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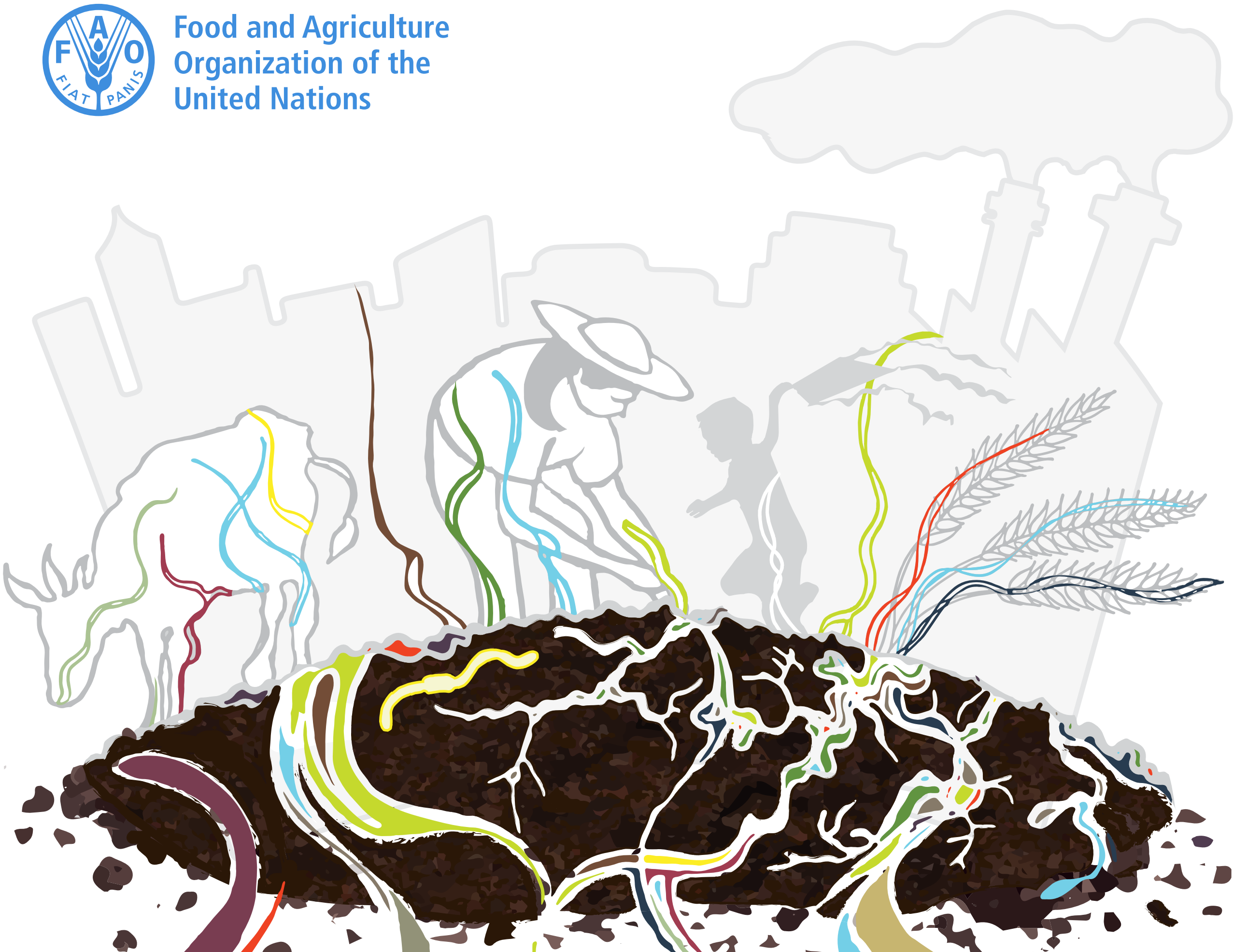

SOIL POLLUTION: A HIDDEN REALITY

GLOBAL SOIL PARTNERSHIP

SOIL POLLUTION
A HIDDEN REALITY

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EXECUTIVE SUMMARY

"Soil pollution" refers to the presence in the soil of a chemical or substance out of place and/or present at a **higher than normal concentration** that has adverse effects on any non-targeted organism. Soil pollution often cannot be directly assessed or visually perceived, making it a hidden danger.

The Status of the World's Soil Resources Report (SWSR) identified soil pollution as one of the main soil threats affecting global soils and the ecosystems services provided by them.

Concerns about soil pollution are growing in every region. Recently, the United Nations Environmental Assembly (UNEA-3) adopted a resolution calling for accelerated actions and collaboration to address and manage soil pollution. This consensus, achieved by more than 170 countries, is a clear sign of the global relevance of soil pollution and of the willingness of these countries to develop concrete solutions to address the causes and impacts of this major threat.

The main anthropogenic sources of soil pollution are the chemicals used in or produced as byproducts of industrial activities, domestic, livestock and municipal wastes (including wastewater), agrochemicals, and petroleum-derived products. These chemicals are released to the environment accidentally, for example from oil spills or leaching from landfills, or intentionally, as is the case with the use of fertilizers and pesticides, irrigation with untreated wastewater, or land application of sewage sludge. Soil pollution also results from atmospheric deposition from smelting, transportation, spray drift from pesticide applications and incomplete combustion of many substances as well as radionuclide deposition from atmospheric weapons testing and nuclear accidents. New concerns are being raised about emerging pollutants such as pharmaceuticals, endocrine disruptors, hormones and toxins, among others, and biological pollutants, such as micropollutants in soils, which include bacteria and viruses.

Based on scientific evidence, soil pollution can severely degrade the major ecosystem services provided by soil. Soil pollution reduces food security by both reducing crop yields due to toxic levels of contaminants and by causing crops produced from polluted soils to be unsafe for consumption by animals and humans. Many contaminants (including major nutrients such as nitrogen and phosphorus) are transported from the soil to surface waters and ground water, causing great environmental harm through eutrophication and direct human health issues due to polluted drinking water. Pollutants also directly harm soil microorganisms and larger soil-dwelling organisms and hence affect soil biodiversity and the services provided by the affected organisms.

The results of scientific research demonstrate that soil pollution directly affects human health. Risks to human health arise from contamination from elements such as arsenic, lead, and cadmium, organic chemicals such as PCBs (polychlorinated biphenyls) and PAHs (polycyclic aromatic hydrocarbons), and pharmaceuticals such as antibiotics. The health risks associated with the widespread soil contamination by radionuclides from the Chernobyl disaster in 1986 are an enduring memory for many people.

Remediation of polluted soils is essential, and research continues to develop novel, science-based remediation methods. Risk assessment approaches are similar worldwide and consist of a series of steps to be taken to identify and evaluate whether natural or human-made substances are responsible for polluting the soil, and the extent to which that pollution is posing a risk to the environment and to human health. Increasingly expensive physical remediation methods such as chemical inactivation or sequestration in landfills are being replaced by science-based biological methods such as enhanced microbial degradation or phytoremediation.

FAO's *Revised World Soil Charter* recommends that national governments implement regulations on soil pollution and limit the accumulation of contaminants beyond established levels in order to guarantee human health and wellbeing, a healthy environment and safe food. Governments are also urged to facilitate remediation of contaminated soils that exceed levels established to protect the health of humans and the environment. It is also essential to limit pollution from agricultural sources by the global implementation of sustainable soil management practices.

This book aims to summarise the state of the art of soil pollution, and to identify the main pollutants and their sources affecting human health and the environment, paying special attention to those pollutants that are present in agricultural systems and that reach humans through the food chain. It concludes with some case studies of the best available techniques for assessing and remediating contaminated soils.

This book has been developed within the framework of the Global Symposium on Soil Pollution (GSOP18), identifying the main gaps in knowledge on soil pollution worldwide and serving as a basis for future discussions.

GLOSSARY

Contaminant: substance or agent present in the soil as a result of human activity (ISO, 2013).

Leaching: the dissolution and movement of dissolved substances by water (ISO, 2013).

Parent material: The original material (mineral and/or organic) from which soil developed by pedogenetic processes.

Persistent organic pollutant (POP): Synthesized carbon-based compounds from agrochemicals and industrial products that generally biodegrade very poorly and most of which will bioaccumulate in tissues of organisms. Some pesticides are POPs, as are Polychlorinated dibenzodioxins (PCDDs), Polychlorinated dibenzofurans (PCDFs), Polychlorinated biphenyls (PCBs), and Polycyclic aromatic hydrocarbons (PAHs).

Soil: the upper layer of the Earth's crust transformed by weathering and physical/ chemical and biological processes. It is composed of mineral particles, organic matter, water, air and living organisms organized in genetic soil horizons (ISO, 2013).

Soil ecosystem functions: description of the significance of soils to humans and the environment. Examples are: (1) control of substance and energy cycles within ecosystems; (2) basis for the life of plants, animals and man; (3) basis for the stability of buildings and roads; (4) basis for agriculture and forestry; (5) carrier of genetic reservoir; (6) document of natural history; and (7) archaeological and paleo-ecological document (ISO, 2013).

Soil health: the continued capacity of the soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal, and human health (Doran, Stamatiadis and Haberern, 2002).

Soil ecosystem services: the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly (Groot, 1992).

Food security: it is defined as the availability, access, utilization and stability of food supply.

Soil contamination: occurs when the concentration of a chemical or substance is higher than would occur naturally but is not necessarily causing harm (this volume).

Soil pollution: refers to the presence of a chemical or substance out of place and/ or present at higher than normal concentration that has adverse effects on any non-targeted organism (this volume).

3 | MANAGEMENT AND REMEDIATION OF POLLUTED SOILS

The first step in the assessment and management of polluted soils is the identification of the problem; in this case, the pollutions in the soil. In general, when an area is affected by an accident such as an oil spill, a nuclear accident, or the rupture of a dam tailing, measures to control the extent and prevent further occurrences generally start immediately. However, in legacy polluted soils or where diffuse pollution could be an issue, there are often no established protocols to be followed. In some countries or regions in the world, there are national, regional or local agencies who are responsible for initiating a preliminary investigation to determine whether or not pollution is present and whether further action is needed, while there are many others where no regulation or protocols have been defined (Teh *et al.*, 2016).

In the past, criteria for land reclamation were established using standards based on background concentration and safe limits. New approaches try to adopt a more comprehensive assessment of the risk that pollutants pose to the environment, humans and food safety. The characterization of the potential risk to the environment and human health is not an easy task, due to the complexity of the matrix, the lack of knowledge on the fate of contaminants in soil and the scarcely available information of toxicological and integrated studies (Cachada *et al.*, 2016). Exposure routes for these compartments modelled taking into consideration certain land-use types (e.g. residential, industrial, and recreational) (Provoost, Cornelis and Swartjes, 2006).

3.1 | RISK ASSESSMENT APPROACHES

Assessing risks means that, based on scientific evidence, one can estimate the likelihood of a certain outcome and the gravity of that outcome, and use this knowledge to help in decision making. Uncertainties must be reduced when possible, and clearly the remaining uncertainties need to be clearly identified and explained (FAO, 2000). Risk management decisions for soils or sediments focus on identifying relevant pathways of exposure that pose a risk to human health or the environment and developing appropriate remedial measures. These could include treating or removing sources, or cutting off pathways, or both (Committee on Bioavailability of Contaminants in Soils and Sediments, 2002).

Risk assessment approaches (RAA) are similar worldwide and consist of a series of steps to be taken to identify and evaluate whether exogenous or indigenous substances have caused or are causing soil pollution, and to what extent that pollution is posing a risk to the environment and to human health (Figure 19). Risk assessment approaches are tools to enable science-based political and technical decisions and to take action when needed. Risk assessment tools often use a chemical-by-chemical approach, focusing on a single medium, a single source, and a single toxic endpoint, although integrated approaches are gaining popularity. Such approaches use models combining human exposure and effect-based environmental parameters, based on deterministic or probabilistic techniques (DEA, 2010; Hope, 2006; Provoost, Cornelis and Swartjes, 2006). The end user is interested in whether the soil is "fit for use," mainly in industrial and urban sites where local and diffuse pollution may be present. In these cases, a site-specific approach is necessary to obtain an integrated overview of exposure and risk information (Posthuma *et al.*, 2008) .

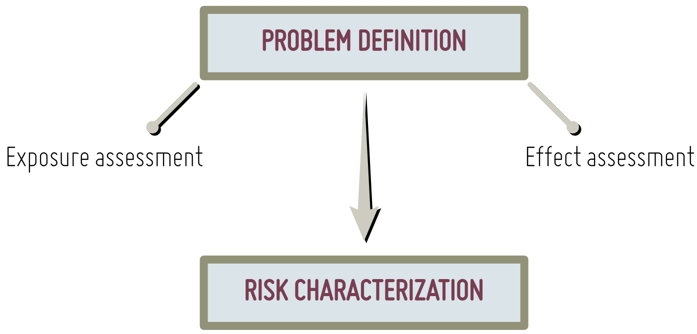

Figure 19. The "universal risk assessment paradigm". Source: Posthuma *et al.*, 2008

Once there is a suspicion of pollution, and after preliminary research on the historical use of the site, an initial assessment should be carried out to define whether exogenous substances are present, which ones are present and whether they pose any risk to the environment and human health. If pollution is confirmed and remediation measures are necessary, a detailed investigation must be accomplished to determine the extent and possible remediation measures. Risk management and/or remediation strategies are subsequently defined and implemented. After-clean-up measures are essential to confirm that the risk has been reduced and that the source of pollution has been controlled.

Worldwide, policies and regulation are based on RAA to forecast risks that cannot be directly measured (Hough, 2007). Regulations include guidelines to identify and assess soil pollution using soil quality standards, in many cases considering national characteristic of soils or site-specific conditions. Because RAA are complex and time-consuming processes, however, not every country in the world can afford to investigate pollution. This is also because no comprehensive information is available, and approaches on a site basis are frequently adopted. As Hope has pointed out, accessing documentation about ecological risk assessment and its regulatory uses is complex, especially in developing countries (Hope, 2006). In those cases, the United States Environmental Protection Agency (US EPA, 1986), Canadian guidelines (Canadian Council of Ministers of the Environment, 1999), and Netherlands guidelines (Brand, Otte and Lijzen, 2007) among others may be used as a reference, even though the characteristics of climate, soil or the local populations are not the same (Li *et al.*, 2014). Some international efforts, such as the one proposed by FAO (FAO, 2000), which provides guidelines to assess the environmental and human health risk posed by stock of obsolete pesticides with more detailed information on the steps of assessment in Environmental Management ToolKit (Volume5), or the guidelines for Integrated Risk Assessment developed by several international organizations (IAEA, 1998; Meek *et al.*, 2011; WHO, 2001a) are attempts to provide an integrated multichemical, multimedia, multiroute, and multispecies exposures analysis.

It is widely recognized that an integrative approach that includes complex mixtures of pollutants is needed to develop more precise risk assessment tools and a better understanding of the potential impacts and their extent (Reeves *et al.*, 2001). Albert launched the question "Is it possible to predict toxicity of complex mixtures?" more than 30 years ago (Albert, 1987). Since then, many researchers have tried to come up with a suitable solution or at least a more comprehensive study of interactions in complex mixtures, to determine whether additive, synergistic or antagonistic toxic effects occur when pollutant mixtures are present (Chen *et al.*, 2015). The specificity and great variability of pollutant mixtures present in each site, which depend on industrial operations or processes carried out, slow down the progress on the definition of limit values appropriate for a general risk assessment approach (Callahan and Sexton, 2007). The Dutch approach, among others, includes a protocol to analyze the risk when more than one substance is present (Cachada *et al.*, 2016). Normally, a cumulative calculation is used, considering the individual risk and the sum across the potential toxicity and risk, but it does not consider possible interactions and synergies between substances that may attenuate or increase their potential risk (Callahan and Sexton, 2007). Chen *et al.* found that the more complex the mixtures of pollutants, the greater the synergistic toxicity (Chen *et al.*, 2015). They suggest that the use of a Combination Index (CI) is more accurate to estimate the ecotoxicological risk than the conventional concentration addition (CA) or independent action (IA) models (Figure 20), not only in aquatic environments (Rosal *et al.*, 2010) but also in soils (González-Naranjo and Boltes, 2014; González-Naranjo *et al.*, 2015). The synergistic/antagonistic effect has been confirmed not only for a combination of pesticides (Yang *et al.*, 2017a) but also in other complex mixtures, such as the pollutant mixture found in landfills (Baderna *et al.*, 2011) or in railway tracks. In the latter case, Wierzbicka *et al.* found highly toxic effects of the pollutant mixture on numerous test organisms from different trophic levels, even though the single concentration of each pollutant did not exceed admissible values (Wierzbicka, Bemowska-Kałabun and Gworek, 2015). However, as explained in Sarigiannis and Hansen, combined toxicology approaches have limited applicability under specific conditions, and data cannot be generalized (Sarigiannis and Hansen, 2012).

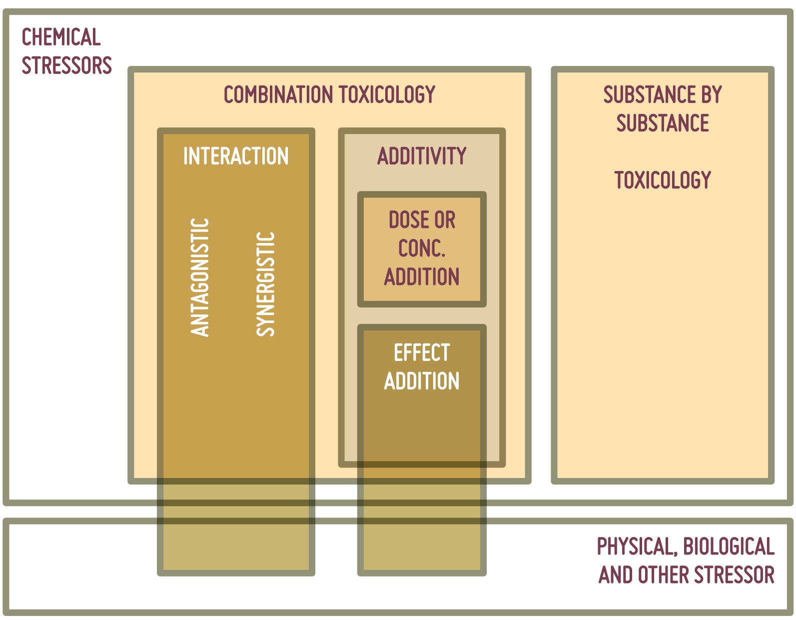

Figure 20. Risk assessment approaches based on independent action of substance by substance, additivity of doses and effects or considering interactions for the combined model. Source: Sarigiannis and Hansen, 2012

The sequence of steps to deal with polluted sites described above is a general one, and depending on national or regional approaches some steps may be omitted or others may be added (Contaminated Sites Management Working Group, 1999; DEA, 2010; FOEN, 2013; Luque, 2014).

Human health risk assessment (HHRA) can be conducted in different ways and for the purpose of meeting different objectives. This approach can be used for the following:

- derivation of soil quality standards
- site-specific risk assessment
- development of remediation objectives
- ranking of contaminated sites by priority of intervention.

Soil screening values (SSVs) are generic soil quality standards based on generic exposure pathways and scenarios (e.g. inhalation of vapours in residential or industrial areas) adopted in many countries to regulate the management of polluted soils. Soil screening values or soil quality standards are identified by different terms around the world: trigger values, reference values, target values, intervention values, cleanup values, cut-off values and others (Carlon *et al.,* 2007; Swartjes *et al.,* 2012). Furthermore, the threshold values are based on different national strategies in environmental policies and rarely take soil properties into account.

In cases of soil pollution by heavy metals, total metal concentration provides little information on the potential risk (Naidu *et al.,* 2015). It is important to identify the available and unavailable forms of the heavy metals to ensure that the soil is managed in such a way as to prevent the unavailable forms from becoming available. This can be done by using biological tests to determine the bioavailability and toxicity of metal(loid)s (Romero-Freire, Martin Peinado and van Gestel, 2015). In this case, soil quality standards or threshold values must be corrected, taking into account soil properties such as pH, soil texture and organic matter content, because it has been widely demonstrated that in many cases quality standards that do not consider soil properties under- or overestimate the actual risk (Appel and Ma, 2002; Bradl, 2004; Rodrigues *et al.,* 2012; Romero-Freire, Martin Peinado and van Gestel, 2015). In addition, by analyzing and including bioavailability during risk assessment instead of assuming that the target pollutants are 100 percent bioavailable, remediation efforts will be optimized and enhance profitability of the remediation efforts (Naidu *et al.,* 2015; Romero-Freire, Martin Peinado and van Gestel, 2015).

It is therefore crucial to develop regulations and legislation to certify the quality of food depending on its heavy metal content. The international literature contains multiple methodologies and evaluation criteria that identify permissible heavy metal values for soils that differ in magnitude (Table 7). This is generally due to the criteria considered for their establishment (Muñiz, 2008). The obtaining of reference values for soil quality in terms of heavy metal content has been established in many countries, which developed their respective environmental policies for soil protection and food safety assurance. The one developed by USEPA (US EPA, 1998, 2014a) is especially important because several other countries follow it. These standards are based on risk assessment policies and define background levels and the study of human and environmental toxicity. When it comes to food, the FAO Codex Standard is of major importance. It defines the values for contaminants and toxins (including heavy metals) permissible in food products, and it is constantly being reviewed and updated (WHO and FAO, 1995).

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Table 7. Threshold values of some heavy metals for residential land-use for various countries.
Modified from Provoost, Cornelis and Swartjes, 2006

Contaminant (mg/kg dm)	Belgium[1]	France	Germany[2]	Great Britain + plant[3]	Great Britain – plant[4]	Hungary[5]	Netherlands	Poland[6]
Arsenic	110	37	50	20	20	15	55	2
Cadmium	6	20	20	8[10]	30	1	12	4
Chromium III	300	130[11]	400	130	200	75	380	--
Copper	400	190	N.A.	N.A.	N.A.	30	190	150
Mercury	15	7	20	8	8	0.5	10	--
Lead	700	400	400	450	450	100	530	100
Nickel	470	140	140	50	75	40	210	--
Zinc	1000	9000	N.A.	N.A.	N.A.	200	720	300

1 Soil Remediation Decree named Vlarebo from July 8, 2002

2 Standards applicable as national legislation for 'wirkungspad Boden-Mensch' (exposure path soil — humans)

3 Residential area with vegetable garden

4 Residential area without vegetable garden

5 Hungarian Governmental regulation number 10/2000

6 Polish soil quality standards for the top soil layer (0-30 cm), established for the group B of land use (agricultural lands, forest, residential and recreational areas) Regulation 2002

7 Royal Decree 1310/1990 of 29 October 1990 regulating the use of sewage sludge in agriculture. (B. O. E. No. 262, November 1,1990). Values for soils with pH lower or higher than 7.

8 GUIDELINE ON Investigation Levels for Soil and Groundwater. National Environment Protection (Assessment of Site Contamination) Measure as varied 2011.

9 SEPA (1995) Environmental quality standards for soils. State Environmental Protection Administration, China, GB 15618-1995

10 1/2/8 mg/kg dm related to the soil clean-up standards at pH 6, 7, 8, respectively. The clean-up standard of 8 mg/kg dm was used in this comparison.

11 Chromium total

12 Chromium (VI)

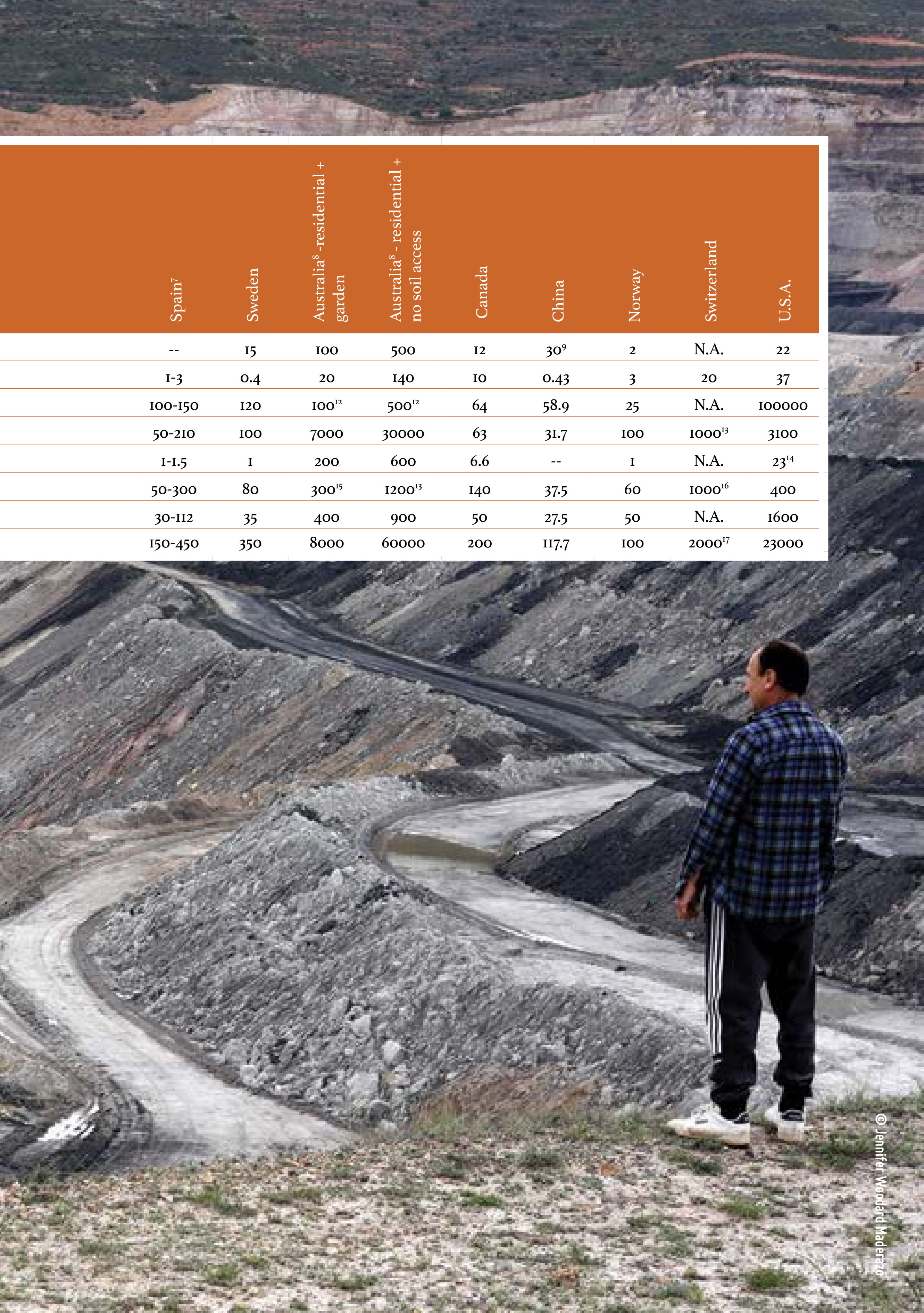
13 1000/4 related to the soil clean-up standard as total concentration and soluble concentration. The clean-up standard of 1000 mg/kg dm was used in this comparison.

14 23/6.1 describes the chlorinated mercury and organic-mercury. The clean-up standard of 23 mg/kg dm was used in this comparison.

15 HIL for lead based on blood lead models (IEUBK for HILs A, B and C and adult lead model for HIL D where 50% oral bioavailability has been considered)

16 1000/0.1 related to the soil clean-up standard as total concentration and soluble concentration. The clean-up standard of 1000 mg/kg dm was used in this comparison.

17 2000/5 related to the soil clean-up standard as total concentration and soluble concentration. The clean-up standard of 2000 mg/kg dm was used in this comparison.



Spain[7]	Sweden	Australia[8] -residential + garden	Australia[8] - residential + no soil access	Canada	China	Norway	Switzerland	U.S.A.
--	15	100	500	12	30[9]	2	N.A.	22
1-3	0.4	20	140	10	0.43	3	20	37
100-150	120	100[12]	500[12]	64	58.9	25	N.A.	100000
50-210	100	7000	30000	63	31.7	100	1000[13]	3100
1-1.5	1	200	600	6.6	--	1	N.A.	23[14]
50-300	80	300[15]	1200[13]	140	37.5	60	1000[16]	400
30-112	35	400	900	50	27.5	50	N.A.	1600
150-450	350	8000	60000	200	117.7	100	2000[17]	23000

Frank Vincentz

3.2 | MAIN TECHNIQUES FOR REMEDIATING POLLUTED SITES

Nathanail referred to sustainable remediation as "remediation that eliminates and/or controls unacceptable risks in a safe and timely manner, and which maximizes the overall environmental, social and economic benefits of the remediation work" (Nathanail, 2011). Sustainable management requires the incorporation of the best available techniques, not only during the remediation process itself, but for the whole process, including risk assessment and risk reduction. Best management practices (BMPs) are individual or combinations of management, cultural and structural practices that researchers (academic or governmental) have identified as the most effective and economical way of reducing damage to the environment (Cestti, Srivastava and Jung, 2003). Remediation is commonly done on a site-by-site basis, since for every combination of pollutant, soil property, land use, property and liability regimes and technical and economic reality of the site or area, a different technique or combination of techniques may be more appropriate (Swartjes, 2011).

Remediation techniques can be divided in two main groups: *in situ* (on the site) and *ex situ* (removal of contaminated soil for treatment off the site) remediation. Available remediation options include physical, chemical and biological treatments, and these options offer potential technical solutions to most soil pollution (Scullion, 2006). For both *in situ* and *ex situ*, the net effect on the contaminants can be categorized as reducing the concentration, reducing the bioavailability without reducing the concentration, encapsulating in an inert matrix, containment, and removal (Pierzynski, Sims and Vance, 2005). The management of polluted sites is a site-specific approach that includes characterization, risk assessment and remediation technologies selection, and therefore is mainly focused on local or point-source contamination.

Scullion presented a review of the main treatment approaches to remediate polluted soils and their effect on pollutants (Scullion, 2006), specifying whether they are degraded, separated from soil components, extracted from the matrix or stabilized (Table 8).

Table 8. Main remediation methodologies and their effects on soil pollutants (√ = main process, (√) = subsidiary process limited in extent or in the range of pollutants affected). Source: Scullion, 2006

Process treatment	Destruction/ degradation	Solid separation	Extraction/ loss	Stabilisation
Physical remediation methodologies				
Thermal	√		√	
Solidification	(√)			√
Vapour extraction			√	
Air sparging	(√)		√	
Washing/pump and treat	(√)		√	
Electroremediation	(√)		√	
Particle sorting		√		
Chemical remediation methodologies				
Oxidation	√		√	√

Process treatment	Destruction/ degradation	Solid separation	Extraction/ loss	Stabilisation
Reduction	(√)		√	√
Hydrolysis	√		√	
Solubilisation	(√)		√	
Dechlorination	(√)			
pH manipulation	(√)		√	√
Biological remediation methodologies				
Microbial activity				
Landfarming	√		(√)	√
Biopiling	√		(√)	√
Composting	√		(√)	√
Bioreactor	√			(√)
Bioleaching			√	
Plant activity				
Phytostabilisation	(√)		(√)	√
Phytoextraction	(√)		√	(√)
Phytodegradation	√		(√)	(√)

What makes many of the currently available physical methods so expensive is partially the cost of excavating and transporting large quantities of contaminated materials for *ex situ* treatment such as chemical inactivation or thermal degradation. The high cost has led to an increasing interest in alternative technologies for *in situ* applications, in particular those based on the biological remediation capability of plants and microorganisms (Chaudhry *et al.*, 2005). Bioremediation is a technology that destroys or renders harmless various contaminants, using the biological activity of certain microorganisms. Bioremediation actually relies on the microbial growth and activity; its effectiveness is highly dependent on the applied environmental parameters that influence the microbial growth and the degradation rate. Bioremediation is considered a very promising technology with great potential when dealing with certain types of contaminated sites (Zouboulis, Moussas and Nriagu, 2011). Bioremediation has been used worldwide, including in Europe, with varying success (Zouboulis, Moussas and Nriagu, 2011).

According to Alexander, several conditions must be satisfied for bioremediation by microbial activity to take place in the soil (Alexander, 1999). These include the following: 1) the organism must be present in the soil containing the pesticide; 2) an organism must have the necessary enzymes to bring about the biodegradation; 3) the pesticide must be accessible to the organism having the requisite enzymes; 4) if the initial enzyme bringing about degradation is extracellular, the bonds acted upon by that enzyme must be exposed for the catalyst to function; 5) should the enzymes catalyzing the initial degradation be intracellular, that molecule must penetrate the surface of the cell to the internal sites where the enzyme acts; and 6) because the population or biomass of bacteria or fungi acting on many synthetic compounds is initially small, conditions in the soil must be conducive to allow proliferation of the potentially active microorganisms.

Compost made from sawdust, wood chips, bark, straw, plant waste and food waste from households is another common source of organic matter to be added to the soil (Kuo *et al.*, 2004). Addition of organic matter to the soil may help to decrease the mobility of heavy metals and other pollutants (Grobelak and Napora, 2015; Wuana and Okieimen, 2011), reducing the risk to the environment and to human health.

The addition of manure and sewage sludge can be an effective bioremediation tool, but care needs to be taken to ensure that effective pre-treatment of the organic material has occurred. To attenuate the negative impacts associated with livestock manure, simple techniques such as composting can be applied before their application to the land (Zhang *et al.*, 2015a). Compared to fresh manure, composted manure generally has higher contents of lignin and polyphenol, which reduces CH_4 emission while further enhancing the potential of SOC sequestration (Xia, Wang and Yan, 2014). Lv *et al.* observed a positive effect of worms present in the composting process, resulting in the stabilization of heavy metals present in animal manure (Lv, Xing and Yang, 2016). The composting of fresh manure has been proven as an effective method for reducing various types of environmental pathogens and antimicrobial resistant bacteria (Cole, 2015; Holman *et al.*, 2016). Storing slurries for one to three months, composting at high temperatures, spreading in a manner that reduces potential volatilization and avoiding long-distance transport of manure are some of the recommendations proposed by Nicholson *et al.* in order to reduce pathogen levels in manure and slurries prior their land application (Nicholson *et al.*, 2003). Despite the observed persistence of certain antibiotics in soil and their negligible mineralization due to strong sorption to soil components, several authors highlight the importance of storage time and composting for dissipation of antibiotic compounds in manure before land application (Arikan, Mulbry and Rice, 2009; Halling-Sørensen *et al.*, 2001; Kim *et al.*, 2011; Tien *et al.*, 2017).

The planting of trees that have good resistance to high levels of toxic substances and a high capacity to collect and store pollutants can also be a good practice for bioremediation process in soils (Paz-Alberto and Sigua, 2013). According to Wisłocka *et al.*, the most popular trees exhibiting a high capacity to accumulate heavy metals are silver birch (*Betula pendula*), alder (*Alnus tenuifolia*), black locust (*Robinia pseudoacacia*), willow (*Salix sp.*), and conifer trees (Wislocka *et al.*, 2006). Selected energy crops such as *Miscanthus giganteus* have excellent adaptability to change habitat conditions, the possibility to gradually reclaim degraded lands, and the ability to prevent the migration of heavy metals into the soil and groundwater.

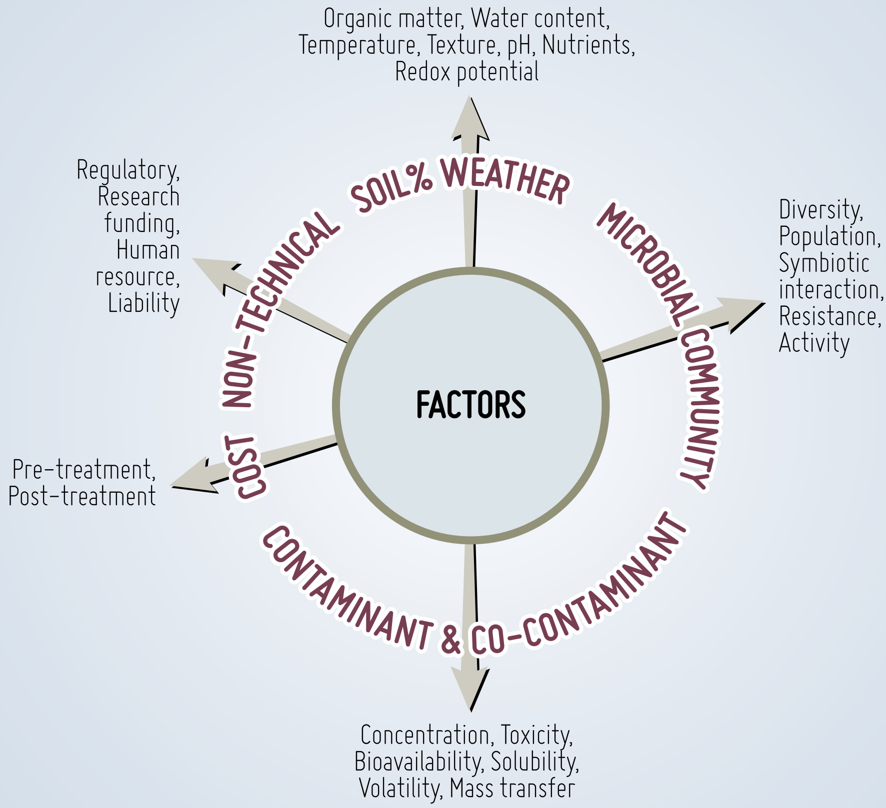


Figure 21. Factors affecting field-scale remediation of PAH-polluted soils. Source: Kuppusamy *et al.*, 2017

Interest in biochar is also growing among scientists, who are particularly interested in how the chemical and physical properties of biochar particles affect water moving through soil, remove pollutants, alter microbial communities and reduce emissions of greenhouse gases. The hope is that biochar can help farmers around the world, particularly those in developing regions who often struggle with poor soils. Biochar has ancient roots. Hundreds to thousands of years ago, residents of the Amazon produced it by heating organic matter to create rich, fertile soils called *terra preta*. The practice was abandoned around the time that European nations invaded South America, and relatively few farmers elsewhere have routinely used biochar. Scientists first took an interest in the material about a decade ago, when growing concerns over global warming led some to tout biochar as a way to store huge amounts of carbon underground. Hope for that application has faded somewhat due to the high cost of biochar, but soil scientists are now exploring its use in agriculture and in remediating soil pollution (Cernansky, 2015).

New technologies for remediation involve the application of nanoparticles for remediating polluted soils (Pan and Xing, 2012). The most widely recognized nanotechnology in soil remediation is the application of nano-zero-valent iron (nZVI) for reducing the impact of both organic and inorganic pollutants. For example, nZVI can effectively degrade chlorinated hydrocarbons and organochlorine pesticides (Singh *et al.,* 2011; Zhanqiang, 2010). Carbon nanotubes have been demonstrated to be a feasible remediation material because of their large sorption capacity for metal ions (Rao, Lu and Su, 2007), radionuclides (Ren *et al.,* 2011) and organic compounds (Pan and Xing, 2008).

Integrated approaches and emerging technologies, such as electrokinetic remediation, enzyme-mediated bioremediation, multi-process phytoremediation and vermiremediation have been employed in the treatment of PAH-contaminated soils (Kuppusamy *et al.,* 2016). The selection of the best available techniques and their success in remediating polluted soils will depend on physical, economical, regulatory and technical factors (Figure 21) (Kuppusamy *et al.,* 2017).

The critical factor affecting remediation of PCBs, PAHs and PBDEs is the strong sorption of these molecules on soil and sediments, as demonstrated by their long persistence despite heavy restrictions on their use for over 30 years. The ability to desorb these contaminants determines, in most cases, the effectiveness of remediation technologies (Gomes, Dias-Ferreira and Ribeiro, 2013). The most commonly used remediation technique for these polluted soils is "dig-and-dump," but this is not sustainable. Other techniques such as bioremediation, thermal desorption, and anaerobic dechlorination have been tested in recent years with good results (Gomes, Dias-Ferreira and Ribeiro, 2013). The technologies previously described, although aiming to destroy or transform PCB, operate in very different ways and consequently have different clean-up times, costs, breakdown products and environmental impacts. Their effectiveness is also site-specific, since each technology depends on the contaminants, the aging of the contamination, the type of soil and geomorphologic conditions, and other environmental factors such as mobility of the contaminants or sorption to soil particles (Gomes, Dias-Ferreira and Ribeiro, 2013; Wang and He, 2013).

3.3 | CHANGES IN AGRONOMIC PRACTICES TO MINIMISE FOOD-CHAIN CONTAMINATION AND IMPACTS ON ECOSYSTEM SERVICES

The Voluntary Guidelines for Sustainable Soil Management (VGSSM) aim to provide countries, farmers and other stakeholders with generally accepted, practically proven and scientifically based principles to promote sustainable soil management (SSM) (FAO, 2017). These guidelines describe SSM as follows: "Soil management is sustainable if the supporting, provisioning, regulating, and cultural services provided by soil are maintained or enhanced without significantly impairing either the soil functions that enable those services or biodiversity." SSM are related to the agronomic practices cited in this chapter. (FAO, 2017. Voluntary Guidelines for Sustainable Soil Management. Food and Agriculture Organization of the United Nations. Rome, Italy).

3.3.1 | FERTILIZERS

Integrated crop management (ICM) is a method of farming that balances the requirements of running a profitable business with responsibility and sensitivity to the environment. It presents a realistic solution to many of the problems facing agriculture. It includes practices that can be used to avoid waste, enhance energy efficiency and minimise pollution. Integrated crop management combines the best of modern technology with some basic principles of good farming practice and is a whole-farm, long-term strategy (EC, 2002).

Components of ICM for field crops are as follows:

1- Quantify nutrient source: soil reserve, manure, crop residue ;

2- Soil test: pH, lime requirement, phosphorus, potassium (calcium and magnesium optional);

3- Manure analysis: nitrogen (ammonium N, total N), phosphorus, potassium;

4- Calibration of manure and fertilizer spreaders: tonnes, 1000's gallons, lbs. per acre;

5- Fertilization plan: manure application rate, supplemental fertilizer; utilize excess manure on alternative crops (hay crops); avoid applying large amounts of manure on fields with excessive P found using soil tests; do not over apply nitrogen from manure or fertilizer, and nitrogen soil test: side- or top-dressing supplemental nitrogen fertilizer;

6- Cover crop: to reduce soil loss and nitrate leaching; consider a legume-based cover crop on vegetable farms and on distant fields on dairy farms where manure is not spread;

7- Planting plan: to ensure early harvest of crops to allow early cover crop planting on most erosion prone fields; and

8- Minimum tillage: to reduce nutrient loss through soil erosion.

Integrated Soil Fertility Management is an approach based on the following principles: 1) Neither practices based solely on mineral fertilizers nor solely on organic matter management are sufficient for sustainable agricultural production; 2) well-adapted, disease- and pest-resistant germplasm is necessary to make efficient use of available nutrients; and 3) good agronomic practices – in terms of planting dates, planting densities, and weeding – are essential for ensuring the efficient use of scarce nutrient resources (CGIAR and CCAFS, 2018). There is also a need to target nutrient resources within crop rotation cycles, preferably including legumes, thus going beyond recommendations for single crops.

Integrated nutrient management can play a role in improving plant growth. Dry matter partitioning and total crop biomass (Amanullah and Inamullah, 2016; Amanullah *et al.,* 2016), including root biomass (Amanullah and Stewart, 2013), have a significant impact on the efficiency of phytoremediation processes of degraded soils (Grobelak, 2016). Maintaining organic carbon-rich soils, restoring and improving degraded agricultural lands and, in general terms, increasing the soil carbon content all play an important role in addressing the three-fold challenge of food security, adaptation of food systems and people to climate change, and the mitigation of anthropogenic emissions (UNFCCC, 2015).

Bio-fertilizers, products containing living cells of different types of beneficial microbes (bacteria, fungi, protozoa, algae and viruses), are known to play a number of vital roles in soil fertility, crop productivity and profitability. Some of the more commonly used beneficial microbes in agriculture include *Rhizobia, Mycorrhizae, Azospirillum, Bacillus, Pseudomonas, Trichoderma, and Streptomyces* species. Beneficial microbes are essential for decomposing organic matter in the soil and for increasing the availability of essential macro-nutrients (nitrogen, phosphorus, potassium, sulfur, calcium and magnesium) and micro-nutrients (boron, copper, chlorine, iron, manganese, molybdenum and zinc) to crop plants. Beneficial microbes also play a significant role in solid waste and sewage management. Beneficial microbes increase plant tolerance to different environmental stresses (e.g. drought, heat, cold, salinity) and increase plant resistance to insects and disease. Beneficial microbes not only improve crop growth and productivity by increasing photosynthesis and producing hormones and enzymes, but also improve crop quality by controlling different insects and various plant diseases. Beneficial microbes reduce the need for the use of chemical fertilizers and thereby reduce environmental pollution caused by chemical fertilizers. They reduce the cost of production and therefore increase the grower's income and profitability. Beneficial microbes are very important in increasing crop productivity, profitability and sustainability. Applications of organic manures such as animal manure, poultry manure, green manure, composts, farm yard manure, biochar, and ash increase the beneficial microbes in the soil and improve soil health and overall sustainability (Amanullah, 2015).

3.3.2 | PESTICIDES

For achieving a pollution-free world, the Voluntary Guidelines for Sustainable Soil Management (FAO, 2017), which include integrated or organic pest management practices, are recommended worldwide.

Integrated pest management (IPM) is an approach based on prevention, monitoring, and control that offers the opportunity to eliminate or drastically reduce the use of pesticides, and thus reduce the risks of pesticide to human health and the environment. Integrated pest management does this by utilizing a variety of methods and techniques, including cultural, biological and structural strategies to control a multitude of pest problems (Beyond Pesticides, 2018). Moreover, IPM encourages the use of crop rotations, which can considerably lower the need for pesticides (García-Préchac *et al.*, 2004).

In intensive agroecosystems, the most common practice of using pesticides is the spray application, although other application systems like seed treatment, granules applied on the ground or soil drenching as well as soil fumigation. Up to 30–50 percent of the amount applied is lost by deposition on the ground, via spray drift to neighboring environmental compartments, or volatilized, not reaching the target pest (Diaconu *et al.*, 2017; Viret *et al.*, 2003). The "polluter pays" principle (adding the environmental and public health costs to the price paid by consumers) can be an effective approach to internalizing the social costs of pesticide use. The fees and taxes generated can be used to promote improved (sustainable) pest management (Popp, Pető and Nagy, 2013). Controlling the misuse of pesticides along with promoting more environmentally-friendly techniques, such as biological pest control (Popp, Pet and Nagy, 2013), can contribute to reducing contamination in agricultural fields.

Integrated weed management (IWM) is the control of weeds through a long-term management approach, using several weed management techniques such as physical control, chemical control, biological control and cultural control.

As noted in earlier sections, the most widespread type of contamination of soils that could adversely affect food quality is related to metals, metalloids and radionuclides. This has contributed to a wealth of studies examining agricultural practices to reduce food-chain contamination by these pollutants. As pollution of soils by organic chemicals is generally more restricted in areal extent, much less research has been conducted on these chemicals and they are not considered further here.

3.3.3 | METALS

Cadmium (Cd) is the most widely studied metal in terms of food-chain contamination, and there are a number of options to minimise plant uptake of Cd from soil (Grant *et al.*, 1999). They are summarised in Table 9 and can be grouped into manipulation of crops (species, cultivar and rotation), of soil conditions and of water (irrigation) attributes.

Table 9. Agronomic management practices to reduce food-chain contamination by Cd.

Crop manipulation	Soil manipulation	Water manipulation
Plant species	Site selection	Use low (Cl) salinity water
Plant cultivar	Cultivation (dilution/burial)	
Crop rotation	Lime addition	
Phytoextraction	Zinc addition	
	Sorbent addition	

It has been known for over 40 years that different species vary in their ability to accumulate Cd in edible portions. Leafy vegetables, for example, generally accumulate higher concentrations of Cd than do grain or fruit crops (Bingham *et al.*, 1975; Chaney and Hornick, 1977). Farmers have the option to change the type of crops grown in a specific plot of land if the soil is Cd polluted. If this is not a possibility, it is still possible to grow the same crop species if a lower-accumulating Cd cultivar is chosen. It is well known that different cultivars of the same species accumulate Cd at different rates, and this may be related to different rooting patterns, different root uptake of Cd, or different patterns of Cd translocation within the plant (Grant *et al.*, 2008). Commercialisation of specially bred low-Cd-accumulating cultivars has ensued in some countries (Clarke *et al.*, 1997), while in others, farmers can choose a low-Cd cultivar from the commercially available ones (where this information is accessible). Food-chain contamination by Cd can also be minimised by selecting an appropriate crop rotation plan: there is evidence that certain sequences of crops (e.g. wheat grown after lupin crops) (Oliver *et al.*, 1993) may encourage more Cd accumulation, although the reasons for this are not clear and may be related to the modification of soil chemical or physical conditions (e.g. changes in soil pH). Finally, farmers may also choose to grow a crop to extract available Cd from the soil (phytoextraction) and dispose of the plant material before growing a food crop (Murakami *et al.*, 2009). This strategy is now maturing to the stage of being practically possible (Abe *et al.*, 2017).

Selection or manipulation of soil chemical and physical conditions is also practised by farmers to minimise food-chain accumulation of Cd. Selection of soil conditions is effected through site selection (if possible); soils higher in pH, clay, organic matter, zinc (Zn) and lower in Cd are more likely to have minimal accumulation of Cd in crops (Grant *et al.*, 1999). If site selection is not possible, soil manipulation may be attempted. As Cd is a cationic metal, the addition of lime to raise soil pH and increase the cation-exchange capacity of soil can be used to increase soil sorption and reduce crop uptake, although effects are not consistent in field studies. Acting through similar mechanisms, sorbents can be added to soils to bind Cd more strongly and minimise its uptake by crops (Komárek, Vaněk and Ettler, 2013; Tang *et al.*, 2016), although high application rates are usually needed (tonnes per hectare) and the longevity of the remediation is unknown. The addition of Zn has also been shown to reduce crop Cd concentrations (Oliver *et al.*, 1994) through a competitive uptake of Zn over Cd for loading into edible portions (Welch *et al.*, 1999). Finally, if the Cd contamination is anthropogenic and not geogenic, it is likely that contamination is restricted to the surface soil layer. As for many contaminants, cultivation and burial or dilution of the contaminated layer can reduce Cd uptake by crops, as most crop roots are active only in the top 10–20 cm of soil.

Avoidance of irrigation waters rich in Cl will also reduce food chain contamination by Cd, due to chloro-complexation of the Cd^{2+} ion that increases mobility in soil and hence increases plant Cd uptake (McLaughlin *et al.*, 1994).

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3.3.4 | METALLOIDS

Arsenic (As) is the most widespread and serious metalloid pollutant in agricultural soils, with geogenic sources being more widespread than anthropogenic sources (Bhattacharya *et al.*, 2007). Food-chain contamination by As occurs principally in flooded rice-based cropping systems, where the low redox conditions in flooded paddy soils mobilizes As by solubilising iron-oxide minerals that bind to As, and also reducing the arsenate ion to arsenite, which is more mobile in soil than arsenate (Hamon *et al.*, 2004). Due to these soil chemical reactions and root uptake pathways, accumulation of As in rice can be minimised through careful water management (raised beds, mid-season drainage or dryland cultivation) to increase soil redox (Hu *et al.*, 2013) and the addition of Si fertilizers. However, the disadvantage of aerobic rice cultivation is that Cd accumulation may be increased compared to flooded rice cultivation (Hu *et al.*, 2013). Cultivar differences can also be exploited to reduce As in harvested rice grain (Norton *et al.*, 2009).

3.3.5 | RADIONUCLIDES

Agronomic practices to reduce accumulation of radionuclides in the food chain are derived principally from research surrounding the Chernobyl, Goiănia and Fukushima nuclear accidents (Fesenko *et al.*, 2017). The main isotopes of concern are ^{131}I in the early period following the contamination event, and caesium and strontium isotopes (^{134}Cs, ^{137}Cs and ^{90}Sr) for many years after contamination. Iodine-131 is a short-lived isotope (half-life 8.02 days) and the main risk pathway is the forage-cow-milk-human chain. Hence the main agricultural management practices needed immediately following a contamination event with ^{131}I are to restrict access of animals to contaminated pastures, by feeding them from sources outside of the zone of contamination (if possible). For the radioisotopes of Cs and Sr, being cationic, remediation measures are similar to those for Cd where differences in crop species and cultivar, use of sorbents with high CEC, liming and fertilizer management can be employed (Fesenko *et al.*, 2007). For Cs, potassium-based fertilizers are particularly effective in reducing uptake by plants due to competition of K^+ with Cs^+ for root uptake (Shaw, 1993), while calcium-based amendments are effective for ^{90}Sr (Nisbet *et al.*, 1993). Ammonium-based fertilizers should be avoided as they may enhance uptake of ^{37}Cs and ^{90}Sr (Guillén *et al.*, 2017). Soil inversion/ploughing or soil removal may also be used to dilute or reduce isotope concentrations in soil and/or to bury the surface contamination into deeper layers (Fesenko *et al.*, 2017).


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4 | CASE STUDIES ON SOIL POLLUTION AND REMEDIATION

4.1 | REMEDIATION BY ENHANCED NATURAL ATTENUATION OF POL POLLUTED SITES IN UN FIELD MISSIONS: A CASE STUDY ON THE UNITED NATIONS OPERATION IN CÔTE D'IVOIRE (ONUCI)[18]

The consumption of petroleum oil and lubricants (POL) in field missions is inevitable due to their use in generating electricity and operating mechanical equipment to support peacekeeping operations. Through these processes, which have a major environmental footprint, the potential of soil contamination arises. This section presents a case study of remediation work conducted by Global Service Centre/Environmental Technical Support Unit on POL polluted sites during the liquidation of a United Nations field operation in Côte d'Ivoire (ONUCI).

The goal of the project was to reduce the level of total petroleum hydrocarbon (TPH) in polluted soil (36 000 to 75 000 mg/kg) to a background TPH level of 400 to 1 000 mg/kg, providing an enabling environment for revegetation of plants. The project entailed the removal of over 1 200 tonnes of POL contaminated soil from sites and replacing it with fresh soil. The excavated contaminated soil was treated using naturally occurring materials derived locally.

The contaminated soil was deposited in a large concrete mixer to tumble and aerate in order to promote microbial growth and the breaking down of POL. Two ingredients (poultry waste and naturally occurring surface active materials (NOSAM) or palm ash soap (also known as black soap)) were added to the mix to improve the condition of the soil and to accelerate the microbial remediation.

The result showed a reduction of over 95 percent in TPH levels immediately after remediation, with natural microbial activities ensuring more reduction in TPH within a 14-day period. Native grasses were planted in the restored areas. The case study highlights the importance of implementing low cost remediation techniques in mitigating POL polluted sites within the UN field missions.

18 Environmental Technical Support Unit (ETSU) (GSC Environmental Technical Support Unit, Apulia, Italy)

4.2 | CONTEMPORARY APPROACHES TO REMEDIATION OF OIL-POLLUTED LANDS IN THE TAIGA ZONE OF WESTERN SIBERIA[19]

The Russian Federation occupies one of the leading places in oil production over the globe. More than 70 percent of Russian Federation oil is extracted in the Taiga zone of western Siberia. In the 1990s oil-production enterprises of this region experienced a drastic increase in pipeline accidents and oil pollution of ecosystems. Under conditions of insufficient state control over statutory compliance of environmental protection legislation, this led to a significant number of oil-polluted lands that have not been remediated for a long time, forming a so-called "historical heritage" for new companies that are currently producing oil on this territory.

Oil companies have made significant efforts to restore oil-polluted lands in the last 10–15 years, but this problem has not been completely resolved. This is mostly due to the special environmental conditions of the region: the average annual temperature ranges from -0.1 °C to -5 °C, the average temperature in January is -18 °C to -24 °C (with the recorded minimum as -62 °C); the duration of the period with a stable snow cover achieves 180–200 days; and precipitation significantly exceeds evaporation. The West Siberian lowland is a vast, weakly dissected plain, which experienced active development of swamp formation during the Holocene epoch: in some areas, swamps cover 90 percent of the territory. Spills therefore occur mainly in wetland ecosystems, which greatly complicates the use of machinery for reclamation operations.

Not only were there unfavourable weather conditions, but remediation technologies were applied that were not appropriate for wetland soils, as they were originally developed for mineral soils. Basic technological solutions included surface oil pickup (if any), agrotechnical practices (liming, mineral fertilization), biostimulation (activation of native oil-oxidizing microorganisms) or bioaugmentation (application of commercial bio-products with oil-oxidizing action), periodic loosening and phyto-melioration (sowing of meadow grasses). However, for remediation of oil-contaminated peat bog soils, some other approaches were needed.

Peat soils have a very high sorption capacity to oil. It is therefore difficult to collect spilled oil even immediately after the spill, and after thickening of the oil it is impossible. At the same time, the concentration of oil hydrocarbons in the upper, most contaminated part of the peat bog soil profile can reach 80 percent or more, which is significantly higher than the levels that oil-destructive microorganisms can consume. The above-described traditional technological solutions are therefore ineffective, even after being repeated for several processing seasons.

Effectiveness of reclamation is significantly increased if mechanical removal (shearing) of the uppermost contaminated layer (usually 10–15 cm) is performed in the oil-contaminated area first. In this layer, in addition to heavy oil hydrocarbons, a large number of resins and asphaltenes accumulate. This accumulation effectively seals the soil, preventing water and gas transfer. This in turn drastically decreases microbiological activity in the contaminated soil. At the initial stage of implementation of this technological operation, manual labour was used. This explains why despite the high efficiency of remediation on certain oil-contaminated sites, the total area of reclaimed land remained low.

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Figure 22. Work of floating excavator (Pxhere)

Later, when this technological operation started being conducted using excavators (Figure 22), it became possible to multiply the total area of oil-contaminated lands reclaimed annually.

After the removal of the upper layer, the concentration of oil hydrocarbons in soils usually does not exceed the levels at which activity of microbial oil destructors is impossible; this allows using the traditional methods of biological reclamation. However, a further decrease in oil hydrocarbons concentration up to acceptable levels is still a difficult task.

One of the most important problems is the optimization of soil acid–base regime. It is known that the optimal pH values for the activity of bacterial oil destructors are 6–8. But peat soils, as a rule, have pH values of 3.5–4.5 and are characterized by high values of exchangeable and pH-dependent acidity. The amount of lime that must therefore be added to achieve optimal pH values is so great that it makes this task technically and economically unfeasible and unreasonable.

One of the ways to solve this problem is by using biodegradation agents, which are capable of oxidizing hydrocarbons at pH 4–4.5. For effective oil destruction, however, it is necessary to provide a proper aeration of bog peat soils, which is extremely difficult to achieve in practice. To overcome this problem, it seems very promising to use a combination of bioaugmentation and phyto-melioration technologies (Glick, 2003; Khan *et al.*, 2013). This combination will provide a symbiotic interaction between microorganisms in biodegradation agent and bog plants, which have an ability to transport air to the root system via arenchyma, followed by diffusion of air oxygen into the rhizosphere, which would provide the possibility for oil oxidation by oil-destructive bacteria.

In addition to providing oxygen, plants can stimulate functioning of microbiota in the rhizosphere via root exudates (Bais *et al.*, 2006). In turn, bacteria can stimulate plant development by producing various phytohormones and anti-stress substances (Safronova *et al.*, 2006), thus allowing plants to grow even in conditions of heavy oil pollution. Moreover, bacteria can fix molecular nitrogen, mobilize hydrolysable phosphates, and produce siderophores, which can also promote plant development. Currently, however, the biodegradation agents possessing all the above functions have not been produced. This makes the task of development and practical implementation of appropriate biodegradation agents extremely urgent, as is the development of seed breeding of bog plants typical for the Taiga zone of Western Siberia.

4.3 | AIDED PHYTOSTABILIZATION: AN EFFECTIVE REMEDIATION TECHNIQUE FOR TAILINGS IN SE SPAIN[20,21]

Mining has been present in Sierra Minera de Cartagena–La Unión (Murcia, Spain) for more than 2 500 years. This activity has generated large amounts of tailings from the exploitation of mineral sulfides (mainly ZnS and PbS). Tailing ponds were abandoned after the cessation of the activity in 1991 and are of great concern due to the risk associated with the high content of toxic metal(loid)s.

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Moreover, these tailings have low fertility, low organic matter content and high acidity. Therefore, the establishment of native vegetation is very difficult unless organic and/or inorganic amendments are applied (García and Lobo, 2013). Phytoremediation is considered an economic and environmentally-conscious method to remediate polluted soils (Wan, Lei and Chen, 2016). Among phytoremediation techniques, aided phytostabilization can be a solution to reduce the risk of pollutant dispersion (Yang *et al.,* 2016). Several amendments have been proposed to stabilize metal(loid)s in soils (Kumpiene, Lagerkvist and Maurice, 2008). Organic amendments and materials rich in carbonates have been successfully used to reduce the bioavailability of metals and to restore the ecological function of contaminated soils (Park *et al.,* 2011).

The main goal of this study was to determine the effectiveness of aided phytostabilization applied to a tailings pond from Zn/Pb mining 30 months after its reclamation. The effectiveness was evaluated by monitoring physicochemical and biochemical properties and bioavailable metal(loid) (As, Cd, Pb and Zn) contents in the tailings. In addition, the metal(loid) translocation to plant species (root, stem and leaf) and evolution of plant communities were also evaluated. The initial hypothesis was that the implementation of phytostabilization with native plant species with inorganic and organic amendments would decrease the mobility of metal(loid)s, decrease the risks for environment and public health, and increase soil quality and fertility and vegetation cover. Plants should accumulate high contents of metal(loid)s in their roots with low translocation to shoots.

The study was performed in Santa Antonieta tailings pond, located in Cartagena–La Unión mining district. The pond has a surface of 1.4 ha. Marble waste was used as a source of carbonates to neutralize acidity, immobilize metals and develop soil structure. Pig slurry and its solid phase (manure) after physical separation was used as a source of organic matter and nutrients for soil development and vegetation establishment.

The following species were planted in 2012: *Atriplex halimus* L., *Cistus albidus* L., *Helichrysum stoechas* (L.) Moench., *Hyparrhenia hirta* (L.) Stapf., *Lavandula dentata* L., *Lygeum spartum* (L.) Kunth., *Rosmarinus officinalis* L., *Phagnalon saxatile* (L.) Cass, *Piptatherum miliaceum*, *Cynodon dactylon*, *Limonium caesium*, *Sonchus tenerrimus*, and *Atriplex halimus.*

The results of the study showed that the combination of marble waste, pig slurry and manure was efficient for the reclamation of an acidic tailings pond by aided phytostabilization. The technique increased soil pH, CEC, TOC and nutrients content, improved soil structure and reduced the mobility of metals, mainly Cd, Pb and Zn up to 90–99 percent. *Lygeum spartum* and *Piptatherum miliaceum* were effective in phytostabilization of Pb, Zn and As, since they accumulated high metal concentrations in roots, with low aerial translocation. *Atriplex halimus* and *Phagnalon saxatile* presented phytotoxic concentrations of Zn in leaves. Therefore, the use of these species should be avoided in soils contaminated with high concentrations of Zn.

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