EIP-AGRI Focus Group

Protecting agricultural soils from contamination

MINIPAPER 1: Agricultural sources of soil contamination

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1. Introduction

Many potential contaminants which can affect agricultural soils do not originate from agricultural activities, but from diffusive sources (e.g. traffic emissions from domestic fuels and power plants, gaseous emissions from metal smelters and metallurgical activities, waste disposal and incineration, acid rain). However, there are different agricultural practices which are potential sources of soil contamination. This mini-paper focuses on those contaminants that are related to agricultural practices.

In some cases, these practices started decades ago, and the additive effects of contaminants to soils are notorious, like the build-up of heavy metals in soils supplied with contaminated sewage sludge. For those contaminants, legal documents with limit values have been adopted, both at the European Union (EU) level and in the different EU and non-EU countries. For other contaminants, like the organic contaminants, which can also reach agricultural soils from biowaste-based amendments, limit values have been added to the legislation adopted in some of the EU-countries.

However, the same practices may have emitted contaminants to soils which are not monitored at a regular basis, the so-called emerging contaminants (e.g. pharmaceuticals, plastic debris, personal care products). For those, it is very important to know their concentrations in potentially contaminated agricultural soils, to evaluate the risks, and to possibly establish limit values to be adopted.

Taking this into consideration, it is important to: (i) clarify which agricultural practices can, potentially, contaminate soils, and (ii) define the main families / groups of contaminants which can enter the soils and, from there, reach other environmental compartments. Only with this knowledge, it is possible to establish some prevention measures, which can be delivered to the producers, and, in some cases, understand why the contamination has achieved critical levels and remediation measures have to be taken.

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2. Sources of contamination

2.1. Major contaminants

There are different families of contaminants that can affect agricultural soils (Rodríguez Eugenio et al., 2018), namely: nutrients, pesticides (plant protection products), potentially toxic trace elements (PTEs), persistent organic pollutants (POPs, industrial xenobiotics and by-products), plastics debris, pharmaceuticals (e.g. antibiotics, hormones, anti-inflammatory substances), including veterinary products, and personnel care products (PCPs).

From those, it is very important to distinguish between inorganic (Box 1) and organic contaminants (Box 2).

BOX 1: Facts about inorganic contaminants

Inorganic contaminants include metallic elements, comprising an important group usually called heavy metals, like cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), and zinc (Zn), and metalloids, like arsenic (As), antimony (Sb) or selenium (Se), with some characteristics similar to metals and others to non-metals. The whole group can be termed potentially toxic trace elements (PTEs), because their toxicity is not absolute, but highly dependent on different factors (e.g. total concentration, bioavailability, environmental conditions, target organism).

Some PTEs are essential micronutrients, like Cu, Ni, and Zn, while others, like Cd, Pb and Hg, have no recognised physiological role.

Some elements, like N and P, are macronutrients that exist in the soil as molecular ions, like nitrate (NO_3-), ammonium (NH_4^+), and phosphate (PO_4^{3-}), or their salts. If their input into soils exceeds the demands of the vegetation, they may become contaminants because of the risk of their transfer to surface and ground waters.

They are all naturally occurring chemical species, which can be found in the environment because of the physical, chemical and biochemical processes occurring in soil.

They are considered contaminants when they are found in soils in concentrations above natural background values, and pollutants when their concentrations reach values that endanger human health, or another living organism.

Inorganic contaminants cannot be degraded in soils: they can be taken up by plants, leached to groundwater, move in the runoff to surface water (partly associated to soil particles as soil erosion).

Their excess input to soil can become a risk, since inorganic contaminants can accumulate in soil, mainly if they are in a cationic form, or, for the anionic contaminants, like NO3-, which are only weakly sorbed by soil organic matter, they may reach ground or surface waters.

The build-up of inorganic contaminants in soils poses a threat to human health because of the consumption of vegetables and other crops produced in these soils.

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BOX 2: Facts about organic contaminants

Organic contaminants include the majority of the pesticides formulations (insecticides, as organophosphates, carbamates, and neonicotinoids, herbicides, like acetochlor, glyphosate and triazines), persistent organic pollutants (which can include organochlorine insecticides, like DDT[1], and industrial xenobiotics and by-products, like polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polychlorinated di-benzo-p-dioxins and -furans (PCDD/Fs), pharmaceuticals and PCPs.

Most of them have an anthropogenic origin (the only exception are PAHs, which can occur in significant amounts in natural deposits of fossil fuels or emitted during forest fires).

Some of the organic contaminants characteristics, like half-life time (t1/2), partition coefficient octanol/water (Kow), (eco)toxicity, solubility in water and volatility, are important properties to evaluate their persistence in the environment, risk of bioaccumulation and biomagnification, and risk of transference to the water or air compartment (Weil and Brady, 2017).

Organic contaminants in soil are submitted to several dynamic processes of transference (volatilization, adsorption, transport, leaching and runoff), or degradation, which can be biotic (microbial metabolism, plant uptake and breakdown) or abiotic (chemical and photochemical degradation), that can dissipate them from soils.

The fact that they can be degraded, namely by soil microorganisms, makes a huge difference from the inorganic contaminants, and that fact will have to be considered in the adoption of remediation measures.

2.2. Agricultural practices as potential sources of soil contamination

There are different agricultural practices that can potentially disseminate contaminants to soils (Figure 1), namely:

- Excessive fertilization, with mineral fertilizers, manures, and slurries, and the application of organic amendments (e.g., sewage sludge, urban waste compost, green waste or agricultural wastes compost, digestate, biochar);
- Irrigation with wastewater or contaminated water;
- Improper application of plant protection products (insecticides, herbicides, fungicides, etc.);
- Plastic use (to cover crops, much films, irrigation tubes, greenhouse structures, silage bales).

[1] DDT: Dichlorodiphenyltrichloroethane

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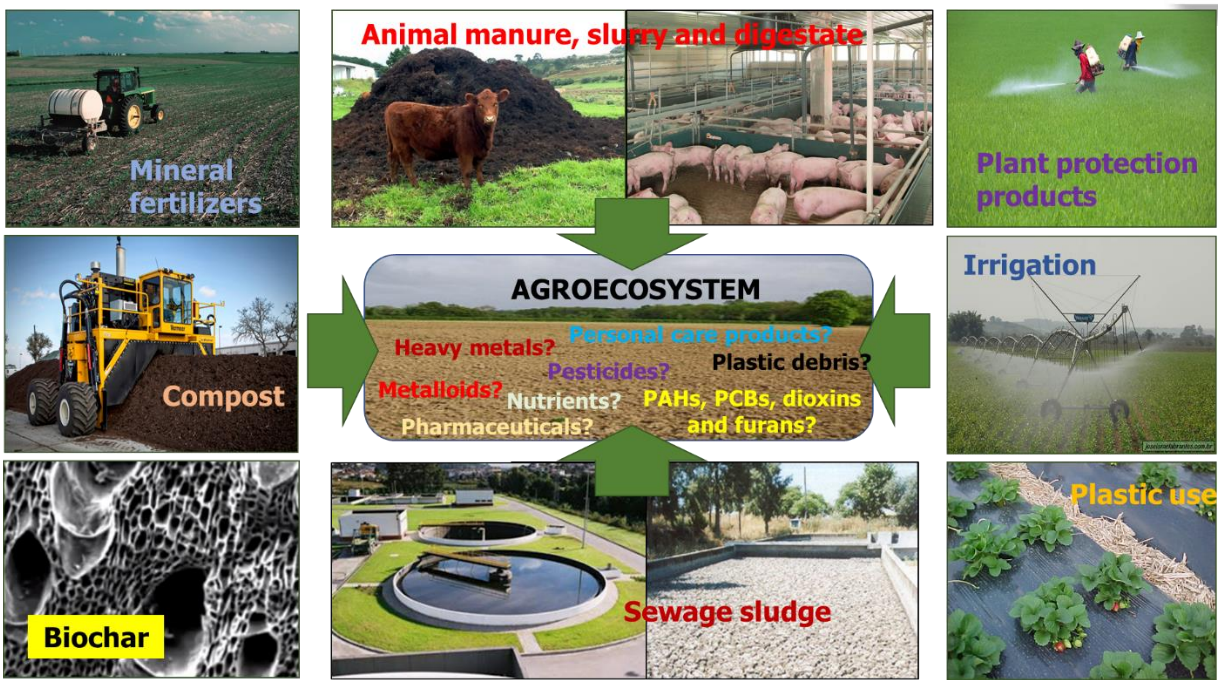

Figure 1. Contaminants that can potentially enter agroecosystems from different agricultural practices (Some Photos are courtesy of StockFreeImages.com https://www.stockfreeimages.com/)

2.2.1. Fertilization

Mineral fertilizers and fresh manure

Although traditional fertilizer practices have been performed since long, in the second half of the 20th century, the green revolution started with new productive varieties which needed fertilizers, pesticides and irrigation to achieve their full potential. Despite the impressive productivity gains, several damages have been done to the environment.

Fertilizers can be classified in terms of the nutrients they contain, but also according to their origin: organic, organo-mineral, and inorganic fertilizers (Regulation EU 2019/1009). Mineral fertilizers are characterized by containing high concentration of nutrients required for plant growth. There are several types, according to their nutrient content, although the fertilizer industry is focused in the production of compounds with the primary macronutrients: nitrogen (N), phosphorus (P) and potassium (K). While reports show that fertiliser sales have remained stable or fallen slightly in EU-15 countries, consumption in the whole Europe has continued to grow steadily during recent years. In some EU countries, there is a trend to reduce the use of mineral fertilizers, and to increase the use of by-products from waste/manure treatments, as part of the bioeconomy strategy.

Traditionally, animal husbandry was part of the subsistence farmer's way of life, not only producing their food but also the transport, the clothing and the fertilizer. Therefore, the traditional agriculture integrated livestock with arable activity in family farms. The value of manure is still recognised by farmers, because of its content of organic matter and nutrients. However, negative impacts to the environment may arise if manure and slurry are not used appropriately and application guidelines are not considered.

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During the 20th century, there has been an intensification of livestock and arable farming in many countries, which led to a disconnection between livestock and crop lands. Brittanny (France), Northern Germany, the Netherlands, Catalonia (Spain) or Lombardy (Italy) are some regions with high livestock density problems.

Compared to mineral fertilizers, manure may have low and unbalanced nutrient levels that do not completely cover plant requirements. Manure frequently contains more P than N relative to what crops need. If manure is applied at rates to meet the crop N needs, P in the soil can build up to levels that become a risk to water bodies.

The agricultural over-application of mineral fertilizers or manure tends to accumulate nutrients, mainly N and P, in agricultural soils, which may be lost to surface or groundwaters by runoff, leaching and erosion. The runoff of an excess of nutrients to surface waters causes the growing of massive algae blooms. Their decomposition leads to an oxygen depletion in water, affecting the aquatic system's organisms, sometimes with toxic effects. Such phenomenon is called eutrophication and it is recognised as a water pollution problem.

Good farming practices should be adopted to reduce the risk of pollution of ground and surface waters from mineral fertilizers and manure applications. Factors, such as soils characteristics, should be taken into consideration, because they are relevant to nutrients availability/solubility. Moreover, the chemical form of the nutrient also affects its mobility, for instance: organic N is quite immobile in soil, slowly released according to the mineralization rate, whereas nitrate has greater mobility, being easier to be lost by leaching than ammonium, which can be adsorbed onto the soil cation exchange complex. The leaching of high amounts of nitrates to groundwater supplies leads to its contamination, affecting drinking water quality. The Nitrates Directive (Council Directive 91/676/EEC) was released with the aim of protecting water quality across Europe by preventing nitrates from agricultural sources to reach ground and surface waters, by promoting the use of good farming practices. Also, P tends to precipitate with iron and aluminium in acidic soils, and with calcium in alkaline soils, presenting a lower risk to water pollution.

However, P fertilizers are obtained from phosphate rock, which usually contains small amounts of PTEs, like As, Cd, U, Cu, Ni and Zn (Weil and Brady, 2017). Their concentration in the P-fertilizers highly depends on the source of phosphate rock used to their production, being high in some countries. The main problem is usually related to Cd (P fertilizers can account to an input of Cd as high as 150 g/ha/year to agricultural soils; Kabata-Pendias, 2011). As a consequence, P fertilization increases the risk of Cd accumulation in soils and transfer to the food chain, despite the fact that its availability in soils depends on several factors (e.g. soil pH, organic matter content, salinity, macro and micronutrient fertilizers, crops species and cultivar, and tillage) (Roberts, 2014). Considering the risk of Cd accumulation in agricultural soils, and their transference to crops, some countries and the EU have limits restricting the Cd content of P fertilizers (Roberts, 2014; Ulrich, 2019; Regulation EU 2019/1009).

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BOX 3: Potential contamination from excessive fertilizers application

- Transport of nutrients, mainly nitrates, to the water bodies, by leaching or runoff, causing eutrophication of surface aquatic ecosystems and contamination of groundwater;
- Soil contamination with heavy metals, mainly Cd, and metalloids, mainly As, from the application of phosphate fertilizers;
- Reduction in crops yield and products quality as a consequence of luxury uptake of nutrients;
- Antagonism of zinc, and calcium in a lower degree, and boron in lower pH soils

Compost

Composting is a spontaneous biooxidative process of microbial decomposition involving the mineralisation and partial humification of the organic matter, leading to a stabilised final product (compost), free of phytotoxicity and pathogens, which is beneficial for plant growth (Bernal et al., 2009). During the process, the organic material is degraded by bacteria, fungi and other microorganisms under a predominantly aerobic environment, releasing CO_2, water and a stable and dry organic material. The compost can be used in agriculture as organic fertiliser or organic soil amendment. The technology is widely established to treat the organic fraction of the municipal solid wastes or biowaste and green wastes, but also applied for sewage sludge, animal manures or wastes from the agro-food industry (e.g. olive mill and winery industries) (Bernal et al., 2017). The characteristics of the compost depend on the input materials, the composting conditions and the technology. As the organic material is partially degraded during the process, the PTEs and persistent organic compounds can remain concentrated in the compost.

Compost produced from the municipal solid wastes obtained by mechanical and biological treatment is considered of low quality, due to the presence of inorganic particles (glass, metals, etc.), plastic debris, high concentration of some heavy metals and, sometimes, organic pollutants (PAHs, PCDD/Fs and PCBs). Therefore, successive applications of those materials in soils can lead to pollution. However, such materials are nowadays not considered as compost, and they have been specifically excluded from the legislation of EU marked fertiliser (Regulation EU 2019/1009). Compost from source-separated organic fraction of municipal solid waste and green wastes (biowaste) have low concentration of contaminants (heavy metals and organic pollutants), in comparison with the previously obtained from non-source separated wastes. Source-separated organic fraction of municipal solid waste also contains microplastics after industrial composting process (Weithmann et al. 2018). Also, compost prepared from sewage sludge present a risk of contamination with inorganic and organic compounds. In a similar way, compost from manure can contain high levels of heavy metals. It is especially the case for pig manure because Cu and Zn are added in great amounts to the pig feed for pharmacological effects.

Limits for heavy metal concentrations in compost, for agricultural use, have been established in different countries in Europe and worldwide (Bernal et al., 2017). The European Regulation (EU) 2019/1009 for EU fertilising products indicates the limit values of contaminants in an organic fertiliser or an organic soil improver as: Cd 1.5-2; Cu 300; Cr(VI) 2; Hg 1; Ni 50; Pb 120; inorganic-As 40; and Zn 800 (all in mg/kg dry matter). Although the limits have been established for total heavy metal concentrations, their solubility, availability and behaviour in the soil are key factors to understand the risk linked to their use in soils (Alvarenga et al., 2015)

Compost from different origin are possible media for the entrance of emerging contaminants, such as pharmaceutical compounds, personal care products, and veterinary products (hormones, antibiotics, etc.) into agro-ecosystems (Hu et al. 2010). The degradation processes of these contaminants during composting and in soils are complex and not fully understood (Ho et al., 2013). The persistence during composting, and later in soils, their degradation pathways, and their effects on crop production and quality represent a challenge for researchers (Bernal, 2017). Due to the difficulty of their accurate analysis (and cost) the emerging contaminants have not been included in the criteria for compost quality by the different countries. Only limit for PAH_{16} <6 mg/kg[2] dry matter for compost is included in the EU legislation for fertilisers (Regulation EU 2019/1009).

Box 4: Potential contamination from improper compost application to soil

- High concentration of heavy metals and, possibly, organic pollutants (PAHs, PCDD/Fs and PCBs) in compost produced from municipal solid wastes obtained by mechanical and biological treatment;
- Composting of manures or sewage sludge can produce a compost with high concentrations of some heavy metals, namely Cu and Zn;
- The entrance of emerging contaminants through the application of compost from unknown origins, when the contaminant degradation during the composting process and in soil is still under investigation.
- Biotic contaminants or weed seeds if temperature during composting was too low.

Sewage sludge

Sewage sludge (SS) is produced in massive quantities as a by-product in wastewater treatment plants and is rich in organic matter and nutrients. The agronomic benefits of SS application to land are well recognized and include improvement of soil fertility and productivity. However, the presence of toxic contaminants such PAHs, PCBs, PCDD/Fs, PTEs (including V, Cr, Mn, Fe, Co, Ni, Zn, Cu, As, Cd, Hg and Pb), and potentially pathogenic organisms, restricts the application of SS to agricultural land (USEPA, 1995; EC, 2001; USEPA, 2018; Hudcova et al., 2019). Sewage sludge can also contain other harmful toxic compounds, such as detergents, pesticides, pharmaceutical products and personnel care products (PCP) (USEPA, 2018), as well as microplastics (Corradini et al., 2019). In fact, tyre abrasion on roads, clothe washing and use of personal care products containing plastics release microplastic that are collected in waste waters and end up in sewage sludges. Between 63 000-430 000 tonnes of microplastic are introduced into agricultural soils trough sludge application each year in the European Union (Nizzetto et al., 2016). The Directive 91/271/EEC seeks to encourage the use of SS in agriculture and to regulate its use in such a way as to prevent effects on soil, vegetation, animals and humans (Inglezakis et al., 2014). The

[2] Sum of naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, indeno[1,2,3-cd]pyrene, dibenzo[a,h]anthracene and benzo[ghi]perylene.

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maximum permissible limits values for PTEs in SS for land applications are defined in Directive 86/278/EEC and in national regulations, some with more stringent limits, compared with the European Directive, like in Denmark, Finland, Sweden and Netherlands, followed by Austria, Belgium, France and Germany. In some countries or regions, the application of SS to agricultural soils is generally forbidden, and the trend leads to mono-incineration of SS. The characteristics of SS vary among wastewater treatment plants, and depend on the quality of water, on the size and type of the population served, and on type of treatment processes (Inglezakis et al., 2014).

Box 5: Potential contamination from improper sewage sludge application to soils

- Possible soil pollution due to PTEs, PAHs, PCB, PCDD/Fs, plastic debris, pharmaceuticals, steroids and hormones that may be present in SS;
- Potential contamination with pathogenic microorganisms;
- Potential transfer of contaminants to plants and crops, with hazardous to the human health, animals and plants;
- Potential adverse changes of soil physical, chemical, biochemical and biological properties, affecting soil organisms.

Biochar

Biochar is a carbon-based solid obtained from pyrolysis of biomass residues in the absence of oxygen, recognized for its unique properties such as chemical recalcitrance, high porosity, high sorption capacity, and large surface area (Wu et al., 2017). Its application to agricultural soils is an increasing emerging technology, due to the changes in soil physics, chemical, biochemical and biological properties that may improve soil quality and fertility, sequester carbon (C long-term storage), reduce greenhouse gas emissions and improve soil water holding capacity (Marks et al., 2016). Biochar can be used, for instance, in the remediation of soils (Wu et al., 2017), or in the reduction of nutrients losses and volatilization of ammonia and nitrous oxide (Laird et al., 2010; Wu et al., 2017).

However, large-scale application of low-quality biochar on soils may lead to their contamination with PTEs and organic compounds which are formed during pyrolysis (PAHs, PCDD/F) (Shinogi et al., 2003; Hale et al., 2012; Quilliam et al., 2013).

Despite the potential of biochar use as soil amendment to provide effective responses to policy priorities in the EU, such as soil protection, sustainable waste management, and climate change mitigation (Montanarella and Lugato, 2013), there are still major concerns about long-term effects on ecosystems and human health (Thies et al., 2015; Marks et al., 2016; Wang et al., 2018; McCormack et al., 2019).

One of the main constraints of biochar utilization as an amendment has been the variability of composition and quality parameters, strongly dependent on the feedstock and production process (Rutherford et al., 2012). Therefore, detailed guidelines for the input selection, process parameters, analytical parameters of the biochar and contaminant thresholds have been established and are the basis for the European Biochar Certificate (EBC)[3], or for the Biochar Certification Program, officially launched by the International Biochar Initiative (IBI)[4].

Box 6: Potential contamination from improper biochar application to soils

- Accumulation of PTEs and organic compounds (PAHs, PCDD/F) that may be present in biochar;
- Impacts on terrestrial and aquatic ecosystems, affecting the activity and structure of edaphic and freshwater communities, their survival and reproduction, trophic relationships and functional diversity, ultimately affecting soil functions.

2.2.2. Irrigation with wastewater

With the gradual decline in availability of fresh water to be used for irrigation in peri-urban areas of developing countries, or in arid and semiarid regions, there is a growing tendency to use sewage, treated wastewater, recycled runoff and other industrial effluents in field irrigation. Unlike clean water, wastewater flows do not vary with seasons, climatic conditions, or precipitation levels, thus allowing farmers to grow crops throughout the year. Moreover, wastewater contains nutrients that can boost crop growth and reduce chemical fertilizer use. However, there are potential risks of soil, surface and groundwater contamination with heavy metals and other toxic compounds and salts (Ma et al., 2015). In fact, there is an increasing concern regarding the exceedance of statutory and advisory food standards for heavy metals in these cases (WHO, 2006).

Wastewater may also carry pathogenic microorganisms, with risks to public health, and emerging contaminants, such as pharmaceuticals, steroids, and hormones (Mohapatra et al. 2016), and microplastics (Mintenig et al. 2017), which can accumulate in soils, with the risk of crop contamination. Therefore, it is very important to comply with national and international regulations concerning the use of wastewater to irrigation.

Box 7: Potential soil contamination by the irrigation with improper wastewater

- Potentially toxic trace elements accumulation in soil and transference into the human food chain;
- Potential source of pathogenic microorganisms, with risks to public health;
- Potential source or emerging contaminants (e.g., pharmaceutical compounds, personal care products, and veterinary products);
- Potential contamination with microplastics.

[3] http://www.european-biochar.org/en/
[4] https://biochar-international.org/characterizationstandard/

2.2.3. Excessive application of pesticides

Pesticides are chemicals used to kill pests or unwanted organisms and can be classified according to: (i) the organism targeted (e.g. insecticides, herbicides, fungicides, etc.); (ii) their mode or period of action; or (iii) their chemical structure (Arias-Estévez et al., 2008). Even though the pesticides can either be organic or inorganic, most of the pesticides used nowadays are synthetic organic chemicals. Some examples of inorganic pesticides are Cu-based fungicides, and lime sulfur used to control fungi and mites (Arias-Estévez et al., 2008). When they started to be used, since 1960, their use greatly increased productivity and vector disease control, like of malaria and typhus (Aktar et al., 2009). But most of the pesticides were highly toxic insecticides, like DDT, a chlorinated hydrocarbon, very persistent in the environment, and their production and use was discontinued (Weil and Brady, 2017). Despite the efforts to discover and produce pesticide formulations more target-specific, and with lower persistence in the environment, their increased use in the last decades, and the unequivocal presence of pesticides residues in soil, sediments and water samples has raised public and scientific awareness about their use and fate in the environment (Vryzas, 2018).

Despite the chemical, photochemical and microbiological degradation of pesticide molecules in soil, and their adsorption onto soil particles, a large fraction is mobilized by runoff and leaching water (Vryzas, 2018), which is the greatest concern regarding human exposure to pesticides (Arias-Estévez et al., 2008). The extent of each of these processes define the concentration of each pesticide found in the soil-sediment-water compartment, and are highly dependent on some of their characteristics, namely: solubility in water (S_w), partition coefficient octanol-water (K_{ow}), and half-life for transformation, in aerobic soil and in water (Weil and Brady, 2017), as well as on the water regime and the water permeability (Arias-Estévez et al., 2008).

Frequently, some pesticides which are no longer approved, and their residues, are found in groundwaters, like endosulfan, an organochorine insecticide (Odukkathil and Vasudevan, 2016), and the herbicide atrazine (Arias-Estévez et al., 2008).

Silva et al. (2019) thoroughly evaluated the presence of pesticides and their residues in European agricultural soils (76 residues of pesticides and 317 topsoil samples), and concluded that the presence of mixtures of pesticides are the rule, rather than the exception, indicating that environmental risk assessment procedures should be adopted to minimize risks to soil life and beyond. In this study, 83% of the soil samples contained one or more residues, and 58% contained mixtures (Silva et al., 2019).

Box 8: Potential contamination from improper pesticide application to soils

- Once in the soil, pesticides can contribute to the pollution of groundwater, dissolved in the infiltration water, or on surface waters, either in the dissolved state in runoff water, or adsorbed onto soil particles which reach the surface water by erosion;
- Pesticides can persist for long periods in the environment and enter the food chain where they can undergo biomagnification;
- The use of pesticides has collateral undesired effects on other organisms, like humans, domestic animals, natural enemies, birds, honeybees, wild bees, fish, soil organisms, etc.

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2.2.4. Plastic use

Plastic debris can enter into the agricultural soil via soil amendment with municipal solid waste compost (Weithmann et al. 2018), sewage sludge (Corradini et al., 2019) and irrigation (Mohapatra et al. 2016). A more direct source of plastic contamination in soil is the degradation of plastics used in agriculture, namely greenhouses, tunnels, mulch, irrigation systems, silage and packaging (Rillig et al., 2017; Ng et al., 2018). It is possible to distinguish between long term use plastic, that are designed to resist some years of use (e.g. greenhouses, tunnels and irrigation systems), and single use plastic, that are designed to disposed after usage (mulch, silage and packaging). Therefore, among the different use of plastic in agriculture, plastic mulching is the more likely to lead to plastic contamination in soil (Hayes et al., 2017).

The most common plastic used for mulching is Low Density Polyethylene (LDPE) which is highly resistant. LDPE mulch must be removed after harvest and uncompleted removal lead to plastic accumulation in soil (Figure 2).

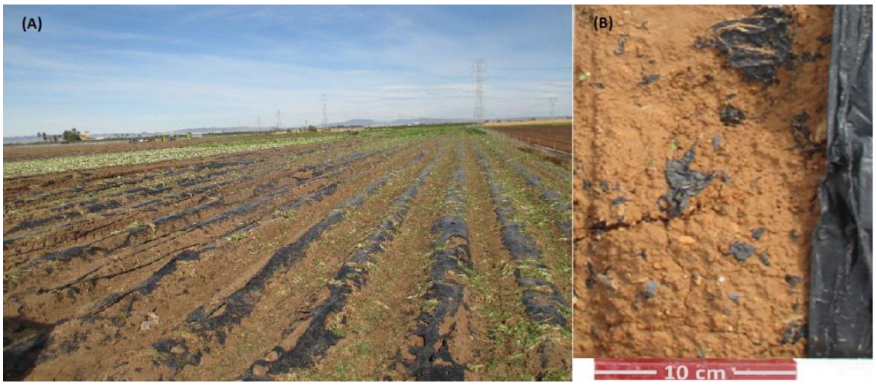

Figure 2. Mulch decomposition in an agricultural field (A), contributing to the contamination of soils with plastic debris (B) (Source: N. Beriot).

To reduce the cost of plastic mulch removal, plastic producers try to improve the degradation processes of the plastic. Pro-oxidant Additive Containing (PAC) plastics are polymers, mainly LDPE, which contain a pro-oxidant additive that is used to enhance oxidation and photo-degradation (Selke et al., 2015). In the presence of light and under aerobic conditions, PAC plastics degrade into small pieces faster. PAC plastics are also known as "oxo-degradable" or "oxo-biodegradable". However, when incorporated to the soil, the absence of UV-light may result in lower degradation rates of PAC plastic debris (Hogg et al., 2016) and PAC debris may accumulate. Over the last few years, new mulching films that can be degraded by microorganisms in the soil have been developed (Sintim and Flury 2017). They are usually sold as "biodegradable" mulch. Biodegradable mulch can be made of a diversity of polymers (Kijchavengkul and Auras, 2008) either biobased or synthetic or a blend of both. The actual degradation rate of biodegradable plastic in the soil is controversial as biodegradation standard tests are often conducted in optimum environment with constant humidity, temperature and oxygenation that differ from field conditions (Napper and Thompson, 2019).

Box 9: Potential impacts of soil contamination from plastic use in agricultural practices

- Leakage of plastic additives during plastic degradation, such as phthalates, which can be harmful for the soil organisms and human health;
- Toxicity for some soil macro-organisms, which are negatively affected in growth and reproduction by the presence of micro-plastics through their ingestion, like earthworms and collembolan;
- Plastics in soil are potential sources of C and energy for microorganism able to decompose them, but additives may be toxic for other microorganism, causing shifts in the soil microbiome;
- The diversity of polymers and shapes of plastic polymers can change the soil physical properties (e.g. decrease the soil bulk density and porosity, increase the water repellence and hydraulic conductivity);
- Plastic debris could affect plants growth, an impact already reported for wheat and spring onion;
- Nano and micro plastics can be taken up by plants and then enter the food chain.

3. Conclusions

In some cases, from the same agricultural practice, different contaminants can potentially reach the soil (Table 1). However, the probability of that occurrence is different, depending on the practice, and it is very important that the farmer knows the risk of contamination associated to each practice, in order to control it and, if needed, remediate the soils.

As for the risk of transference of contaminants from soils to ground or surface waters, and despite some positive progress, nutrients overload from agriculture is still one of the most important pressures on the aquatic systems, and needs to be addressed (EC, 2018).

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Table 1. Different agricultural practices and the corresponding potential soil contaminants. Classification of impact risks if EU regulations, national standards and good agricultural practices are not considered: xxx – High; xx – Moderate; x – Low; 0 – Not relevant; ? – Potential probability, but with research needs.

		Nutrients	PTEs	Pesticides	Persistent organic pollutants	Plastics	Emerging contaminants: pharmaceuticals, veterinary products and PCPs
Fertilization and soil amendment	Mineral fertilizers	xxx	x	0	0	0	0
	Animal manures and slurries	xxx	x	0	0	?	?
	Sewage sludge	x	xxx	0	xx	xxx	?
	Mixed- Urban waste compost	x	xxx	0	x	xx	?
	Green-waste derived compost	x	x	x	0	?	0
	Biochar	0	xx	0	xx	0	0
Irrigation with wastewater		x	xx	0	x	xx	xxx
Plant protection		0	x	xxx	x	0	0
Plastic use		0	0	0	x	xxx	0

4. Research needs

Knowledge gaps about the inputs, concentrations, behaviour, (eco)toxic effects, and limit values of some contaminants in soils were identified, and need investigation:

1. Long-term build-up of **persistent organic contaminants** in agricultural soils, accumulation, bioavailability, effects on soil biota, interactions with soil constituents, and potential leaching and runoff;
2. **Pesticides**: environmental risk assessment of their mixtures, and the establishment of threshold values in soils for approved currently used pesticides;
3. **Biochar and compost**: potential absorption and adsorption of contaminants, specific mechanisms in soils amended with biochar and compost on the (im)mobilization of organic and inorganic contaminants, on the modification of their (eco)toxic effects, on the translocation of these contaminants from roots to shoots, and on the migration towards groundwater;

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5. Ideas for innovations

The main areas of innovation concerning the contamination of agricultural soils are:

1. Use of molecular biological tools to facilitate **breeding of disease-resistant and nutrient-efficient cultivars,** which need less input of factors of production (e.g. fertilizers, pesticides).
2. Development of **agricultural practices to prevent contamination of soils**, like precision agriculture tools to control the application of fertilizers, pesticides, irrigation, etc.
3. **Development of materials alternative to plastics,** or **polymers that can degrade** in a reasonable amount of time in different soil conditions.

6. Proposal for potential operational groups

1. **Evaluation of emerging contaminants (pharmaceuticals, veterinary products and PCPs) in agricultural soils:** inputs, concentrations, bioavailability, behaviour, (eco)toxic effects, and the possibility of proposing threshold values.
2. **Plastics in agricultural soils**: potential sources, transport, content and behaviour in soil, additives leaked after plastic decomposition and their (eco)toxicity, short and long-term effects of the plastic debris on soil microbiota and plants, biodegradation of different polymers in soil, and the possibility of proposing some policy measures regarding threshold values and use.
3. **Uptake of contaminants by crops**, their entrance into the human food chain, and the consequences for human health;
4. **Technological transformation of biowaste-based amendments** (e.g. manure, slurry, sewage sludge, compost), to allow their nutrient and organic matter valorisation, avoiding their whole use and the input of their contaminants load to soils.
5. Linking the **crop**, and soil **amendments** with the **soil health status**.
6. Evaluation of bioavailability, bioaccessibility and solubility of **contaminants in agricultural soils** to protect crops and water.

The potential operational groups 5 and 6 can be relevant to define the main soil contaminants of agricultural origin and establish preventative measures in addition to developing biological remediation practices (see mini-paper on "Biological remediation of contaminated agricultural soils").

Further research needs coming from practice, ideas for EIP AGRI operational groups and other proposals for innovation can be found at the final report of the focus group, available at the FG webpage.

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