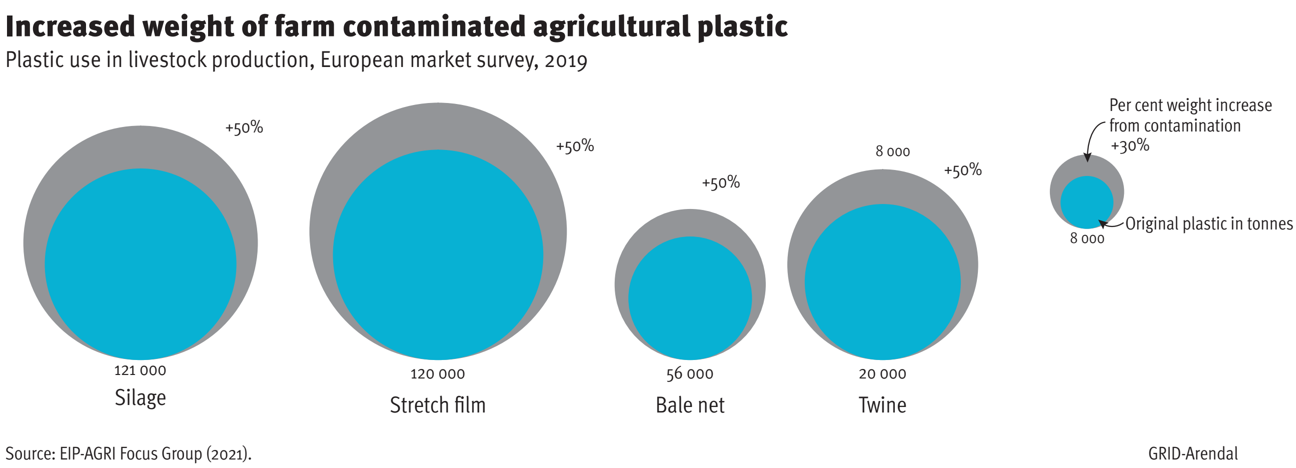


Figure 9. Increased weight of farm-contaminated agricultural plastic used in livestock production in Europe (EIP-AGRI Focus Group 2021).



The EU does not currently have targets for the management of APW. None of the five EU member states that have national collection schemes for agricultural waste currently accept mulch. There is no accessible information on the volume or current fate of collected APW in the EU, but data from 2014 indicates that 28 per cent of collected APW was recycled, 30 per cent sent to energy recovery and 42 per cent to landfills (European Court of Auditors 2020, p. 55). The Agriculture Plastics Environment (APE) initiative was established in 2009; in France a high percentage of marketers of agriculture plastic film support the initiative and collect used mulch for recycling and disposal (Adivalor 2021). The United Kingdom of Great Britain and Northern Ireland established a voluntary APE scheme for the collection of APW in 2019. The scheme, which became operational in 2021, is funded by adding a £20 per tonne fee on the purchase of plastic products by farmers. It is operated by a not-for-profit company which is expected to collect 44,000 tonnes/year of APW, of which 35 per cent will be recycled (Agricultural Plastics Environment Europe 2021).

5.2 Nature-based solutions that support nature-positive food systems

Steps are being taken to improve the manufacture and management of agricultural products containing plastic, with considerable research into replacing non-biodegradable plastics. However non-biodegradables still dominate the agricultural plastic market. If we continue to contaminate the soil with plastic, it will be difficult to remedy. Although there is considerable research into replacing non-biodegradable plastics with safer alternatives, there are also some "old fashioned" farming practices that are being revisited (see Box 2).

Box 2. Natural mulch – cover crops

Plastic mulch and more natural mulches have differing costs, benefits, and shortcomings. The effectiveness of plastic mulch, such as warming the soil and controlling weeds, as well as the disadvantages, including microplastic soil contamination and waste, have been discussed. In the short term, the advantages may outweigh the disadvantages, but in the long term farmers may see lasting negative impacts on soil health. By contrast, more natural mulch solutions may have short-term disadvantages, but in the long term preserve or improve soil productivity. 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/product (plastic or natural mulch) is analysed. Farmers may also choose to find alternatives to plastic mulch such as cover crops, due to consumer demand for more sustainably produced products. Cover crops function effectively as a weed deterrent, regulate soil temperature, and help retain soil moisture (Haapala *et al.* 2014). They also provide habitat for beneficial organisms.

Many different plants, either dead or alive, can be used as cover crops (Table 3). A cover crop such as cereal rye or hairy vetch can be planted during winter and then killed 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 all fix nitrogen and therefore increase soil fertility and reduce the cost of nitrogen fertilizer. They can also act as nutrient scavengers, taking up excess nutrients and preventing them from leaching out of the soil into waterways.

Table 3. Examples of temperate cover crops and the services they can provide (King's AgriSeeds Inc. 2017).

Examples of temperate cover crops and the services they can provide

Individual plant type	Build soil organic matter	Scavenge nitrogen	Improve soil nitrogen	Loosen compacted subsoil	Suppress weeds	Suppress Soil disease	Attract beneficial insects and pollinators
Alfalfa			√	√			
Annual rye-grass	√	√		√	√		
Brassicas		√				√	
Buckwheat					√		√
Crimson Clover			√				√
Daikon Radish		√		√	√	√	
Hairy Vetch			√		√		√
Oats & other small grains	√	√		√	√		
Red Clover			√	√			√
Sorghum-sudangrass	√	√		√	√	√	
Sweetclover	√		√	√	√		√
White Clover			√				√
Winter cereal rye	√	√		√	√	√	
Winter peas/spring peas			√				
Group of plants types							
Red clover, yellow blossom sweet clover and ladino white clover			√				√
Oats, Annual Ryegrass, and Crimson Clover	√	√	√				√
Peas, Hairy Vetch, and Oats		√	√				√

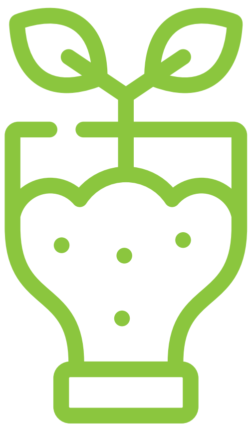
Source: King's AgriSeeds Inc. (2017)

Finding out which mulch works best with different crops, soil types, and weather will require further testing. When using natural mulch, the benefits come with challenges, which perhaps include an increase in the initial cost, more labour-intensive handling, and a decreased yield. However, such challenges do not necessarily mean a reduction in profit. For example, Sanders *et al.* (2017) looked at growing corn in conjunction with a living white clover cover crop. They found that the use of the living mulch system produced a slightly lower corn yield than more conventional systems, yet the cost savings in other areas compensated for this. For example, the living mulch led to a 75–80 per cent reduction in the use of herbicide due to the clover outcompeting harmful weeds. There was also less nitrogen fertilizer required because the corn received nutrients from the clover. In this case, overall profit from the conventionally grown corn field and living mulch field would have been similar, but the use of the cover crop provided additional environmental benefits.

There are barriers to the widespread roll-out of agricultural nature-positive food systems, key factors being the potential reduction in yields and the perception that nature-positive farming is more expensive. Yet as stated by the United Nations Food Systems Summit (2021):

> 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.

While many aspects of agricultural nature-positive food systems can be seen as 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. It might also be necessary to financially incentivize agricultural nature-positive food systems.



References

Accinelli, C., Abbas, H.K., Shier, W.T., Vicari, A., Little, N.S., Aloise, M.R. *et al.* (2019). Degradation of microplastic seed film-coating fragments in soil. *Chemosphere* 226, 645-650. https://doi.org/10.1016/j.chemosphere.2019.03.161.

Adivalor (2021). Plastic films. https://www.adivalor.fr/en/Adivalor/fau/index.html. Accessed November 2021.

Agricultural Plastics Environment Europe (2021). UK National Collection Scheme. https://apeeurope.eu/ape-uk/. Accessed November 2021.

Allen, S., Allen, D., Phoenix, V.R., Le Roux, G., Jiménez, P.D., Simonneau, A. *et al.* (2019). Atmospheric transport and deposition of microplastics in a remote mountain catchment. *Nature Geoscience* 12(5), 339-344. https://doi.org/10.1038/s41561-019-0335-5.

Australia, Department of Agriculture, Water, and the Environment (2020). *2018-2019 Australian Plastics Recycling Survey, Final Report*. https://www.awe.gov.au/sites/default/files/documents/australian-plastics-recycling-survey-report-2018-19.pdf.

Australia, Department of the Environment and Energy (2019). *National Waste Policy Action Plan 2019*. https://www.environment.gov.au/system/files/resources/5b86c9f8-074e-4d66-ab11-08bbc69da240/files/national-waste-policy-action-plan-2019.pdf.

Beriot, N., Peek, J., Zornoza, R., Geissen, V. and Lwanga, E.H. (2021). Low density-microplastics detected in sheep faeces and soil: A case study from the intensive vegetable farming in Southeast Spain. *Science of The Total Environment* 755(1), 142653. https://doi.org/10.1016/j.scitotenv.2020.142653.

Bläsing, M. and Amelung, W. (2018). Plastics in soil: Analytical methods and possible sources. *Science of The Total Environment* 612, 422-435. https://doi.org/10.1016/j.scitotenv.2017.08.086.

Bouma, J., Montanarella, L. and Evanylo, G. (2019). The challenge for the soil science community to contribute to the implementation of the UN Sustainable Development Goals. *Soil Use and Management* 35(4), 538-546. https://doi.org/10.1111/sum.12518.

Bouwman, H., Minnaar, K., Bezuidenhout, C. and Verster, C. (2018). *Microplastics in Freshwater Environments – A Scoping Study*. Pretoria: Water Research Commission. http://www.wrc.org.za/wp-content/uploads/mdocs/2610-1-18.pdf.

Brahney, J., Hallerud, M., Heim, E., Hahnenberger, M. and Sukumaran, S. (2020). Plastic rain in protected areas of the United States. *Science* 368(6496), 1257-1260. https://doi.org/10.1126/science.aaz5819.

Büks, F. and Kaupenjohann, M. (2020). Global concentrations of microplastics in soils – A review. *Soil* 6(2), 649-662. https://doi.org/10.5194/soil-6-649-2020.

Cai, L., Wang, J., Peng, J., Tan, Z., Zhan, Z., Tan, X. *et al.* (2017). Characteristic of microplastics in the atmospheric fallout from Dongguan city, China: preliminary research and first evidence. *Environmental Science and Pollution Research* 24, 24928-24935. https://doi.org/10.1007/s11356-017-0116-x.

Carr, S.A., Liu, J. and Tesoro, A.G. (2016). Transport and fate of microplastic particles in wastewater treatment plants. *Water Research* 91, 174-182. https://doi.org/10.1016/j.watres.2016.01.002.

Chandran, V. and Mathew, L. (2021). Methods for controlled release of fertilizers. In *Controlled Release Fertilizers for Sustainable Agriculture*. Lewu, F.B., Volova, T. G., Thomas, S. and Rakhimol, K.R. (eds.) Cambridge: Academic Press. Chapter 5. 79-93. https://doi.org/10.1016/B978-0-12-819555-0.00005-4.

Cheng, Z., Liu, J.B., Gao, M., Shi, G.Z., Fu, X.J., Cai, P. *et al.* (2019). Occurrence and distribution of phthalate esters in freshwater aquaculture fish ponds in Pearl River Delta, China. *Environmental Pollution* 245, 883-888. https://doi.org/10.1016/j.envpol.2018.11.085.

Christodoulou, A. and Stamatelatou, K. (2016). Overview of legislation on sewage sludge management in developed countries worldwide. *Water Science and Technology* 73(3), 453-462. https://doi.org/10.2166/wst.2015.521.

Conti, G.O., Ferrante, M., Banni, M., Favara, C., Nicolosi, I., Cristaldi, A. *et al.* (2020). Micro- and nano-plastics in edible fruit and vegetables. The first diet risks assessment for the general population. *Environmental Research* 187, 109677. https://doi.org/10.1016/j.envres.2020.109677.

Corradini, F., Meza, P., Eguiluz, R., Casado, F., Huerta-Lwanga, E. and Geissen, V. (2019). Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. *Science of The Total Environment* 671, 411-420. https://doi.org/10.1016/j.scitotenv.2019.03.368.

Cox, K.D., Covernton, G.A., Davies, H.L., Dower, J.F., Juanes, F. and Dudas, S.E. (2019). Human consumption of microplastics. *Environmental Science & Technology* 53(12), 7068-7074. https://doi.org/10.1021/acs.est.9b01517.

Dairy Australia (2019). *Australian Dairy Industry Sustainability Report 2019: Towards our 2030 Goals*. Melbourne. https://cdn-prod.dairyaustralia.com.au/-/media/project/murraydairy/national-home/resources/2020/07/08/dairy-sustainability-report-2019/dairy-sustainability-report-2019.pdf.

Dris, R., Gasperi, J., Rocher, V., Saad, M., Renault, N. and Tassin, B. (2015). Microplastic contamination in an urban area: a case study in Greater Paris. *Environmental Chemistry* 12(5), 592-599. https://doi.org/10.1071/EN14167.

Espí, E., Salmerón, A., Fontecha, A., García, Y. and Real, A. I. (2006). Plastic films for agricultural applications. *Journal of Plastic Film & Sheeting*, 22(2), 85-102.

European Chemicals Agency (2019). Microplastics. https://echa.europa.eu/hot-topics/microplastics. Accessed 23 November 2021.

European Committee for Standardization (2018). EN 17033:2018, Plastics-Biodegradable mulch films for use in agriculture and horticulture. Requirements and test methods. Brussels, Belgium: European Standard, European Committee for Standardization.

European Court of Auditors (2020). *EU action to tackle the issue of plastic waste. Review No. 4.* https://www.eca.europa.eu/Lists/ECADocuments/RW20_04/RW_Plastic_waste_EN.pdf.

European Innovation Partnership for Agricultural productivity and Sustainability Focus Group (2021). *Reducing the Plastic Footprint of Agriculture. Final Report.* Brussels. https://ec.europa.eu/eip/agriculture/sites/default/files/eip-agri_fg_plastic_footprint_final_report_2021_en.pdf.

European Union (2019). Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003. PE/76/2018/REV/1. http://data.europa.eu/eli/reg/2019/1009/oj.

Fierer, N., Schimel, J.P. and Holden, P.A. (2003). Variations in microbial community composition through two soil depth profiles. *Soil Biology and Biochemistry* 35(1), 167-176. https://doi.org/10.1016/S0038-0717(02)00251-1.

Food and Agriculture Organization of the United Nations (2021). *Global Assessment of Soil Pollution*. https://www.fao.org/3/cb4894en/online/cb4894en.html.

Ganesh Kumar A., Anjana, K., Hinduja, M., Sujitha, K. and Dharani, G. (2020). Review on plastic wastes in marine environment – Biodegradation and biotechnological solutions. *Marine Pollution Bulletin* 150, 110733. https://doi.org/10.1016/j.marpolbul.2019.110733.

Gatidou, G., Arvaniti, O.S. and Stasinakis, A.S. (2019). Review on the occurrence and fate of microplastics in Sewage Treatment Plants. *Journal of Hazardous Materials* 367, 504-512. https://doi.org/10.1016/j.jhazmat.2018.12.081.

Global Industry Analysts Inc. (2021). *Mulch Films: Global Market Trajectory and Analytics.* https://www.strategyr.com/market-report-mulch-films-forecasts-global-industry-analysts-inc.asp.

Haapala, T., Palonen, P., Korpela, A. and Ahokas, J. (2014). Feasibility of paper mulches in crop production - A review. *Agricultural and Food Science* 23(1), 60-79. https://doi.org/10.23986/afsci.8542.

Hayes, D.G. (2021). Enhanced end-of-life performance for biodegradable plastic mulch films through improving standards and addressing research gaps. *Current Opinion in Chemical Engineering* 33, 100695. https://doi.org/10.1016/j.coche.2021.100695.

Hayes, D.G., Anunciado, M.B., DeBruyn, J.M., Bandopadhyay, S., Schaeffer, S., English, M. *et al.* (2019). Biodegradable plastic mulch films for sustainable specialty crop production. In *Polymers for Agri-food Applications*. Gutiérrez, T. (ed.). Cham: Springer. Chapter 11. 183-213.

Hidayaturrahman, H. and Lee, T.G. (2019). A study on characteristics of microplastic in wastewater of South Korea: Identification, quantification, and fate of microplastics during treatment process. *Marine Pollution Bulletin* 146, 696-702. https://doi.org/10.1016/j.marpolbul.2019.06.071.

Huang, Y., Liu, Q., Jia, W., Yan, C. and Wang, J. (2020). Agricultural plastic mulching as a source of microplastics in the terrestrial environment. *Environmental Pollution* 260, 114096. https://doi.org/10.1016/j.envpol.2020.114096.

Istel, K. and Jedelhauser M. (2021). *Plastics in Soil.* Berlin: Nature and Biodiversity Conservation Union (NABU). https://www.nabu.de/imperia/md/content/nabude/konsumressourcenmuell/2021_factsheet_nabu_plastics_soils_english.pdf.

Kasirajan, S. and Ngouajio, M. (2012). Polyethylene and biodegradable mulches for agricultural applications: A review. *Agronomy for Sustainable Development* 32(2), 501-529. https://doi.org/10.1007/s13593-011-0068-3.

Katsumi, N., Kusube, T., Nagao, S. and Okochi, H. (2021). Accumulation of microcapsules derived from coated fertilizer in paddy fields. *Chemosphere* 267, 129185. https://doi.org/10.1016/j.chemosphere.2020.129185.

Kershawa, P., Turrab, A. and Galganic F. (eds.) (2019). *Guidelines for the Monitoring and Assessment of Plastic Litter in the Ocean.* Nairobi: United Nations Environment Programme. http://www.gesamp.org/publications/guidelines-for-the-monitoring-and-assessment-of-plastic-litter-in-the-ocean.

King's AgriSeeds Inc. (2017). *Understanding Cover Crops, Benefits, and Selection: A Guide to Saving Your Soil.* Dave Wilson and Genevieve Slocum. https://www.kingsagriseeds.com/wp-content/uploads/2013/07/Cover-Crop-Book-4th-Edition-3-2017.pdf.

Lares, M., Ncibi, M.C., Sillanpää, M. and Sillanpää, M. (2018). Occurrence, identification and removal of microplastic particles and fibers in conventional activated sludge process and advanced MBR technology. *Water Research* 133, 236-246. https://doi.org/10.1016/j.watres.2018.01.049.

Lawrencia, D., Wong, S.K., Low, D.Y.S., Goh, B.H., Goh, J.K., Ruktanonchai, U.R. *et al.* (2021). Controlled release fertilizers: A review on coating materials and mechanism of release. *Plants* 10(2), 238. https://doi.org/10.3390/plants10020238.

Lehner, R., Weder, C., Petri-Fink, A. and Rothen-Rutishauser, B. (2019). Emergence of nanoplastic in the environment and possible impact on human health. *Environmental Science & Technology* 53(4), 1748-1765. https://doi.org/10.1021/acs.est.8b05512.

LeMoine, B., Erälinna, L., Trovati, G., Casallo, I.M., Amate, J.J., Zlatar, K. *et al.* (2021) *Minipaper B: The Agri-Plastic End-Of-Life Management.* Brussels: European Innovation Partnership for Agricultural productivity and Sustainability. https://ec.europa.eu/eip/agriculture/sites/default/files/eip-agri_fg_plastic_footprint_minipaper_b_final.pdf.

Li, L., Luo, Y., Li, R., Zhou, Q., Peijnenburg, W.J., Yin, N. *et al.* (2020). Effective uptake of submicrometre plastics by crop plants via a crack-entry mode. *Nature sustainability* 3(11), 929-937. https://doi.org/10.1038/s41893-020-0567-9.

Li, L., Zhou, Q., Yin, N., Tu, C. and Luo, Y. (2019). Uptake and accumulation of microplastics in an edible plant. *Chinese Science Bulletin* 64(9), 928-934. https://doi.org/10.1360/N972018-00845.

Lithner, D., Damberg, J., Dave, G. and Larsson, Å. (2009). Leachates from plastic consumer products–screening for toxicity with Daphnia magna. *Chemosphere* 74(9), 1195-1200. https://doi.org/10.1016/j.chemosphere.2008.11.022.

Lwanga, E.H., Gertsen, H., Gooren, H., Peters, P., Salánki, T., van der Ploeg, M. *et al.* (2017). Incorporation of microplastics from litter into burrows of Lumbricus terrestris. *Environmental Pollution* 220(A), 523-531. https://doi.org/10.1016/j.envpol.2016.09.096.

Ma, J., Niu, X., Zhang, D., Lu, L., Ye, X., Deng, W. *et al.* (2020). High levels of microplastic pollution in aquaculture water of fish ponds in the Pearl River Estuary of Guangzhou, China. *Science of the Total Environment* 744, 140679. https://doi.org/10.1016/j.scitotenv.2020.140679.

Markets and Markets (2020). *Seed Coating Market by Additive (Polymers, Colorants, Pellets, Minerals/ Pumice, Active Ingredients), Process (Film Coating, Encrusting, Pelleting), Active Ingredient (Protectants and Phytoactive Promoters), Crop Type, Region - Global Forecast to 2025*. https://www.marketsandmarkets.com/Market-Reports/seed-coating-materials-market-149045530.html.

McCormick, A., Hoellein, T.J., Mason, S.A., Schluep, J. and Kelly, J.J. (2014). Microplastic is an abundant and distinct microbial habitat in an urban river. *Environmental Science & Technology* 48(20), 11863-11871. https://doi.org/10.1021/es503610r.

Mohajerani, A. and Karabatak, B. (2020). Microplastics and pollutants in biosolids have contaminated agricultural soils: An analytical study and a proposal to cease the use of biosolids in farmlands and utilise them in sustainable bricks. *Waste Management* 107, 252-265. https://doi.org/10.1016/j.wasman.2020.04.021.

Nizzetto, L., Futter, M. and Langaas, S. (2016). Are agricultural soils dumps for microplastics of urban origin? *Environmental Science & Technology*, 50(20). https://doi.org/10.1021/acs.est.6b04140.

O'Connor, D., Pan, S., Shen, Z., Song, Y., Jin, Y., Wu, W.M. *et al.* (2019). Microplastics undergo accelerated vertical migration in sand soil due to small size and wet-dry cycles. *Environmental Pollution* 249, 527-534. 10777–10779. https://doi.org/10.1016/j.envpol.2019.03.092.

Okoffo, E.D., Tscharke, B.J., O'Brien, J.W., O'Brien, S., Ribeiro, F., Burrows, S.D. *et al.* (2020). Release of plastics to Australian land from biosolids end-use. *Environmental Science & Technology* 54(23), 15132-15141. https://pubs.acs.org/doi/10.1021/acs.est.0c05867.

Okoffo, E.D., O'Brien, S., Ribeiro, F., Burrows, S.D., Toapanta, T., Rauert, C. *et al.* (2021). Plastic particles in soil: State of the knowledge on sources, occurrence and distribution, analytical methods, and ecological impacts. *Environmental Science: Processes & Impacts* 23(2), 240-274. https://doi.org/10.1039/d0em00312c.

Orzolek, M. (ed.) (2017). *A Guide to the Manufacture, Performance, and Potential of Plastics in Agriculture*. Oxford: Elsevier.

Pedrini, S., Merritt, D.J., Stevens, J. and Dixon, K. (2017). Seed coating: Science or marketing spin? *Trends in Plant Science* 22(2), 106-116. https://doi.org/10.1016/j.tplants.2016.11.002.

People's Republic of China, Ministry of Agriculture and Rural Affairs (2020). http://zdscxx.moa.gov.cn:8080/nyb/pc/index.jsp.

Priyanka, M. and Dey, S. (2018). Ruminal impaction due to plastic materials – An increasing threat to ruminants and its impact on human health in developing countries. *Veterinary World* 11(9), 1307-1315. https://dx.doi.org/10.14202%2Fvetworld.2018.1307-1315.

Qi, Y., Beriot, N., Gort, G., Lwanga, E.H., Gooren, H., Yang, X. *et al.* (2020). Impact of plastic mulch film debris on soil physicochemical and hydrological properties. *Environmental Pollution* 266(3), 115097. https://doi.org/10.1016/j.envpol.2020.115097.

Rayns, F., Carranca, C., Miličić, V., Fonteyne, K., Peñalva, C, Hernandez, A. *et al.* (2021). *Minipaper C: New plastics in agriculture*. Brussels: European Innovation Partnership for Agricultural productivity and Sustainability. https://ec.europa.eu/eip/agriculture/sites/default/files/eip-agri_fg_plastic_footprint_minipaper_c_final.pdf.

Ren, Z., Gui, X., Xu, X., Zhao, L., Qiu, H. and Cao, X. (2021). Microplastics in the soil-groundwater environment: Aging, migration, and co-transport of contaminants – A critical review. *Journal of Hazardous Materials* 419, 126455. https://doi.org/10.1016/j.jhazmat.2021.126455.

Rillig, M.C. (2012). Microplastic in terrestrial ecosystems and the soil? *Environmental Science & Technology* 46(12), 6453–6454. https://doi.org/10.1021/es302011r.

Rillig, M.C. and Lehmann, A. (2020). Microplastic in terrestrial ecosystems. *Science* 368(6498) 1430-1431. https://doi.org/10.1126/science.abb5979.

Rillig, M.C., Lehmann, A., de Souza Machado, A.A. and Yang, G. (2019). Microplastic effects on plants. *New Phytologist* 223(3), 1066-1070. https://doi.org/10.1111/nph.15794.

Rillig, M.C., Leifheit, E. and Lehmann, J. (2021). Microplastic effects on carbon cycling processes in soils. *PLoS Biology* 19(3), p.e3001130. https://doi.org/10.1371/journal.pbio.3001130.

Rillig, M.C., Ziersch, L. and Hempel, S. (2017). Microplastic transport in soil by earthworms. *Scientific Reports* 7(1), 1362. https://doi.org/10.1038/s41598-017-01594-7.

Sanders, Z.P., Andrews, J.S., Saha, U.K., Vencill, W., Lee, R.D. and Hill, N.S. (2017). Optimizing agronomic practices for clover persistence and corn yield in a white clover–corn living mulch system. *Agronomy Journal* 109(5), 2025-2032. https://doi.org/10.2134/agronj2017.02.0106.

Scarascia-Mugnozza, G., Sica, C. and Russo, G. (2011). Plastic materials in European agriculture: Actual use and perspectives. *Journal of Agricultural Engineering* 42(3), 15-28. http://dx.doi.org/10.4081/jae.2011.3.15.

Scialabba, N.E.H. and Obst, C. (2021). From practice to policy: New metrics for the 21st century. In *True Cost Accounting for Food*. Gemmill-Herren, B., Baker, L.E., Daniels, P.A. (eds.). London: Routledge. Chapter 1. 13-25.

Sommer, F., Dietze, V., Baum, A., Sauer, J., Gilge, S., Maschowski, C. *et al.* (2018). Tire abrasion as a major source of microplastics in the environment. *Aerosol and Air Quality Research* 18(8), 2014-2028. https://doi.org/10.4209/aaqr.2018.03.0099.

de Souza Machado, A.A., Lau, C.W., Kloas, W., Bergmann, J., Bachelier, J.B., Faltin, E. *et al.* (2019). Microplastics can change soil properties and affect plant performance. *Environmental Science & Technology* 53(10), 6044-6052. https://doi.org/10.1021/acs.est.9b01339.

Susanti, R., Yuniastuti, A. and Fibriana, F. (2021). The evidence of microplastic contamination in central Javanese local ducks from intensive animal husbandry. *Water, Air, & Soil Pollution* 232(5), 1-10. https://doi.org/10.1007/s11270-021-05142-y.

Teuten, E.L., Rowland, S.J., Galloway, T.S. and Thompson, R.C. (2007). Potential for plastics to transport hydrophobic contaminants. *Environmental Science & Technology* 41(22), 7759-7764. https://doi.org/10.1021/es071737s.

United Nations Environment Programme (2015). *Biodegradable Plastics and Marine Litter. Misconceptions, concerns and impacts on marine environments*. Nairobi. https://www.unep.org/resources/report/biodegradable-plastics-and-marine-litter-misconceptions-concerns-and-impacts.

United Nations Environment Programme (2019). *Global Environment Outlook–GEO-6: healthy planet, healthy people*. Cambridge. https://doi.org/10.1017/9781108627146

United Nations Environment Programme (2021). *From Pollution to Solution: A Global Assessment of Marine Litter and Plastic Pollution*. Nairobi. https://www.unep.org/resources/pollution-solution-global-assessment-marine-litter-and-plastic-pollution.

United States of America, Department of Agriculture (2015). *Report on Biodegradable Biobased Mulch Films*. https://www.ams.usda.gov/sites/default/files/media/Biobased%20mulches%20report.pdf.

Vox, G., Loisi, R.V., Blanco, I., Mugnozza, G.S. and Schettini, E. (2016). Mapping of agriculture plastic waste. *Agriculture and Agricultural Science Procedia* 8, 583-591. https://doi.org/10.1016/j.aaspro.2016.02.080.

Wang, F., Wang, B., Duan, L., Zhang, Y., Zhou, Y., Sui, Q. *et al.* (2020). Occurrence and distribution of microplastics in domestic, industrial, agricultural and aquacultural wastewater sources: A case study in Changzhou, China. *Water Research* 182, 115956. https://doi.org/10.1016/j.watres.2020.115956.

Weideman, E.A., Perold, V. and Ryan, P.G. (2020). Limited long-distance transport of plastic pollution by the Orange-Vaal River system, South Africa. *Science of the Total Environment* 727, 138653. https://doi.org/10.1016/j.scitotenv.2020.138653.

Weithmann, N., Möller, J.N., Löder, M.G., Piehl, S., Laforsch, C. and Freitag, R. (2018). Organic fertilizer as a vehicle for the entry of microplastic into the environment. *Science Advances* 4(4), eaap8060. https://doi.org/10.1126/sciadv.aap8060.

Wu, R.T., Cai, Y.F., Chen, Y.X., Yang, Y.W., Xing, S.C. and Liao, X.D. (2021). Occurrence of microplastic in livestock and poultry manure in South China. *Environmental Pollution* 277, 116790. https://doi.org/10.1016/j.envpol.2021.116790.

van der Zee, M. (2021). *Biodegradability of Biodegradable Mulch Film: A Review of the Scientific Literature on the Biodegradability of Materials Used for Biodegradable Mulch Film (No. 2138)*. Wageningen: Wageningen Food & Biobased Research. https://doi.org/10.18174/544211.

Yan, C.R., He, W.Q. and Mei, X.R. (2010). *Agricultural Application of Plastic Film and its Residue Pollution Prevention*. Beijing: Science Press.

Zhang, Y., Kang, S., Allen, S., Allen, D., Gao, T. and Sillanpää, M. (2020). Atmospheric microplastics: A review on current status and perspectives. *Earth-Science Reviews* 203, 103118. https://doi.org/10.1016/j.earscirev.2020.103118.

Zhou, Q., Tian, C. and Luo, Y. (2017). Various forms and deposition fluxes of microplastics identified in the coastal urban atmosphere. *Chinese Science Bulletin* 62(33), 3902-3909. https://doi.org/10.1360/N972017-00956.

Zhu, F., Zhu, C., Wang, C. and Gu, C. (2019). Occurrence and ecological impacts of microplastics in soil systems: a review. *Bulletin of Environmental Contamination and Toxicology* 102(6), 741-749. https://doi.org/10.1007/s00128-019-02623-z.

Zubris, K.A.V. and Richards, B.K. (2005). Synthetic fibers as an indicator of land application of sludge. *Environmental Pollution* 138(2), 201-211. https://doi.org/10.1016/j.envpol.2005.04.013.

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