Written evidence submitted by Canterbury Christ Church University (SH0097)

The Ecology Research Group (ERG) within the section of Natural and Applied Sciences at Canterbury Christ Church University has been active for over 30 years. The ERG aims to deliver user-defined solutions through research and consultancy. Research within the ERG is organised into three research clusters, which are all relevant to this funding call: ‘Agriculture and Food Security’, ‘Environmental Change and Resilience’ and ‘Biodiversity and Conservation’.

Naomi Rintoul-Hynes has expertise in various aspects of soil science, including soil ecology, soil-plant interactions, pollution, remediation and sustainable agriculture. Joseph Galani’s specialises in food science and nutrition, with a focus on emerging contaminants in the food chain. Maya Sollen-Norrlin uses physio-chemical and biological indicators to understand ecosystem and crop health. Finally, Chris Ferguson is interested in the effects of heavy metal pollution in soils and uptake in crops, with expertise in the use of metabarcoding to indicate soil health and the impact of crop contamination on human health. This evidence is submitted based on the outcome of our own research projects and our combined knowledge, with the support of the most up-to-date literature. Although references have been removed to ensure this document is as user-friendly as possible, a fully referenced version of this document is available upon request.

Executive summary

Soils are fundamental to ecosystem functioning in agricultural soils and therefore their ability to provide public goods. Agri-environment policy measure progress towards improving soil health through various physio-chemical or biological means; however, these are no longer fit for purpose. This paper is split into two sections: soil health indicators, covering physio-chemical characteristics and biodiversity, and soil contamination, dealing with heavy metals, pharmaceuticals and microplastics. Within this document, we make a series of recommendations to improve monitoring and subsidy schemes under the new Environmental Land Management schemes. New policy frameworks also need to consider known and emerging contaminants if they are to be a true representation of the health of our soils. Recommendations are given below, split into: physio-chemical characteristics, biodiversity, heavy metals, pharmaceuticals and microplastics.

Physio-chemical indicators:

1. Expand on the soil health indicators quantified under the ELMS to include several more that are mentioned under the Countryside Survey (i.e. pH, bulk density, soil carbon, organic matter, total nitrogen, mineralizable nitrogen and total phosphorous), and offer a set of relevant tests related to soil health, taking into account basic soil characteristics, cropping systems and/or climate.
2. Subsidise costs of soil testing under the ELMS so that farmers can collect good quality data on soil health before and after management interventions to demonstrate if soil health has been improved.
3. Ensure that all tests have a standardised method for soil sampling, storage and testing to enable comparisons and accurately track long-term changes.
4. There is a risk of low farmer participation due to the loosely defined soil assessment methods. There is a need for clear guidance and defined, but easy to use, methodologies and farmers need to have access to expert advice and guidance.
5. Soil quality indicators should be relatable to a specific ecosystem services/public goods, and farmers need clear guidance on how to interpret the results of their soil tests in this context.
6. Conduct a large-scale monitoring scheme to provide a reference dataset for farmers to compare their soil physio-chemical data to, or create a scoring system that is easy for farmers to interpret to use as a comparison or demonstrate changes in soil health.

Biological indicators:

1. Any agreements attaching subsidy payments to improvements in soil biodiversity need to be long-term and might need to include staged and proxy payments. This is to account for the longer timeframe that soil communities may take to respond to new land management approaches compared to physio-chemical characteristics.
2. Current measurements of biological health are no longer appropriate. Since soil biodiversity – especially microbial biodiversity – drives soil functioning and is a key component of soil health, this needs to be included as a soil health indicator under the new ELMS.
3. Although methods for biodiversity assessment using metagenomics are complex, schemes ot monitor soil must be cooperative. Thus, farmers have to be able to on collecting soil samples and sending these for analysis. Similarly, the biodiversity data that is sent back to the farmer also needs to be easily interpreted (i.e. using a simple summary of findings or scoring system).

Heavy metals:

1. Expand on heavy metals that are used as soil health indicators under the Countryside Survey (total copper, zinc, cadmium, and nickel) to include several more that are prevalent in agricultural soils.
2. Include contamination as a soil threat and add Action(s) within the ELMS that targets remediation of contaminated soils.

Pharmaceuticals:

1. First, there is a need for prioritization: there are more than 1,900 active pharmaceutical compounds in use, making it a challenge to study all of them at once. Prioritization will allow identifying those compounds that can pose the greatest risk to the UK soil, plants, environment, and public health.
2. Soil microbiome is diverse and varies with location, soil type, plants, environmental conditions, and human activities. There is a need to understand the effect of prioritized CECs pharmaceuticals on soil microbiome and its interaction with the rhizosphere in different agroecological zones of the UK.
3. How the presence of prioritized CECs in the soil affects the growth, productivity, and nutritional quality of main UK crops needs to be assessed. This will be achieved by evaluating the mechanisms of absorption, plant uptake and metabolism of CECs in main UK crop species.
4. With the anticipated negative effects of the CECs on agriculture and the environment, strategies for the remediation of prioritized CECs from contaminated soils should be developed. Different available bioremediation approaches need to be tested to identify those who would work on those CECs and in the UK context.
5. Considering the current development of climate change and its impact on agriculture, it is inevitable to assess how climate change is affecting / will affect the prioritized CECs in their interaction with plants and soil.

Microplastics:

1. Define ‘microplastics’ clearly as an environmental contaminant in policy documents.
2. More accurate estimates of deliberate and accidental release of plastics are required to reduce uncertainty in approximations of the quantity of plastics entering soils.
3. Well-aligned initiatives, best management practices, more stringent policies and co-operative efforts of the public, manufacturers and government officials are urgently needed to reduce illegal disposal of plastic waste, moderate improper use of plastic products in the agriculture and increase the proportion of plastics undergoing waste management or recycling processes.
4. Better characterisation of MPs (i.e. origin, shape, size, and composition) and evaluation of their in soils (i.e. distribution, transport and degradation) is required, with reference to specific soil characteristics, agricultural systems and climates.
5. Understand how the presence of MPs in the soil affects soil biota and the growth, productivity and nutritional quality of crops, and determine soil guideline values for MPs in soils.
6. Develop a standard set of low-cost, high-efficiency protocols to collect and process soil samples, and then to isolate, identify and quantify microplastics in soils, depending on both the soil characteristics and the type of MPs being quantified.

1. Introduction

Soils are fundamental to the functioning of most terrestrial ecosystems and accommodate a significant proportion of terrestrial biodiversity. Soil health is the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans, and connects agricultural and soil science to policy, stakeholder needs and sustainable supply chain management. The use of intensive agricultural practices has contributed to the degradation of soils in the past century, often at a significant cost to soil biodiversity, ecosystem functioning and productivity of associated landscapes. Therefore, valuing our soil health appropriately is critical to the success of agri-environment schemes, both at the local farm scale and at the policy level. However, quantifying soil health is still dominated by physio-chemical indicators such as bulk density, pH and organic matter content, despite growing appreciation of the importance of soil biodiversity.

This paper will summarise how current academic research and government policy values key indicators of soil health, and future opportunities for the UK government to create a comprehensive framework to subsidise farmers whose management interventions improve the health of our soils and provide public goods as a result. This paper is split into two sections: soil health indicators, covering physio-chemical characteristics and biodiversity, and soil contamination, dealing with heavy metals, pharmaceuticals and microplastics.

2 Soil health indicators

2.1 Physio-chemical characteristics

Under the Agricultural Transition Plan (ATP), the Sustainable Farming Incentive (SFI) is a local-scale initiative that aims to encourage farmer to take actions that improve soil health by managing their land in a way that improves food production and is more environmentally sustainable. Farmers will be paid to provide public goods such as improved water quality, biodiversity and climate change mitigation. Under the Sustainable Farming Incentive (SFI) scheme, participants are required to complete a Soil Assessment that may provide information soil physio-chemical characteristics (usually soil type, structure and/or organic matter content), as well as soil biology.

2.1.1 Choosing the right physio-chemical characteristics

Soil health is a complex concept that is influenced by a wide range of physio-chemical soil properties. Therefore, a major challenge is choosing the right soil health indicators that represent relevant soil functions whilst keeping sampling and testing labour and costs down. Although soil health will likely be affected soil type, structure and organic matter content, frameworks that have been developed for assessing soil health generally all consist of a Minimum Data Set (MDS) of the minimum number of parameters needed to explain the capacity of the soil to respond to agricultural management and to provide ecosystem services. Whilst the current Actions required by participants in the SFI are relevant to soil health, the inclusion of a set of standardised soil tests in the Soil Assessment action would make it more rigorous and allow for more accurate comparisons across years.

As a minimum suggestion, the soil parameters tested under the Countryside Survey would be a good starting point. These include pH, soil carbon, organic matter, total nitrogen, an indicator of total phosphorous, bulk density, mineralizable nitrogen, total copper, zinc, cadmium, and nickel. However, it should be noted that although tests for pH and bulk density can be done by participants on the farm, the other tests would most likely need to be sent off to commercial or academic laboratories and so there would be an associated cost to this. Having said that, many farmers already test nitrogen and phosphorous levels as part of nutrient management, as well as pH, so they might already have this data for the parcels in question. Alternatively, this testing could be subsided under the ELMS so that farmers can collect data on soil health before and after management interventions to demonstrate if soil health has been improved.

Soil health monitoring and indices need to be flexible enough to account for different soil types and any parameters chosen needs to be relatable to management practices. It has been argued that soil health is best assessed in the context of its capacity to fulfil a specific function (or set of functions) and that different soil quality indicators can be used and given different weightings depending on which soil functions and threats are being assessed. Thus, due to the highly context-dependent nature of soil quality indicators, it may be more appropriate to offer a set of tests related to soil health from which farmers can choose the ones that are relevant to their parcel.

2.1.2 Standardisation of methods

Many aspects of sample handling can affect test results, for example nutrient levels can vary widely between samples that have been stored in the fridge vs the freezer vs air-dried. Different methods for testing the same parameter (e.g. nitrogen levels) can also yield different results, as can timing between sampling and test. These differences in results were demonstrated in a recent study at Canterbury Christ Church University, as well as in many other experiments. Therefore, key is to ensure that all tests have a standardised method for soil sampling, storage and testing to enable comparisons and accurately track long-term changes.

2.1.3 Putting physio-chemical data in context

Soil health indicators should be relatable to a specific public good, and farmers need clear guidance on how to interpret the results of their soil tests in this context. Interpretation can be based on a set of reference soils which are tested and deemed to be of very good quality for the specific type of soil being analysed (based on basic soil characteristics, cropping systems and/or climate). However, such reference data can be hard to obtain if soils in a region haven't been tested before, or if they are poorly managed, or have been so in the past. Alternatively, soil quality indicators can be interpreted using scoring functions following the format of a) more is better, b) less is better, or c) optimum range. Again, the establishments of such scoring functions require baseline data or expert judgement based on current literature. An alternative that is perhaps more feasible for individual farmers, and within the scope of the ELMS, is to relate indicator values to the values from different sampling points, and previous years, and score comparatively (i.e., 25% more OM, or top 50%). This approach is more flexible and allows for continual development. If using such a relative interpretation scheme it is imperative to use a standardised and clearly defined set of protocols and procedures, from sampling through storage of samples to testing and data analysis, as otherwise comparisons are meaningless.

2.1.4 Recommendations

Based on the information above, several suggestions for improvements to current agricultural monitoring schemes/policies are given below:

1. Expand on the soil health indicators quantified under the ELMS to include several more that are mentioned under the Countryside Survey (i.e. pH, bulk density, soil carbon, organic matter, total nitrogen, mineralizable nitrogen and total phosphorous), and offer a set of relevant tests related to soil health, taking into account basic soil characteristics, cropping systems and/or climate.
2. Subsidise costs of soil testing under the ELMS so that farmers can collect good quality data on soil health before and after management interventions to demonstrate if soil health has been improved.
3. Ensure that all tests have a standardised method for soil sampling, storage and testing to enable comparisons and accurately track long-term changes.
4. There is a risk of low farmer participation due to the loosely defined soil assessment methods. There is a need for clear guidance and defined, but easy to use, methodologies and farmers need to have access to expert advice and guidance.
5. Soil quality indicators should be relatable to a specific ecosystem services/public goods, and farmers need clear guidance on how to interpret the results of their soil tests in this context.
6. Conduct a large-scale monitoring scheme to provide a reference dataset for farmers to compare their soil physio-chemical data to, or create a scoring system that is easy for farmers to interpret to use as a comparison or demonstrate changes in soil health.

2.2 Biodiversity

Soils are one of the most biodiverse ecosystems on the planet. Soil biodiversity can be valued as a natural capital asset, from which various soil ecosystem services are associated. If soil biodiversity is depleted, there are costs to farmers due to the subsequent increase in inputs to produce crops, but also to society through impacts as soil biodiversity is associated with mitigating environmental impacts. Thus, land use policies must consider soil biodiversity as a natural capital asset, otherwise it has been suggested that society would be misallocating its scarce resources. It has been recommended that soil biodiversity should be a key component of a strategy towards agricultural sustainability when considering the development of more productive farming systems that have a high resource use high efficiency and thus lower economic costs via input requirements and lower environment costs. DEFRA stated that the Environmental Land Management Scheme will support the “30by30” target, to protect 30% of England’s land for biodiversity by 2030. This should include soil biodiversity since soil is among the most diverse and complex habitats on earth.

Although it is often simpler to understand the direct benefits of soil biodiversity to the landowner, there are also indirect impacts on society. For example, soil biodiversity can improve crop yield through improved nutrient cycling and water regulation services, but it will also benefit society by reducing nutrient run-off and subsequent eutrophication of rivers. Thus, these services should be classed as a public good. Although the incentives to sustain healthy, biodiverse soils differs between landowners and society, “actions to secure one set of values cannot be treated separately from actions to secure the other”.

2.2.1 Measuring soil biodiversity

In a document discussing opportunities and issues with the co-designing a sustainable farming scheme for Wales, it was noted that any measurement must be simple, effective and farmer led/owned. Farmers considered measuring improvements in soil biota problematic and potentially expensive versus basic soil sampling for physio-chemical properties (i.e. to estimate bulk density or organic matter). However, there was a call for greater academic input into measuring and analysing soil biosphere and a continuation of assistance with soil sampling. Not only does the protocol for measuring soil biota need to be appropriate, but the timeframe also needs to reflect that changes in soil communities may take longer to occur following management interventions than physio-chemical changes. Thus, any agreements attaching subsidy payments to such improvements need to be long-term and might need to include staged and proxy payments.

Methods of soil biodiversity measurement can be split into three categories: morphological, biochemical or molecular. Morphological analysis is considered the cheapest of the methodologies with techniques ranging from microscopy for morphological identification, cultivation and flow cytometry for microfauna to heat extraction, pitfall traps and wet extraction for mesofauna. These morphological methods, although cost effective, are time consuming and require a high level of specialised expertise to be an effective analytical method. Although this these methods are widely used, the requirements for a high level of expert knowledge can cause selection bias on organisms that are more easily identifiable, such as burrowing soil animals, and can also lead to misidentification of species. It is helpful that organisms are not always required to be identified by species level, but generally the broader the classification, the less useful the information is regarding soil health. In addition, these methods ignore many other functionally important soil organisms (for example, microorganisms such as fungi and bacteria are unlikely to be visually identified).

Biochemical analysis including a wide range of methods such as fumigation-extraction, metaproteomics, phospholipid fatty-acid (PLFA) analyses and metabolomics. These methods of analysis focus mostly on the biomass and functions of microorganism groups within the soil sample and are the most accurate for the estimation of biomass. Major issues associated with biochemical methods are that they tend to be time consuming and costly. Some biochemical methods also require the use of hazardous chemicals, making them more dangerous to carry out. They also require specialist laboratory facilities. These methods are unable to identify groups on their own, and methods that do allow for the identification of functional groups are known to have incomplete databases, resulting in poorly identified groupings.

The majority of the current body of research consists of morphological or biochemical studies quantifying single organisms or groups of organisms within the soils, but far fewer look at soil communities. This makes it difficult to compare data between different studies that have applied very different methods to identify and quantify organisms. Molecular analysis of soil biodiversity is the highest resolution method of soil organism analysis, making it far easier to examine entire soil communities than other methods. Of the four main methods of molecular analysis, qPCR is the most cost-effective molecular method with a high throughput and the ability to target almost any taxa or functional gene of an organism. However, this can be particularly costly if several targets are being investigated. Metabarcoding and amplicon sequencing is the highest throughput method of all, and is thought to be the most cost effective and high-resolution option. These allow us to quantify all organisms with the soil environment and has led to the method to become the most utilised to target groups for soil biodiversity. However, distortion of the observed soil community structure can occur within the analysis depending on the primers that are selected and the amplification efficiency. The final two methods – metagenomics and metatranscriptomics –are both high resolution methods of looking at all organism diversity. However, compared to metabarcoding, these methods are much more costly to run. These, and metabarcoding, also have a shared issue of being limited by the availability of curated reference databanks for the data collected to be compared against with the majority of databanks being for bacteria such as greengenes and SILVA, and to a lesser extend for fungi and protists. This can lead to a sway in the overall soil biodiversity and bias towards bacteria-dominated soil data. Finally, another benefit of using molecular methods is that these can quantify soil microbes - their fast response to environmental changes, even at small spatial scales, can allow landowners to demonstrate improvements to soil health earlier than using other approaches.

2.2.2 Metabarcoding

Of the options described above, molecular methods are the best option for soil community analysis, rather than quantifying one or a few organisms. Of the molecular methods available, metabarcoding is the highest resolution and the cheapest option. It can also be scaled so that soils are screened for specific operational taxonomic units (OTUs) that are associated with specific ecosystem functions or general soil health, significantly reducing the cost. This can provide similar data to that of earthworm counts in morphological assessments which are used as a bioindicator species. It is also the most utilised within the research so data is easily comparable. Extracting environmental DNA (or eDNA) is a simple procedure that can be carried out on fresh soil, or soil that has been frozen or air-dried, making it a good option for farmers who would need to collect soil samples and send them to a laboratory for analysis since minimal processing is required on-site. On the other hand, while eDNA is cost effective in comparison to traditional survey methods when assessing the full range of organisms in soils, it still represents a significant cost for landowners. Unless this cost is partly or fully subsidised as part of land management schemes, there is little incentive for farmers to monitor soil biodiversity and they are more likely to rely on simple physio-chemical indicators of soil health. There is an urgent need to develop robust, comprehensive and policy-relevant indicators for soil health and these must include better soil indicators of soil biodiversity.

2.2.3 Recommendations

Soil biological assessments have been relatively rudimentary in their approach, therefore the following amendments to UK monitoring and land management subsidy schemes are recommended:

1. Any agreements attaching subsidy payments to improvements in soil biodiversity need to be long-term and might need to include staged and proxy payments. This is to account for the longer timeframe that soil communities may take to respond to new land management approaches compared to physio-chemical characteristics.

2. Current measurements of biological health are no longer appropriate. Since soil biodiversity – especially microbial biodiversity – drives soil functioning and is a key component of soil health, this needs to be included as a soil health indicator under the new ELMS.
3. Although methods for biodiversity assessment using metagenomics are complex, schemes ot monitor soil must be cooperative. Thus, farmers have to be able to on collecting soil samples and sending these for analysis. Similarly, the biodiversity data that is sent back to the farmer also needs to be easily interpreted (i.e. using a simple summary of findings or scoring system).

3. Soil contamination

3.1 Heavy metals

3.1.1 Sources and fate of heavy metals

Heavy metals (HMs) are any metals that have densities that are greater than 5 g/cm^3 and usually an atomic number greater than 23, whereas metalloids are chemical elements that, in their standard state, have (a) the electronic band structure of a semiconductor or a semimetal, (b) an intermediate first ionization potential and (c) an intermediate electronegativity. The primary natural source of heavy metals and metalloids in soils is the parent material, or rock, from which they are originated. These can enter the soil environment through natural processes such as meteors, biogenic processes, volcanic activity, forest fires, oceanic gas exchange, erosion, weathering, leaching and surface winds. However, compared with anthropogenic activities, natural sources of heavy metals and metalloids in the environment are usually of little importance.

The main anthropogenic sources are heavy industry, fertilizers, biosolids and manures, biocides (pesticides, fungicides, herbicides and insecticides), wastewater and air-borne sources. Although the metal/metalloid concentration is often relatively low in these materials, their long-term repeated application can eventually result in metal accumulation in the soil. Of all the industrial and commercial contaminants affecting soils in Europe, heavy metals account for the largest proportion (over a third). In Europe alone, estimates suggest that there are over 2.5 million potentially contaminated sites and 342,000 identified contaminated sites. Importantly, HMs do not undergo microbial or chemical degradation in the environment and so if left untreated, they can be found within the soils hundreds of years after their introduction.

There are a multitude of heavy metals and metalloids associated with anthropogenic activities, including aluminium, arsenic, cadmium, chromium, copper, iron, lead, manganese, mercury, nickel and zinc. An inventory of heavy metals in agricultural soils in England and Wales described livestock manures and sewage sludge as important sources of heavy metals, with these accounting for up to 40% of total zinc and up to 17% of all copper. Textile and food industry waste are also key contributors. Both these metals, as well as Pb, Ni, Cr, Cd, As and Hg, have been shown to deposit within agricultural soils in large amounts though atmospheric deposition from sources including power generation, transport, waste incineration and mining. Fertilisers and lime are also an important source of heavy metal pollution, especially for Zn, Cu, Cd and Cr. There is already a large body of evidence documenting that there are a multitude of acute and chronic toxic effects of these heavy metals on soil biota and human health. For humans, effects can include gastrointestinal and kidney defects, nervous system disorders, skin lesions, immune system dysfunction, birth defects and cancer. As well as direct pathway from inhalation and ingestion, the most concerning pathway is via bioaccumulation within food chains resulting in harmful concentrations in crops and products derived from animals.

3.1.2 Monitoring heavy metals

Since soil heavy metal concentration is not routinely tested in most agricultural soils, it is possible that we are underestimating the level of contamination of agricultural land. For example, in a recent study conducted by Canterbury Christ Church University as part of the EU Interreg 2 Seas Grassification project, soil samples were sent to an Environment Agency-approved laboratory for HM analysis to compare soil samples from 8 farms, 8 nature reserves and 9 roadside sites in Kent. Although road verges are considered a pollution risk to the extent that cut roadside vegetation is legally categorised as 'waste' in the UK, arable farms had higher average concentrations of arsenic, nickel, mercury, selenium and manganese, albeit still under the UK guideline values. From this study, some participants were aware that inputs they used on their land (i.e. paper waste) were likely to contain high concentrations of heavy metals, but there is some degree of apathy when it comes to farmers using product that may be high in HMs (or other contaminants). Although there are data available on soil contamination, landowners are often apprehensive about sharing data that may show their site is contaminated, hence why there are a much larger number of potentially contaminated sites in Europe than confirmed contaminated. Thus, the quality of any inventory depends on the availability of the appropriate data and its robustness. Over time, new research can improve the quality of data available, particularly if monitoring for contaminants is incentivised through agri-environment schemes such as ELMS.

3.1.3 Remediation

Since heavy metals are likely to persist in soils for decades, or even centuries, without any intervention, contaminated sites often need to have remediation treatment to reduce the risk to the local ecosystem or human health. There are a multitude of remediation options to remove contaminants form the soil and/or render them less harmful. The viability of some commonly applied remediation treatments are discussed below, although site-specific assessments generally need to be carried out prior to remediation works.

a) Extraction, stabilisation, and solidification

Excavation involves the removal of the contaminated soil, to be replaced by non-contaminated soil. This method is highly destructive to the immediate ecosystem which can have many effects on the local flora and fauna. The contaminated soil may be moved to another site for storage to avoid re-release to the environment. Alternatively, further chemical treatment of this soil through processes known as solidification or stabilisation can take place to reduce the environmental risk of contaminants left within the soil. This is often carried out ex-situ once soil has been removes, but some treatments can be carried out on site. Although this can be effective in preventing the contamination from entering the ecosystem, detrimental effects on the soil biodiversity and soil health can occur. For example, glassy solids can form within the soils following solidification and can reduce soil health and poisonous gases can also be released into the atmosphere and can pose a health threat to the local wildlife and humans.

b) Incineration, vitrification, and electrokinetic treatment

Incineration and vitrification (also known as pyrometallurgical separation) are methods where the soil is subject to high temperatures to volatise contaminants (incineration) or melt contaminating metals and then solidifying to obtain a solid metal waste (vitrification). However, the addition of such heat to the soil has a major effect on the soil biota to such a degree that it is usually not of use for agricultural purposes following treatment. Electrokinetic treatment utilises electrical potential being passed through soil and results in the movement of contaminants to cathodes or anodes. This is highly energy intensive and only works on several soil contaminants, limiting its use.

c) Phytoremediation and microbial remediation

Utilising plants and soil microorganisms, sometimes simultaneously, phytoremediation and microbial remediation have been shown to be a cost effective, environmentally friendly method of remediation. It is still considered to be an emerging remediation technology. Although better for the environment, these remediation methods take considerably longer to carry out the removal of the contaminant- often years rather than days or weeks. These methods are also greatly affected by the type of contaminant that is present. As with any crop, other physio-chemical and biological soil properties can affect the effectiveness of this method as it requires a living organism to accumulate contaminants in sub-optimal conditions. Once the contamination has been remediated, one option to allow for a circular economy approach is to use the left-over plant waste as a biofuel. In addition, there are promising advancements in processes that can recycle economically viable metals from the plant material.

3.1.4 Recommendations

Heavy metals have long been known to have a detrimental impact on the environment and human health, but agri-environment schemes have not focussed on these enough as indicators of soil health. Some recommendations for policy interventions are given below:

3. Expand on heavy metals that are used as soil health indicators under the Countryside Survey (total copper, zinc, cadmium, and nickel) to include several more that are prevalent in agricultural soils.
4. Include contamination as a soil threat and add Action(s) within the ELMS that targets remediation of contaminated soils.

3.2 Pharmaceutical compounds

3.2.1 Wastewater as a source of pharmaceuticals

With climate change and scarcity of water, coupled with higher demand for freshwater for agriculture, it is becoming increasingly common in many countries to use wastewater treatment by-products such as sludges and treated wastewater in agriculture for irrigation. However, treated wastewater can contain a number of chemicals like pharmaceutical compounds (antibiotics, antifungals), household &

personal care chemicals (found in soaps, shampoos, and detergents), and plastics, which can contaminate the soil.

Pharmaceutical compounds originate from both veterinary use and human use: after their pharmacological action in the body of humans or animals, the compounds or their metabolites are excreted through urine and faeces and end up in the waste stream. From 2000 to 2018, the rates of antibiotic consumption globally increased by 46%. Recently, a trend towards a reduction of their consumption has been observed in many high-income countries: in the UK between 2013 and 2017, the use of antibiotics increased in people by 8% and decreased in animals by 51%; between 2017 and 2021, total antibiotic use in England fell by 15.1%. Nevertheless, England still exceeded the government's National Action Plan goal to reduce antibiotic prescription and consumption by 15% (from a 2014 baseline) by 2024. In low- and middle-income countries, however, antibiotic consumption continues to increase, and with the human population increase, this will further rise. This shows that there is a large amount of these pharmaceutical compounds released into the environment, most of which are resistant to biodegradation and can persist for a long time in water, soil, plants, or animals. These formerly uncommon contaminants now found at high concentrations in agricultural water and soils are known as contaminants of emerging concern (CECs). The presence of CECs in the soil can drastically impede soil health, affect plant growth and nutritional quality of produce, or can be accumulated in the plant and foods and affect the health of consumers.

For instance, antibiotics can kill beneficial soil bacteria and fungi and alter the dynamics of the soil microbiome and its interaction with plants. Research found that antifungal compounds from the azole group (clotrimazole, miconazole nitrate and fluconazole) present in the soil, reduce mycorrhizal transfer from the soil into the host plant. Mycorrhizas are associations between plant roots and beneficial fungi found in the soil, that help plants to absorb nutrients, resist disease, and produce better food. By affecting mycorrhiza, these antifungal pharmaceuticals can reduce crop yield and quality. Another example is the application of pharmaceutical waste sludge compost on agricultural land which resulted in increased antibiotic resistance genes among the bacteria found in the soil surrounding the roots of vegetables. These resistant bacteria can be transferred to the edible part of the vegetable and then enter the human food chain resulting in a food safety and public health threat. Besides, it was found that CEC pharmaceuticals commonly present in wastewater can accumulate in the nectar and pollen of flowering plants with potential implications for honeybee health, and further transfer into the human food chain through honey.

3.2.2 An emerging issue in the UK

Although wastewater treatment by-products are not yet approved in the UK for usage in agriculture, current predictions by the Environment Agency show that by 2050, they will become an inevitable alternative for the irrigation of agricultural lands as is currently happening in many countries. In California for example, the use of recycled wastewater for agricultural irrigation currently represents only 4% of the irrigation volume, but due to foreseen water shortages as consequences of climate change and an increase in population and agricultural land, new policy demands a three-fold increase in the total reuse of recycled wastewater by 2030. It is therefore critical now for research in the UK to assess the conditions, implications, consequences, and mitigation measures of pharmaceuticals (and other CECs) from wastewater treatment by-products on UK soils.

3.2.3 Recommendations

Recommendations for research in the UK to assess the conditions, implications, consequences, and mitigation measures of pharmaceuticals in soils are set out below. These findings will help the UK parliament in evidence-based policy for the management of CECs in UK agricultural soils, for example, in fixing the minimum acceptable limits of antibiotics acceptable in irrigation water used on food crops.

1. First, there is a need for prioritization: there are more than 1,900 active pharmaceutical compounds in use, making it a challenge to study all of them at once. Prioritization will allow identifying those compounds that can pose the greatest risk to the UK soil, plants, environment, and public health.
2. Soil microbiome is diverse and varies with location, soil type, plants, environmental conditions, and human activities. There is a need to understand the effect of prioritized CECs pharmaceuticals on soil microbiome and its interaction with the rhizosphere in different agroecological zones of the UK.
3. How the presence of prioritized CECs in the soil affects the growth, productivity, and nutritional quality of main UK crops needs to be assessed. This will be achieved by evaluating the mechanisms of absorption, plant uptake and metabolism of CECs in main UK crop species.
4. With the anticipated negative effects of the CECs on agriculture and the environment, strategies for the remediation of prioritized CECs from contaminated soils should be developed. Different available bioremediation approaches need to be tested to identify those who would work on those CECs and in the UK context.
5. Considering the current development of climate change and its impact on agriculture, it is inevitable to assess how climate change is affecting / will affect the prioritized CECs in their interaction with plants and soil.

3.3 Microplastics

3.3.1 Microplastics are of immediate econcern

Of the CECs associated with agriculture, microplastics are of immediate concern as these are already entering our soils. In Europe, approximately 59 million metric tonnes of plastic were produced in 2014, and approximately one third of the plastics produced are available in terrestrial environments. Despite this, microplastics (MPs) have been extensively studied in aquatic systems, but their presence and fate in terrestrial systems - particularly agricultural soils - are not fully understood. This is particularly concerning the scale of the problem in terrestrial systems, with annual plastic release to land being estimated at 4–23 times that released to oceans.

3.3.2 Microplastics in agriculture

Sources of MPs in agricultural soils include application of biosolids, compost, polymer-based fertilizers and pesticides and mulching film, wastewater irrigation and atmospheric deposition. However, more studies that aim to understand the source of MPs in soil can allow this form of pollution to be controlled from the source. Similarly, Information is available on plastic production and waste management streams but estimates of deliberate or accidental release has been described as one of the greatest uncertainties for emission predictions. Thus, without adequate data on the scale of the problem, it is difficult to manage it. In Europe, only 70% of plastics underwent waste management or recycling processes. Behavioural change of consumers and plastics manufacturers is necessary for reducing the amount of plastic entering the environment and achieving sustainable waste management and food safety. Well-aligned initiatives, best management practices, more stringent policies and co-operative efforts of the public, manufacturers and government officials are urgently needed to reduce illegal disposal of plastic waste and improper use of plastic products in the agricultural industry. Having said that, changing manufacturer and consumer behaviour is a difficult task, particularly given the volume of plastics being manufactured. Therefore, it remains important to understand the potential effects of this ever-accumulating pollution.

Evidence suggests that once in the environment, the fate and distribution of MPs very depending on the soil properties, agricultural management practices and soil organisms. Thus, research is urgently required to better understand the extent and fate of MPs in agricultural environments, including their distribution, transport and degradation. The long-term effects of environmental aging process on MPs from different sources in agricultural soils should also be considered. Future research should be extended to the qualitative characterisation and quantitative assessment of MPs in different types of agricultural soils, with different cropping systems and under variable climates, as well as on their interactions and transformations within soils.

MPs are known to alter the growth, feeding, reproduction and survival rates of flora, fauna and soil biota. However, there are still only very limited data on their interactions with microbes, food crops and soil animals. Since MPs are recognized as emerging persistent pollutants that may transfer across different trophic levels along a food web, it is necessary to investigate their effects on soil biota and crops, but also to understand the potential risk to human health via ingestion of food products derived from crops or livestock.

3.3.3 Quantifying microplastics

Currently, different laboratories apply a wide range of analytical techniques to extract and identify MPs, for example through different methods of purification, separation, extraction, digestion, visual characterisation and quantification of MPs. These protocols will all differ in their ability to produce accurate, reliable results depending on the soil properties (i.e. organic matter content often dictates the protocols used) and the origin, shape, size, and composition of MPs being analysed. As a result, there is a large degree of uncertainty around the volume, composition and diversity of microplastic particles entering the environment. Unlike other pollutants such as HMs, there are no Environment Agency-approved laboratories conducting MP analysis in soils. As a result, Canterbury Christ Church University has been working on developing an appropriate method in their laboratories to quantify MPs in agricultural soils. Thus, a standard method for MP quantification in soils approved by the EA that is fast, convenient, and practical is essential if we are to better understand the extent of the problem and how to best manage it. This can reduce ambiguity and thus allow direct comparison between studies.

3.3.4 Recommendations

Based on the body of scientific evidence, it is clear that our understanding of MPs in the environment is rapidly developing. However, there are still fundamental gaps in the knowledge and in policy documents. To that end, we have suggested the following research challenges and amendments to agricultural policy:

7. Define 'microplastics' clearly as an environmental contaminant in policy documents.
8. More accurate estimates of deliberate and accidental release of plastics are required to reduce uncertainty in approximations of the quantity of plastics entering soils.
9. Well-aligned initiatives, best management practices, more stringent policies and co-operative efforts of the public, manufacturers and government officials are urgently needed to reduce illegal disposal of plastic waste, moderate improper use of plastic products in the agriculture and increase the proportion of plastics undergoing waste management or recycling processes.
10. Better characterisation of MPs (i.e. origin, shape, size, and composition) and evaluation of their in soils (i.e. distribution, transport and degradation) is required, with reference to specific soil characteristics, agricultural systems and climates.
11. Understand how the presence of MPs in the soil affects soil biota and the growth, productivity and nutritional quality of crops, and determine soil guideline values for MPs in soils.
12. Develop a standard set of low-cost, high-efficiency protocols to collect and process soil samples, and then to isolate, identify and quantify microplastics in soils, depending on both the soil characteristics and the type of MPs being quantified.

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