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Co-funded by the European Union

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Annex II

"Toolbox" with innovative on-site techniques for effective environmental site assessment

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Guidelines for assessing soil organic matter status using Pedotransfer Functions (PTFs) and Visual Soil Assessment (VSA)

Decline of soil organic matter (SOM) is widely recognized as one of the most sensitive indicators of soil degradation because SOM plays a central role in regulating nutrient cycling, water retention, soil structure, microbial activity, and carbon sequestration (Lal, 2025). Calculating soil organic C stocks (Mg C ha^{-1}) from C concentrations requires information on soil bulk density. However, bulk density measurements are often missing from soil datasets, limiting the estimation of C stocks and their comparison across sites and soil depths. Pedotransfer functions (PTFs), developed and validated under local conditions, can help address this gap by estimating bulk density from more readily available soil properties, such as texture and organic C content.

Another easy method to assess soil condition and identifying signs of degradation is the Visual Soil Assessment (VSA) [2]. VSA is an effective and internationally recognized diagnostic tool for assessing soil quality through visual indicators of key physical, biological, and chemical soil properties, providing immediate feedback on soil conditions.

This section of the handbook provides practical guidance for implementing the environmental site assessment procedure based on quantification of organic C stock and VSA through a single, coordinated soil survey and sampling campaign, improving time efficiency and ensuring comparability of the resulting data. It focuses on:

- coordinated **soil survey and sampling**: a single field campaign to collect the observations and samples required for both C stock quantification and VSA;
- **quantification of soil organic C stocks**: data requirements and calculation steps, including the use of pedotransfer functions to estimate bulk density when direct measurements are unavailable;

- **application of Visual Soil Assessment (VSA)**: guidance on conducting the assessment and interpreting visual indicators to evaluate soil condition and identify signs of degradation.

Soil survey and sampling

The following steps describe how to conduct a single field campaign to collect the observations and samples needed for both soil organic C stock quantification and VSA.

- At least two representative areas should be assessed at each site. These areas should reflect the overall site conditions, avoiding locations that are heavily disturbed by traffic or situated along the site boundaries
- Record the position of the areas for future monitoring
- At each area, dig a pit of 50x50 cm^2 until a depth of 50 cm with a spade. If bedrock or other material preventing further excavation is encountered within the upper 50 cm, excavation should stop at that depth, and the actual depth reached should be recorded (Fig. 1).
- To quantify soil organic C stocks, soil samples must be taken at fixed depths (0-5, 5-10, 10-15, 15-20, 20-30 and 30-50 cm) in order to measure the amount of organic carbon present [3] and particle size distribution [4]. Particle size distribution may be determined on a subset comprising one-third or more (≥ 1/3) of the total number of soil samples collected. The subset should include samples from both surface and deeper soil layers to ensure that variations in soil texture with depth are adequately represented. Data on particle size distribution should be optional if the calculated PFT based on C organic content has a good accuracy (see “How to proceed for prediction of bulk density by PTF”). Additionally, at a proportion of areas equal to or greater than one-third (≥ 1/3), undisturbed soil cores are taken at fixed depths (0–5, 5–10, 10–15, 15–20, 20–30 and 30–50 cm) for the measurement of bulk density [5] (Fig. 1). For each layer, coarse fragments (CF) content (>2 mm) must be estimated visually in the field as a percentage of the total soil volume in each layer, using reference charts such as those provided in the IUSS Working Group WRB Field Guide [6]. For C stock calculations, divide the percentage by 100 to obtain the volumetric fraction (for example, 20% corresponds to CF = 0.20).
- The VSA is performed in each area by the visual assessment of key soil condition and crop performance indicators of soil quality, presented as a scorecard (see “How to proceed for soil quality assessment by VSA”).



Figure 1. Soil pit dug down to 50 cm for C stock quantification by pedotransfer function (PTF) and Visual Soil Assessment (VSA)

Estimation of soil organic C stocks

Bulk density measurement is needed to quantify the soil C stocks (i.e., soil organic C on an area basis; Mg C ha^{-1}). If bulk density values for each investigated soil layers are available, move to the paragraph "How to calculate soil organic carbon stocks". If bulk density values for some soil layers are missing, the PTF approach has the potential to help to fill gaps in soil database, allowing to calculate soil C stocks. The development of PTF for predicting bulk density is based on textural data and TOC (total organic C) content. A relationship between TOC and/or particle size content (in g kg^{-1}) and bulk density (in Mg m^{-3}) is defined, and the amount of C and particle size content can be used to determine the bulk density values. In paragraph "How proceed for prediction of bulk density by PTF" the development of PTF for predicting bulk density is described. Subsequently, the organic C stock in soils is calculated ("How to calculate soil organic carbon stocks").

How to proceed for prediction of bulk density by PTF

When measured soil bulk density (BD) is unavailable, it can be estimated using a pedotransfer fuction (PTF). A PTF is an equation that predicts a soil property from other, more readily available measurements. The procedure below uses locally measured BD and SOC content to develop this equation. Particle size distribution (sand, silt and clay content) can be included if SOC alone does not provide sufficiently accurate prediction.

- Collect the required data. SOC content should be available for every soil layer, while measured BD should be available for approximately 1/3 of the sampling areas (see paragraph "Soil survey and sampling"). The areas with measured BD should represent the different soil conditions and depths included in the survey. Each BD measurement must be paired with the SOC measurement from the same location and layer. Express SOC in g kg^{-1} and BD in Mg m^{-3}; BD values expressed in g cm^{-3} have the same numerical value.
- Prepare a spreadsheet and separate the data used to develop and check the equation. In a spreadsheet, enter one location-layer combination per row, with columns identifying the sampling area, depth, SOC content and measured BD (Table 1). Where sufficient measurements are available (at least 18-20), reserve some sampling areas for checking the predictions and use the remaining areas to develop the equation.

Table 1. Example of spreadsheet

	A	B	C	D
1	sample _ID	depth (cm)	SOC (g/kg)	BD (g/cm^3)
2	Gyo 1.2.1	0 - 5	15.02	1.07
3	…..	…..	…..	…..
4	…..	…..	…..	…..
5	…..	…..	…..	…..

- Examine the relationship between SOC and measured BD. The relationship between organic carbon (C, in g kg-1) and bulk density (BD, in Mg m-3) is determined using statistical interpolation, and used to develop a pedotransfer function (PTF) to predict bulk density from the organic carbon content.

In the next steps explain how to calculate the PTF using Excel, assuming a linear relationship between SOC and BD. Other models, such as exponential model may provide better results in some cases. However, since linear models are commonly used, the following procedure focuses on calculating a PTF based on a linear relationship.

- Using the data selected to develop the equation, create scatter plot in Excel, with SOC on the horizontal axis and measured bulk density BD on the vertical axis. Add a linear trendline and display its equation and R^2 (coefficient of determination) value. A high R^2 alone does not demonstrate that the equation will accurately predict missing BD values. Start with a simple linear equation (BD= a + b x SOC), where a is the intercept (constant) and b is the slope coefficient.

- Apply the equation to the measurements reserved for checking, calculating for each SOC values the BD by multiplying SOC content for coefficient equation (b) and adding constant value (a).
- Check how closely predicted BD matches measured BD, calculating for reserved measured the root mean square error (RMSE) and mean error (ME) (equations 1 and 2). RMSE is calculated by first subtracting the measured bulk density from the predicted bulk density for each observation. Each difference is then squared, and the squared differences are added together. This total is divided by the number of observations, and the square root of the result is taken. RMSE is expressed in the same units as bulk density (Mg m^{-3} or g cm^{-3}); lower values indicate more accurate predictions. A satisfying performance of the calculated PTF has RMSE value less than 0.26 g cm^{-3} [7]. ME is calculated as difference between the measured and predicted BD values, divided by the number of observations. ME indicates whether predictions tend to be too high or too low: positive values indicate overestimation and negative values indicate underestimation. A value close to zero indicates little overall bias. If predictions are insufficiently accurate for the intended carbon stock assessment, consider adding particle size information. For example, an expanded equation could include SOC, clay and sand contents. Do not include clay, silt and sand together with a constant, because the three fractions sum to 100%. Excel's LINEST function can fit this type of equation using several input columns. Check the revised predictions using the same evaluation procedure. Retain additional variables only if they improve predictive performance; a higher R^2 for the data used to develop the equation is insufficient on its own. If performance remains poor, additional BD measurements may be needed.

$$RMSE = \sqrt{\frac{\sum_1^N (BD_{mi} - BD_{pi})^2}{N}} \quad (1)$$

$$ME = \frac{\sum_1^N (BD_{mi} - BD_{pi})}{N} \quad (2)$$

where BD_{mi} and BD_{pi} were the measured and predicted BD (g cm^{-3}), respectively, for the *i*-th observation, and N is the total number of observations

- Estimate missing BD values by applying the selected PTF only to soil layers without measured BD. The C stock in each area can be calculated ("How to calculate soil organic carbon stocks") using predicted BD.

In Box 1 a summary of how to proceed for prediction of bulk density is reported.

Box 1 - HOW TO PROCEED FOR CF MONITORING BY PTF FOR PREDICTION OF BULK DENSITY

When?

- The prediction of soil bulk density (BD) by pedotransfer function (PTF) should carried out when the BD density data is not available. BD can thus be estimated from other soil parameters, such as soil organic C and/or particle size distribution (clay, silt, sand).

Where?

- For each field, data on C organic content should be available
- For about 1/3 of fields, measured bulk density should be available
- Data on particle size distribution should be optional if the calculated PFT based on C organic content has a good accuracy

What?

- By statistical interpolation the best significant model (higher r^2) relating organic C content and BD measured is evaluated, in order to predict bulk density
- A relationship between organic C (in g kg^{-1}) and bulk density (in Mg m^{-3}) is defined by statistical interpolation, and the PTF predicting the bulk density values from the amount of C is determine
- The accuracy of PTF in predicting soil bulk density is then evaluated by calculating the root mean square error (RMSE, Eq. (1)) and mean error (ME, Eq. (2)) on available data. A satisfying performance of the calculated PTF has RMSE value less than 0.26 g cm^{-3} [7]. If the accuracy of model is not satisfying, particle size distribution should be used in the model verifying then the accuracy of the new PTF.
- The C stock in each field can be calculated by Eq. (3) using predicted BD

How to calculate soil organic carbon stocks

At each area, soil organic C stocks are calculated separately for each sampled layer and then summed to obtain the total stock over the 0–50 cm depth interval, following these steps:

- Compile the data for each samples soil layer: soil organic C concentration (TOC, g kg^{-1}; ISO 10694:1995), bulk density (BD, Mg m^{-3}; measured – ISO 11272:2017 or predicted – see “How to proceed for prediction of bulk density by PTF”), layer thickness (T, m) and coarse fragment content [6] expressed as a volumetric fraction (CF from 0 to 1).
- Calculate the soil organic carbon stock in each soil layer by multiplying the organic carbon concentration in the fine-earth fraction (< 2 mm), expressed in g kg^{-1}, by the bulk density of the fine-earth matrix (Mg m^{-3}), the layer thickness (m), and the

proportion of soil volume occupied by fine earth (1 minus the volumetric fraction of coarse fragments > 2 mm). The result is multiplied by 10 to express the stock in Mg C ha^{-1}(equation 3). If coarse fragments are absent, the correction factor equals 1.

$$C\ stock\ [Mg\ ha^{-1}] = TOC\ [g\ kg^{-1}] \cdot bulk\ density\ [Mg\ m^{-3}] \cdot depth\ [m] \cdot 10\ m^2 ha^{-1} \quad (3)$$

- Apply the calculation of organic carbon stocks to each depth interval: 0-5, 5-10, 10-15, 15-20, 20-30 and 30-50 cm, using layer thicknesses of 0.05, 0.05, 0.05, 0.05, 0.10 and 0.20 m, respectively.
- Calculate the total soil organic C stock between 0 and 50 cm by summing the stocks of all six layers. Where bedrock or another barrier prevents sampling to 50 cm, use the actual thickness of the deepest sampled layer and report the cumulative stock together with the actual depth assessed, without extrapolating to 50 cm. If more than one area has been sampled within a site, the site-level mean soil organic carbon stock is calculated as an area-weighted average, with each sampled area weighted by the proportion of the total site surface it represents if known.

Application of Visual Soil Assessment (VSA)

The VSA method is based on the visual assessment of key soil condition and crop performance indicators of soil quality, presented as a scorecard [2]. Figure 1 shows an example of a scorecard used in the Interreg PoLaRecCE project. For each VSA indicator (texture, structure, porosity, colour, mottles, earthworms, potential rooting depth, surface ponding, surface crusting and cover, erosion), a visual score (VS) from 0 (poor) to 2 (good) is given based on field observations and comparison of soil samples with the photo gallery in the VSA manual [2]. Each score is then multiplied by a weighting factor. The sum of the VS rankings gives the overall Soil Quality Index score for the sample being assessed. Compare this with the rating scale at the bottom of the scorecard to determine whether your soil is in good, moderate or poor condition. The VSA scorecards are specific to land use (annual crops, orchards, etc.), so great care needs to be taken in selecting the most appropriate scorecard [2].

A summary of procedure of the VSA approach is given below. For more details, the reader is referred to the FAO Field Guide [2].

How to proceed for soil quality assessment by VSA

- Download the most appropriate VSA scorecard according to your land use at https://www.fao.org/3/i0007e/i0007e.pdf. The available VSA scorecards refer to annual crops, olive orchards, orchards, vineyards, wheat, pastures, maize.

- The VSA test should be carried out when the soils are moist and suitable for cultivation
- Work through the scorecard, assigning a VS to each indicator by comparing it with the photographs (or table) and description reported in the FAO Field Guide [2]

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Visual Soil Assessment – Annual crops

SOILSCORE CARD – VISUAL INDICATORS FOR ASSESSING SOIL QUALITY IN ANNUAL CROPS (FAO, 2008)

Site identification			
Landowner		**Land use**	
Site location		**GPS coordinates**	
Sample depth		**Date**	
Soil type		**Soil classification**	
Drainage class		**Authors**	

Textural group (upper 1 m)	□ Sandy X Loamy □ Silty □ Clayey □ Other
Moisture condition	□ Dry x Slightly moist □ Moist □ Very moist □ Wet
Seasonal weather condition	□ Dry x Wet □ Cold □ Warm □ Average

Visual indicators of soil quality	Visual score (VS) 0=poor condition 1=moderate condition 2=good condition	weighting	VS ranking
Soil texture	1	X 3	3
Soil structure	1	X 3	3
Soil porosity	1	X 3	3
Soil colour	2	X 2	4
Number and colour of soil mottles	2	X 2	4
Earthworms (number 1)	0	X 3	0
Potential rooting depth (20 cm)	0	X 3	0
Surface ponding	1	X 1	1
Surface crusting and surface cover	2	X 2	4
Soil erosion (wind/water)	2	X 2	4
SOIL QUALITY INDEX (sum of VS ranking)			**26 moderate**

Soil quality assessment	Soil Quality Index
Poor	< 15
Moderate	15-30
Good	> 30

Figure 2. Example of filled Visual Soil Assessment (VSA) scorecard for annual crops

A summary of procedure of the VSA approach is given in Box 2. For more details, the reader is referred to the FAO Field Guide

Box 2 - HOW TO PROCEED FOR SOIL QUALITY ASSESSMENT BY VSA§

When?

- The test should be carried out when the soils are moist and suitable for cultivation.

Where?

- Select sites that are representative of the field avoiding heavily disturbed by traffic or at the field border
- For each field, at least 2 sites should be assessed. For field >1 ha, an adequate number of sites should be assessed (at least 2 sites over 1 ha)
- Record the position of the sites for future monitoring
- Dig a pit of 50x50 cm^2 until a depth of 50 cm with a spade

What?

- Work through the scorecard (Figure 3), assigning a VS to each indicator by comparing it with the photographs (or table) and description reported in the FAO Field Guide [2]

Glossary

A list of notions/terms specific to this document with short explanations

Notion	Description
PTF	Pedotransfer function
VSA	Visual Soil Assessment
BD	Bulk density
Organic C	Soil organic carbon

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Guidelines for using “in situ” soil magnetometry for rapid assessment of soil pollution

Introduction

The objective of document is to provide a guideline for the application of soil magnetometry, which, when properly implemented, can offer insights into the spatial distribution of potentially toxic elements (PTEs) in topsoil. This allows for the identification of contaminated areas that require appropriate management. The method is designed to function as a screening and early warning system that can be applied at various scales—from local to broad regional levels—and can also be used to investigate the long-range atmospheric transport of elements (ISO 21226:2019).

Most magnetic particles found in topsoil are of anthropogenic origin. Technogenic magnetic particles (TMPs) are generated in nearly all high-temperature technological processes, in which various iron-bearing minerals present in raw materials, fuels, and additives are transformed into strongly magnetic iron oxides. TMPs are common components of urban dust and aerosols and are known to act as carriers of trace elements. This property makes it possible to use TMPs as tracers of anthropogenic pollution with potentially toxic elements (PTEs), as their presence—even in trace amounts—can be easily detected in soils through magnetic measurements [2–5]. TMPs and PTEs are typically enriched in the uppermost 10 cm of soil in undisturbed areas, where the highest concentrations of trace elements are commonly observed. Cultivated agricultural soils and industrial or post-industrial lands are also well-suited for the application of magnetic methods to indicate PTE pollution.

Numerous studies conducted to date confirm the reliability of soil magnetometry as an indicator of soil contamination caused by dry and wet deposition [6-9]. These findings highlight its potential for use in standardized, routine soil quality monitoring.

Determination of the content and spatial distribution of TMPs in the soil for a quick and easy assessment of the soil condition and discrimination of polluted areas

The objectives of the proposed approach are to confirm the presence and concentration levels of TMPs and related PTEs. The procedure consists of four steps (Fig. 1):

- **field measurement** of magnetic susceptibility at the soil surface to assess the concentration of TMPs deposited in the topsoil and to identify spatial magnetic anomalies;
- **geostatistical evaluation and processing** of magnetic data to generate a map of the spatial distribution of κ values and to locate magnetic anomalies;

- **targeted sampling** of 30 cm topsoil cores and laboratory measurements of the vertical distribution of the magnetic signal along the cores, in order to distinguish between anthropogenic and natural sources of magnetism;
- **chemical analysis** of heavy metals in core samples collected from magnetic 'hot spots'—areas with the highest probability of pollution by PTEs.

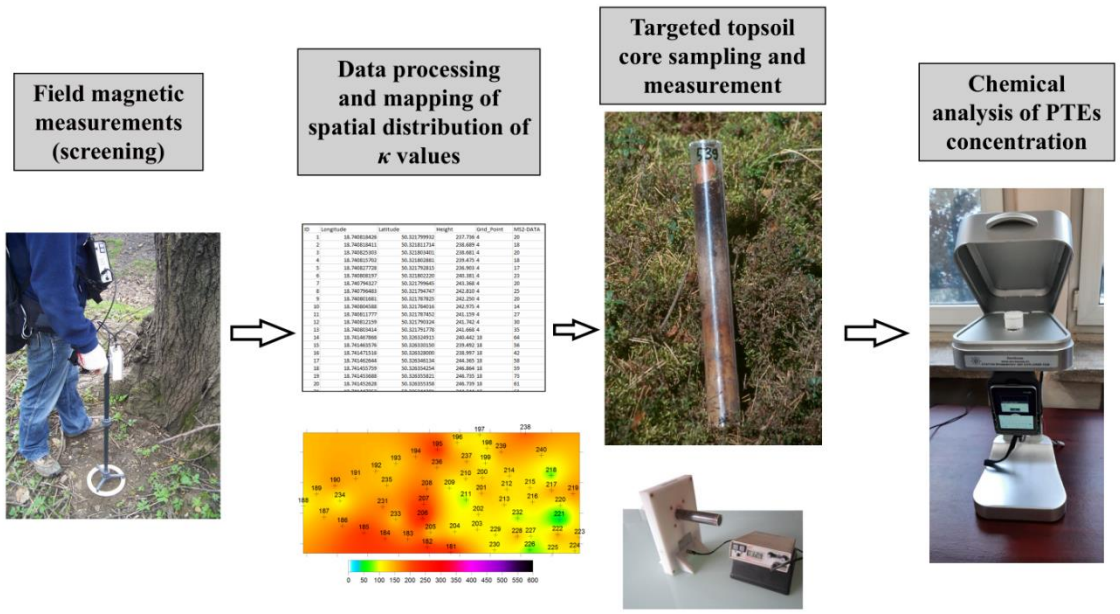


Figure 1. Four steps procedure of soil magnetometry (ISO21226:2019)

Detailed procedure of field magnetic measurements performed on soil surface

Surface measurements of magnetic susceptibility enable a preliminary assessment of the degree of soil contamination in the analysed area. Since elevated magnetic susceptibility values are often associated with increased concentrations of potentially toxic elements (PTEs), this method allows for the rapid identification of areas requiring further investigation or intervention.

According to ISO 21226:2019(E), four pollution levels are distinguished based on magnetic susceptibility values:

- **0 to 30 × 10^{-5} SI units**: likely natural background level, indicating areas not affected by dust deposition (no significant correlation between the magnetic signal and trace element content is expected).
- **30 to 70 × 10^{-5} SI units**: low to moderate probability of pollution with trace elements (a relatively weak correlation between magnetic signal and trace element content may be present).

- **70 to 100 × 10^{-5} SI units**: elevated pollution with trace elements (at least one trace element shows a strong correlation with the magnetic signal).
- **above 100 × 10^{-5} SI units**: high pollution level (several trace elements exhibit a strong correlation with the magnetic signal, and at least one is likely to exceed threshold values).

Magnetic susceptibility values (κ) at the topsoil surface are performed with the use of a portable hand magnetic susceptibility loop sensor in (if possible) regular network points. The density of the measurement grid depends on the size of the area and must always be adjusted to the conditions of a specific area. The position of the point is marked in GPS device. At least 11 (odd numbers) individual magnetic susceptibility measurements should be taken within a radius of approximately 2 m around the GPS position according to the scheme presented in Figure 2. Protocol for the surface measurement is given in Figure 3.

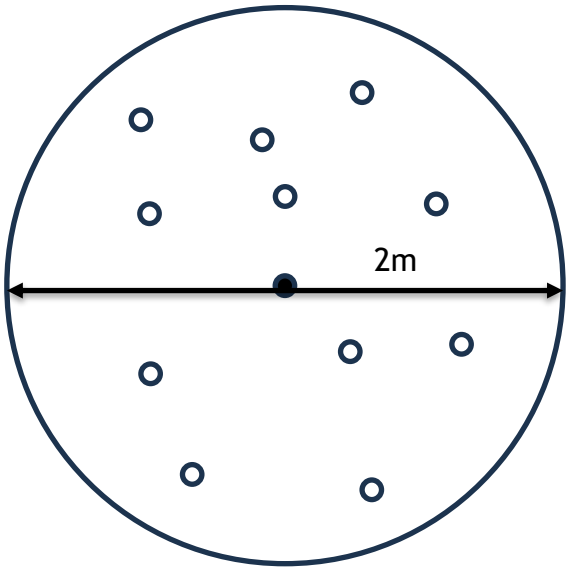


Figure 2. Scheme of field measurement of magnetic susceptibility (κ) values in sample point

Point no	κ values × 10^{-5} SI				Geographical position of a point		
	Measured κ values × 10^{-5} SI	Mean/ median	±sd	Outliers (rejected)	Latitude	Longitude	Altitude
.../1							
.../2							
.../3							
.../4							
.../5							
.../6							
.../7							
.../8							
.../9							
.../...							
.../n							

Figure 3. Protocol for surface measurements

Some additional information related to the measurement conditions and investigated area must be also included in the measurement protocol.

1) Date of measurement
   a) start date of measurement
   b) end date of measurement
   c) total numbers of measurement days
   d) weather conditions during measurements: number of days with:
      i) dry weather;
      ii) wet weather (rain, drizzle, after rain, fog);
      iii) frost
2) Area name
3) Land use category
   a) forest
   b) arable lands
   c) meadow, pasture
   d) post-industrial area
   e) urban area
   f) other
4) Description of the area (obligatory information)
   a) forest - forest type, dominant species, stand age, forest floor, slope gradient (flat, <5%, >5%), other important information
   b) arable lands - current field condition (e.g. stubble, ploughed, sown – crop), slope inclination (flat, <5%, >5%), other important information

c) meadow, pasture - grass height, slope gradient (flat, <5%, >5%), other important information
d) post-industrial area - type of industry, type of waste stored, expected artifacts in the ground, other important information
e) urban area - type of terrain (park, square, lawn, roadside area), expected artifacts in the ground, other important information
f) other - type of terrain, slope of the site (flat, slope < 5%, slope > 5%), slope inclination (flat, < 5%, > 5%), other important information

Data processing to produce the map of spatial distribution of κ value and identify the magnetic anomalies

The κ value reported for each grid point is the mean of 11 individual measurements. Before calculating the mean, the standard deviation of κ should be computed and any outliers must be discarded. The resulting mean values of magnetic susceptibility are then used as input data in visualization, contouring, and surface modelling software to generate 2D or 3D contour maps of magnetic susceptibility distribution in the analysed area. Based on these values and the corresponding geographical coordinates, maps of the spatial distribution of κ can be created.

Such maps make it possible to identify areas with elevated concentrations of PTEs, which may pose a risk to human health. These areas are referred to as "hot spots"—locations where increased κ values indicate a likely accumulation of TMPs and, consequently, PTEs (Fig. 4).

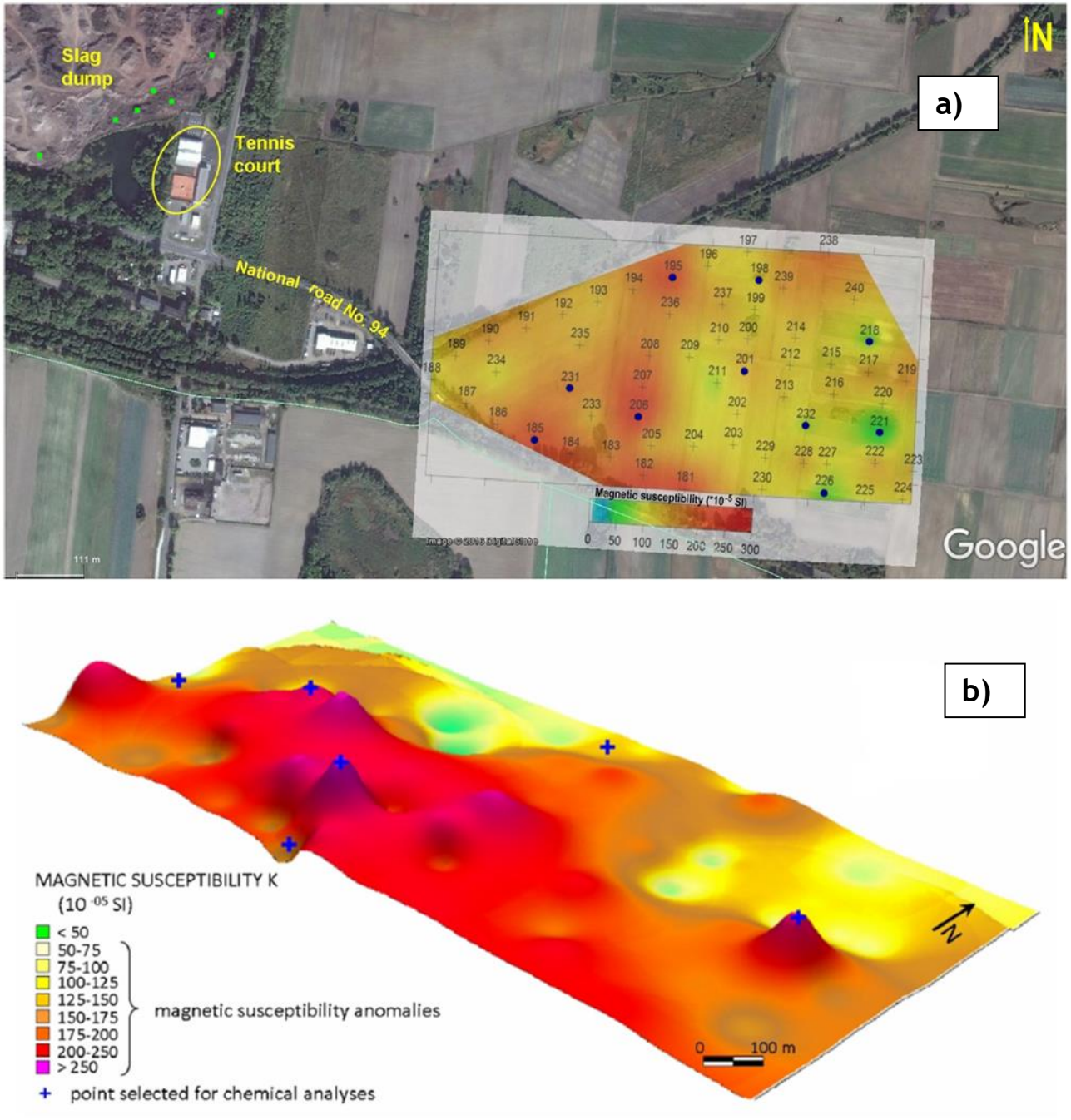


Figure 4. Examples of maps of spatial distribution of magnetic susceptibility values: a) example of 2D map [4], example of 3D map [10].

Targeted sampling of 30 cm topsoil cores and magnetic laboratory measurements

Targeted sampling based on prior magnetic screening allows for a reduction in the number of geochemical analyses required to assess the level of PTE contamination, in accordance with national threshold values for individual elements. Soil cores should be collected using a soil probe equipped with a plastic tubes, driven into the ground with a hammer to a depth of 30 cm (Fig. 5). A visual inspection of the core enables a preliminary assessment of whether the soil profile is natural or has been disturbed—e.g., by agricultural practices (such as ploughing) or by past excavation activities at

the sampling location. In the laboratory, analysis of the vertical distribution of κ values along the core is performed. This allows for distinguishing between the natural magnetic signal and that related to anthropogenic pollution.

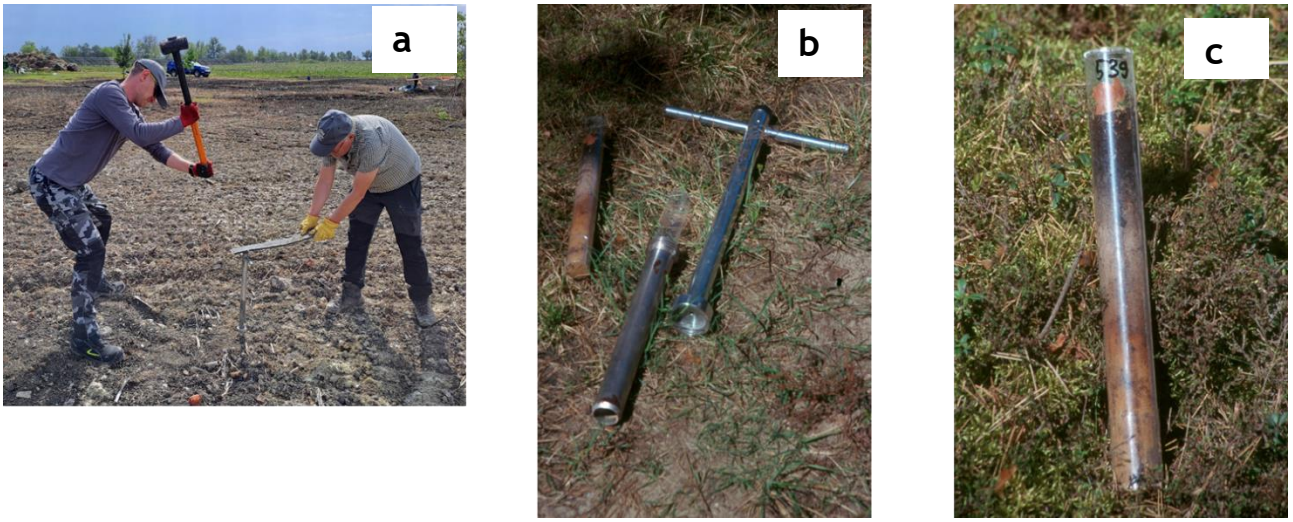


Figure 5. Topsoil core sampling: a) core sampling, b) two parts of Humax core sampler, c) topsoil core.

Topsoil core samples should be collected from areas exhibiting the highest κ values. Additionally, for reference purposes, at least one core should be taken from an area with the lowest and one with moderate magnetic susceptibility. The number of sampling points should be determined individually, based on representativeness. After inspecting the condition of the cores, the plastic tubes should be secured to prevent destabilization by sealing both ends with neutral caps. Each tube should be clearly labelled and tightly wrapped in thin plastic foil to prevent moisture loss. The main objectives of measuring magnetic susceptibility along the topsoil profile are:

a) to determine the vertical distribution of anthropogenic pollution by trace elements, which may result from accumulation in organic horizons or the vertical migration of TMPs;

b) to detect the possible influence of the magnetic properties of the bedrock;

c) to evaluate background magnetic susceptibility values for calculating the Contamination Factor (CF) and Pollution Load Index (PLI)

Measurements of magnetic susceptibility along soil cores can be carried out in two ways:
— by collecting topsoil cores in the field and transporting them to the laboratory for magnetic susceptibility analysis;
— by conducting in situ measurements of the magnetic susceptibility profile (optional).

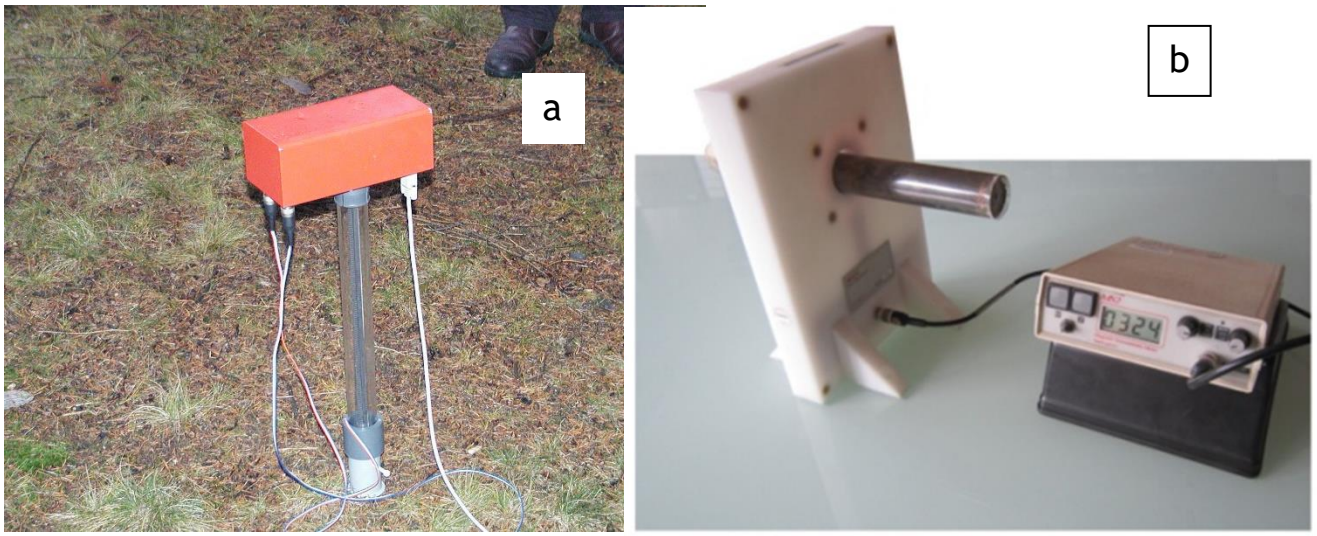


Figure 6. Measurement of vertical distribution of κ value along the topsoil cores: a) automatic field measurement; b) laboratory measurement.

The choice between field and laboratory measurements depends on factors such as convenience, the need for immediate results to guide further sampling, and the availability of equipment.

Direct field measurement of the magnetic susceptibility profile in topsoil can be performed using a core magnetic susceptibility meter designed for field use (Fig. 6a). These measurements help detect the vertical distribution of pollutants and distinguish soil horizons In situ measurements are more time-consuming and may slow down the overall field campaign. They also require preferably dry weather conditions for optimal performance. Such measurements should be conducted when immediate results are necessary for the proper planning and execution of spatial field surveys.

These measurements should be carried out if the results are required for a further proper design and conducting spatial field measurements.

The data, presented in the form of tables and graphs showing magnetic susceptibility values versus layer depth, are available instantly on a laptop connected to the meter. A core magnetic susceptibility meter for automated in situ measurements is not essential equipment, as the same results can be obtained through laboratory analysis of core samples collected in the field. However, in the case of in situ measurements, the diameter of the core sampler must be compatible with the magnetic susceptibility probe.

An alternative approach involves laboratory measurements of κ values using a core magnetic susceptibility sensor (Fig. 6b). To reduce variability, it is recommended to collect samples from two twin cores (A and B) located less than 1 meter apart. Topsoil cores collected in the field should be

transported to the laboratory immediately after sampling, or stored in a refrigerator and measured within a 7-day period. The results should be documented in a measurement protocol and presented in graphical form (Fig. 7).

Core no. .../A	measured $\kappa \times 10^{-5}$ SI	Core no. .../B	measured $\kappa \times 10^{-5}$ SI
depth		depth	
0 cm		0 cm	
1 cm		1 cm	
2 cm		2 cm	
3 cm		3 cm	
4 cm		4 cm	
5 cm		5 cm	

Figure 7. Measurement protocol from the laboratory measurement of vertical distribution of κ valies in

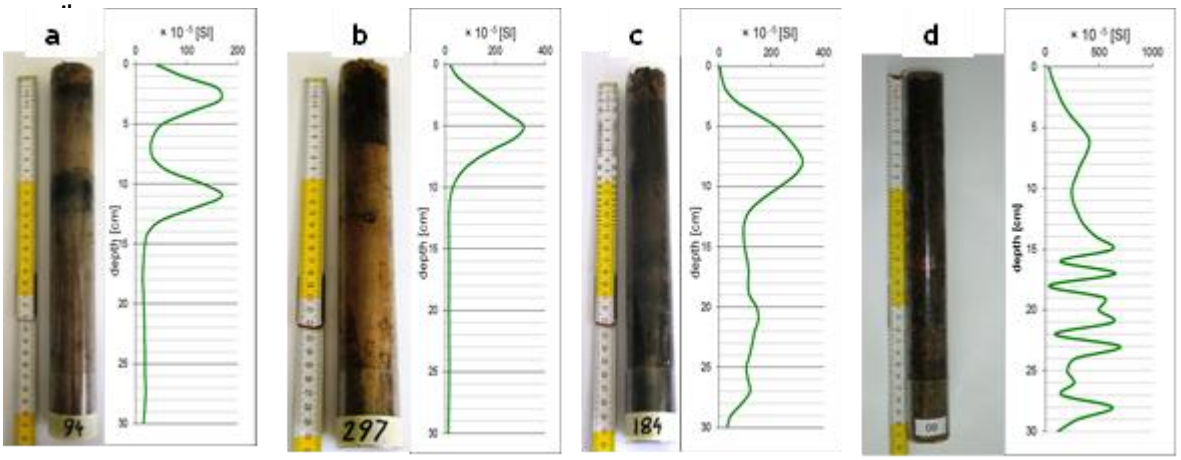


Figure 8. Examples of different topsoil cores and vertical distribution of κ values: a) core with buried organic horizon from polluted areas; b) typical core from polluted area developed on sundy soil; c) core from polluted area developed on chernoziem; d) core from urbanosol developed on anthropogenic background.

Chemical analysis of heavy metals from core samples collected in areas of magnetic ‚hot spots' with the highest probability of pollution by PTEs

Magnetic susceptibility does not differentiate between specific trace elements but reflects the retrospective cumulative load of airborne pollutants deposited in soil via dry and wet deposition of anthropogenic emissions. Typically, 12 PTEs — including V, Cr, Ni, Cu, Zn, As, Se, Mo, Cd, Sn, Sb, and Pb — are transported by TMPs. However, the observed correlations between enhanced κ value and the concentration of individual PTEs are strongly

source-dependent. The actual airborne trace element content in soil represents the cumulative effect of decades of anthropogenic emissions, influenced by industrial development, technological changes, and socio-economic or historical factors. As a result, the current land use or present emission levels may not reflect the real extent of pollution. Soil magnetometry provides a fingerprint of the actual contamination status. Core samples collected from areas showing magnetic anomalies must be verified through chemical analysis to identify which elements exceed threshold values and may pose ecological risks. Various methods can be used for this validation. The fastest technique is portable X-ray fluorescence (pXRF) [11]. Although threshold values differ between countries, they are generally above the detection limits for most commonly detected PTEs — with the exception of cadmium (Cd), which sometimes falls below the detection limit of pXRF. More precise validation methods include classical laboratory techniques such as Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), and Atomic Absorption Spectrometry (AAS).

A higher κ value in the upper part of the core (organic horizon) may indicate the deposition of pollutants from anthropogenic sources, such as industry (e.g. metallurgy, power plants, metal ore processing), road transport, or domestic heating. This layer is typically the most polluted. Conversely, a higher susceptibility value in the lower part of the core may reflect the natural presence of magnetic particles, associated with bedrock containing significant amounts of iron oxides and hydroxides (Fig. 9).

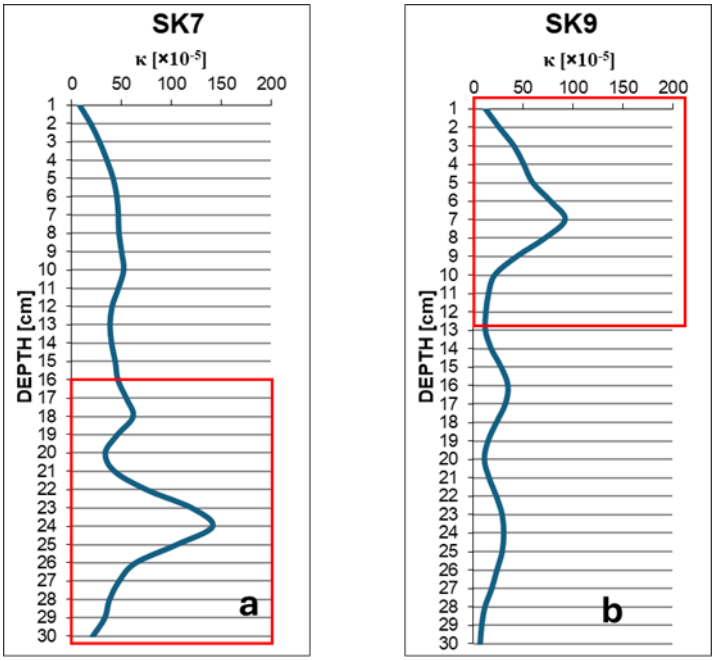


Figure 9. Examples of distribution of magnetic susceptibility values: a) natural (most probably pedogenic) occurrence of magnetic particles; b) accumulation of TMPs as a result of deposition.

For chemical analysis, it is not necessary to collect additional samples. One of the two twin cores should be selected for laboratory analysis. If both cores show a similar vertical distribution of κ values, the one with the higher maximum κ value should be chosen. However, if the twin cores show a significant discrepancy, the core with a distribution pattern more consistent with neighbouring cores should be selected. At peak locations—where significantly elevated κ values are observed—increased concentrations of PTEs can be expected. In such cases, the plastic core tube should be cut at the depth corresponding to the κ peak, and a subsample should be collected for further analysis. An exception is arable land, where a homogenized sample from the upper 20 cm of the cultivated layer is typically selected for analysis. In the case of technogenic or urban soils, both the upper and lower parts of the core should be prepared for chemical analysis.

Before chemical analysis, the soil sample obtained in this way should undergo a low-field magnetic susceptibility (κ) measurement in the laboratory to calculate the mass-specific (χ) magnetic susceptibility using the following equation:

$$\chi = \kappa/\rho \quad (m^3 \times kg^{-1})$$

where ρ is the soil density, measured by placing the sample in a standardized 10 cm^3 plastic container and weighing it. Values of χ allow for the comparison of samples with different densities. After this, the samples are subjected to chemical analysis to determine the content of selected PTEs. The protocol for the sampling procedure is presented in Figure 10.

Core no.	depth of sampled layer (cm)	mean κ value of sampled layer ($\times 10^{-5}$ SI)	mass magnetic susceptibility of soil sample ($\times 10^{-8}$ m^3kg^{-1})	mean mass magnetic susceptibility of soil sample ($\times 10^{-8}$ m^3kg^{-1})	±sd	frequency dependence of magnetic susceptibility (%)

Figure 10. Protocol on core sampling for chemical analysis

Magnetic screening in multisource areas.

In multisource areas, the correlations between magnetic susceptibility and individual elements are usually much lower than in areas with a single dominant pollution source. In such cases, it is challenging to assess the applicability of soil magnetometry for pollution studies at the specific site. In these situations, the calculation of the Pollution Load Index (PLI), which represents a cumulative anthropogenic pollution index, can be useful. PLI

describes the relationship between magnetic susceptibility and overall trace element contamination in topsoil.

The Pollution Load Index can be calculated as a point value (for a single sampling point), as shown in the following formula:

$$PLI_{POINT} = \sqrt[n]{CF_{Zn} \times CF_{Pb} \times CF_{Cd} \times \cdots \times CF_{n}}$$

n – the number of elements selected for PLI calculation in the studied area. The number of elements selected for PLI calculation depends on the number and nature of the emission sources affecting the studied area, but it must be the same for each sampling point.

The contamination factor (CF) is calculated as:

$$CF_n = C_{el}/C_{background}$$

where C_{el} is the measured concentration of elements at the sampling point and $C_{background}$ is the baseline value. For the baseline value in this method, it is recommended to use:

a) the concentration of the element in the subsoil at the reference site, based on soil core analysis;

b) the mean value of the lowest concentrations of the element detected in the surveyed area (in the absence of soil core data).

Applicability and limitations in using soil magnetometry.

The ISO 21226:2019(E) standard specifies the procedure for measuring the magnetic susceptibility of soils (κ or χ) as an indicator of potential soil pollution with trace elements associated with TMPs. It also describes the related procedures, protocols, and guidelines to be applied as a screening geophysical method for determining soil pollution with PTEs. The results of these measurements are used to create maps of magnetic susceptibility in the area of interest. From these maps, areas of elevated and high κ values (magnetic 'hot spots') can be identified, which are most likely to indicate high total trace element pollution load. These areas must then be further investigated using geochemical methods to identify the specific pollutants.

This method is applicable for screening all anthropogenic emission sources related to TMPs, including the long-range transport of airborne elements, for which TMPs serve as carriers and indicators. Such emission sources include the majority of high-temperature industrial processes, where iron is present in any mineralogical form in raw materials, additives, or fuels, and is transformed into ferrimagnetic iron oxides. Examples of these processes include the combustion of fossil solid and liquid fuels, metallurgy, the cement and ceramics industries, coke production, industrial waste landfills, and land transport. However, this method is not applicable for screening anthropogenic emissions that are not associated with TMPs, such as organic pollutants or emissions from agricultural sources.

It is also important to note that non-processing mining wastes from copper, zinc, and other non-ferrous metal ores also contain iron (often in the form of sulfides), as this element is abundant in nearly all environments. In this case, sulfides are transformed into ferrimagnetic iron oxides as a result of weathering, although this process is relatively slow. In areas affected by dust from mining waste, the proportion of TMPs to PTEs is usually lower than in areas impacted by coal combustion or iron metallurgy, for example. Furthermore, not all PTEs are physically associated with or transported by TMPs. As a result, the measured κ values in such areas will generally be lower, despite sometimes extremely high concentrations of certain elements [2].

In rare cases, soils may develop on bedrock with naturally high magnetism, which could lead to false-positive results. However, this influence can typically be identified through measurements of magnetic susceptibility along soil profiles. This method is not applicable when the bedrock exhibits extremely high magnetic signals, although such cases are uncommon.

Glossary

A list of notions/terms specific to this document with short explanations

Notion	Description
PTE	Potentially Toxic Elements
TMPs	Technogenic Magnetic Particles
κ	Volume magnetic susceptibility
χ	Mass-specific magnetic susceptibility
CF	Contamination factor
PLI	Pollution load index
pXRF	**Portable** X-ray fluorescence
ICP-OES	Coupled Plasma-Optical Emission Spectrometry
ICP-MS	Coupled Plasma-Mass Spectrometry
AAS	Atomic Absorption Spectrometry

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Fertilisation requirements and immobilization of PTEs in relation to local environmental conditions

This part of the handbook translates the results of the PoLaRecCE project into practical guidance for regional and local administrations responsible for managing agricultural land contaminated with PTEs. It presents a five-step procedure: assessing soil conditions and contamination levels, evaluating the suitability of the land for non-food agriculture, immobilizing heavy metals in the soil using appropriate soil amendments, determining fertilization needs based on crop requirements and soil nutrient availability, and establishing a long-term environmental monitoring programme.

The handbook provides practical guidelines for assessing fertilization needs, based on the experience gained at the PoLaRecCE pilot sites. It also presents an overview of commonly used methods for determining the availability of the three main plant nutrients: nitrogen (N), phosphorus (P), and potassium (K). In addition, it provides a brief overview of soil remediation techniques and recommends suitable methods for reducing the mobility and availability of potentially toxic elements in contaminated soils.

Particular attention is given to three promising soil amendments: biochar, zeolite, and chitosan. These materials can help immobilize heavy metals in the soil, reducing their availability to plants and their potential environmental impact. Their application can therefore support the preservation or restoration of the biological and agricultural functions of contaminated soils, making them more suitable for non-food agricultural production.

Problem Soil contamination by potentially toxic elements (PTEs)

Soil contamination by PTEs is a widespread environmental problem in Europe. According to Payá Pérez and Rodríguez Eugenio [1], approximately 694,000 contaminated sites have been registered in national and regional inventories, while an estimated 2.8 million sites may be affected by past or ongoing potentially polluting activities. Common contaminants include mercury (Hg), lead (Pb), cadmium (Cd), arsenic (As), zinc (Zn), nickel (Ni), copper (Cu), selenium (Se), and vanadium (V). The main sources of contamination include mining and smelting activities, industrial emissions and wastewater, coal combustion, historical use of leaded petrol, landfills and municipal waste, sewage sludge and manure, and certain pesticides.

For local administrations, soil contamination is an important environmental and public health concern. PTEs can enter the human body through contaminated food crops, drinking water, and inhalation or ingestion of contaminated dust. They can also spread to

neighbouring land and water bodies through leaching and soil erosion. In addition, elevated concentrations of PTEs may negatively affect soil organisms, reduce soil fertility, and limit the possibilities for agricultural land use.

Conventional soil remediation methods, such as excavation and disposal of contaminated soil in landfills or soil washing, can be expensive and may require extensive technical operations. Some of these methods involve removing contaminated soil from the site, while others separate or reduce the concentration of contaminants. An alternative approach is in situ immobilization, which aims to reduce the mobility and bioavailability of PTEs by applying appropriate soil amendments without removing the contaminated soil. This approach can help preserve soil functions and support the safe use of contaminated land for non-food agricultural production, provided that site-specific risks are properly assessed and managed. This method does not remove PTEs from the soil but reduces their mobility and availability for plant uptake and leaching into water. The aim is to limit the environmental risks associated with soil contamination and support the safe use of degraded land for non-food agriculture. Table 1 compares these three remediation approaches of sites contaminated by PTEs.

Table 1. Options for dealing with sites contaminated by PTEs

Approach	What it does	Strengths	Limits
Excavation and landfilling	Removes the contaminated soil and deposits it elsewhere	Fast; the site is freed for any use	Very costly; only relocates the contamination; destroys the soil
Soil washing	Separates contaminants from the excavated soil	Reduces the volume to be disposed of	Costly; still relocates the contaminants; soil structure is lost
In-situ immobilization with non-food use	Binds the metals in the soil with amendments; crops that are not eaten are grown	Low cost; soil and its functions are preserved; land stays productive; can store carbon	Metals remain on site; requires long-term monitoring and land-use restrictions

Legal and policy framework on EU level

Four groups of legal instruments and guidelines determine the permitted uses of contaminated agricultural land: EU soil protection legislation, EU water and nature protection legislation, national legislation on contaminated land, and national regulations and guidelines on fertilization. Applicable EU, national and regional legal requirements always take precedence over the reference values provided in this handbook. Table 2 summarizes the main relevant legal instruments and guidelines.

Table 2. Legal and policy instruments relevant to administrations

Instrument	Relevance for administrations
Directive (EU) 2025/2360 on soil monitoring and resilience (Soil Monitoring Law)	In force since 16 December 2025; transposition into national law by December 2028. Member States must identify and investigate potentially contaminated sites, keep a public georeferenced register, and manage risks with sustainable and proportionate measures such as remediation, use restrictions or containment. Registers are due by the end of 2029 and the identification of potentially contaminated sites by the end of 2035.
Nitrates Directive (91/676/EEC)	No more than 170 kg of manure nitrogen per hectare and year. No fertilizer application in periods with a high risk of nitrate leaching.
Habitats Directive (92/43/EEC) and Birds Directive (2009/147/EC)	Establish the Natura 2000 network. Inside or next to Natura 2000 areas, nitrogen inputs may be restricted further.
National contaminated-site law	Defines who investigates, who pays, how sites are registered and which land uses are permitted. Must be checked before any measure.
National fertilization guidelines	Set crop nutrient needs, soil content classes and correction factors. They are the basis of every fertilization plan.

In practice, immobilization combined with non-food agricultural use can be linked to two risk-reduction measures identified in the EU Soil Monitoring Law: containment and land-use restrictions. Local administrations should confirm with the competent environmental authority whether this approach is acceptable for the specific site and document both the land-use restrictions and the monitoring plan.

Roadmap: From suspected soil contamination to safe non-food agricultural use

Figure 1 illustrates the five steps of the roadmap, the decision-making process for food or non-food agricultural use, and the stakeholders responsible for each step. Steps 1–5 are carried out during the initial site assessment and preparation. Soil nutrient testing should be repeated periodically, and the fertilization plan should be reviewed annually. Environmental monitoring should continue according to the site-specific monitoring plan and applicable regulatory requirements.

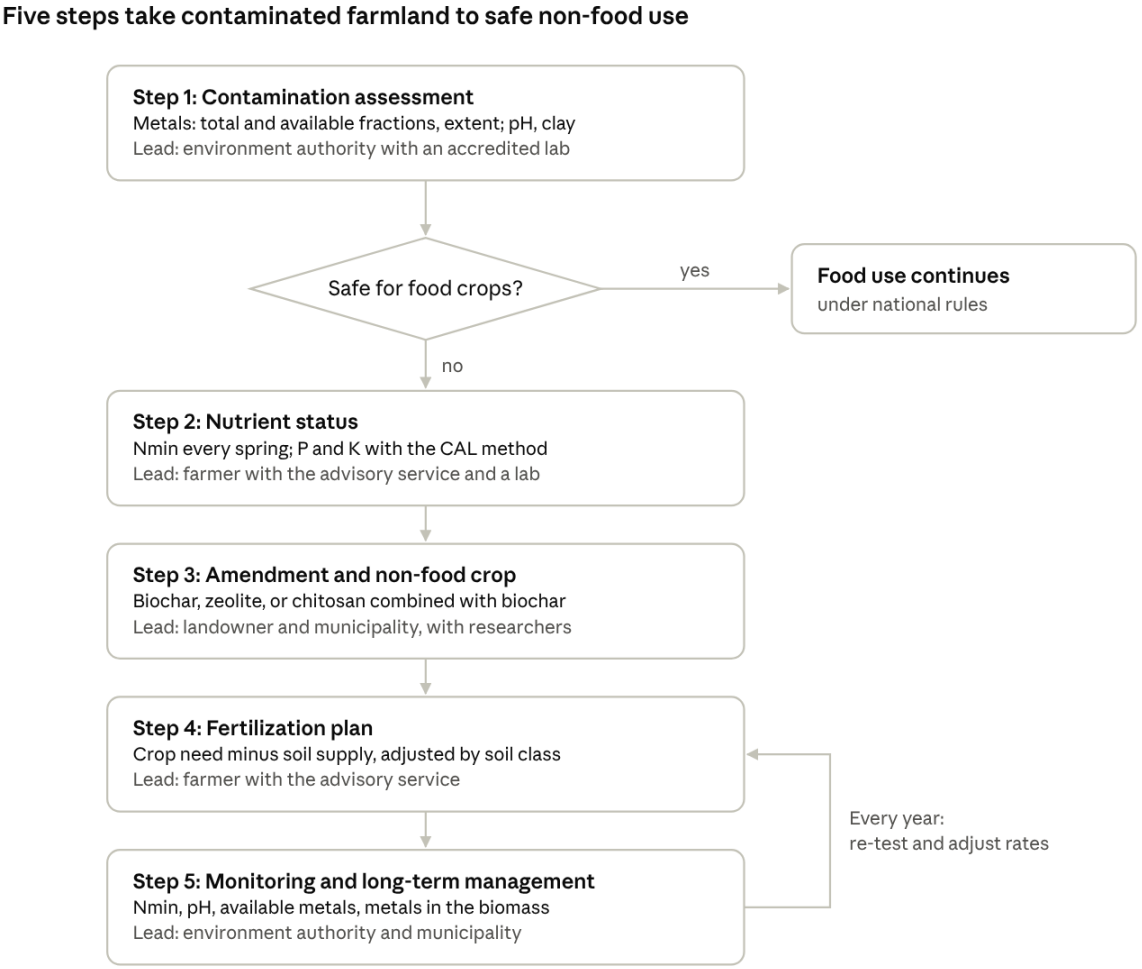


Figure 2. Roadmap from suspected soil contamination to safe non-food agricultural use.

Assessing the site and the soil

Before selecting any management measures, two key aspects must be assessed: the concentrations of metals in the soil and their availability to plants, and the soil's nutrient status. Both assessments provide essential information for subsequent decisions.

Contamination assessment

Commission an environmental site assessment covering the site's history, potential sources of contamination, the types and concentrations of metals present, their total and plant-available fractions, and the depth and spatial extent of contamination.

At the same time, determine the soil properties needed for subsequent assessments: pH, clay content, and organic matter content. Soil pH is used to adjust phosphorus recommendations, while clay content is used to determine potassium availability classes.

Decision: If metal concentrations and the associated risks make the land unsuitable for safe food production, consider non-food agricultural use combined with appropriate

immobilization measures.

Nutrient status assessment

Nutrient analyses should be carried out by an accredited local laboratory using methods consistent with national standards. PoLaRecCE recommends simple colorimetric methods commonly used in Central European countries, where applicable.

Mineral nitrogen (N_{min} = nitrate + ammonium): Soil analysis should be performed before planting and subsequently every year in early spring. Soil samples should be collected from a depth of 0–60 cm or 0–90 cm, depending on national guidelines and the type of crop.

Organic nitrogen: This analysis is optional and can be performed together with N_{min} determination to provide additional information on the soil's potential to supply nitrogen over time.

Phosphorus (P) and potassium (K): Soil analysis should be performed before establishing the plantation and subsequently at intervals specified by national guidelines or recommended by specialists. For soils with a pH below 6, the measured phosphorus content should be corrected using the following equation,

$$P_{corr}=P_{CAL}*0.98+9.2$$

where P_{corr} is the calculated plant-available phosphorus content for soils with pH < 6, and P_{CAL} the phosphorus content determined in the CAL extract, both in mg P/100 g soil.

It should be noted that results obtained using different analytical methods are not always directly comparable. Laboratory reports should clearly specify the analytical methods used.

Colorimetric methods commonly used for phosphorus determination primarily measure inorganic orthophosphate. Organic phosphorus compounds present in the extract may remain undetected. In contrast, ICP-OES determines the total elemental phosphorus concentration in the extract, including both inorganic and organic forms. However, the interpretation of phosphorus test results and their use in fertilization planning must follow the recommendations established for the specific analytical method.

Field methods, such as ion-selective electrodes and near-infrared (NIR) spectroscopy, can provide rapid results but generally require appropriate calibration and validation. They are useful for preliminary screening, while laboratory analyses should be used to confirm the results before making fertilization decisions.

Recommended Procedures for Soil Amendment Application to Immobilize Contaminants

For soils contaminated with potentially toxic elements (PTEs), PoLaRecCE recommends three soil amendments to reduce the mobility and bioavailability of

contaminants: biochar, zeolite, and chitosan. Their effectiveness depends on the types and concentrations of PTEs present and on soil properties. The selection of the most suitable amendment should therefore be based on the results of the site assessment and, where possible, supported by small-scale field trials. Table 3 summarizes the main properties of these amendments.

Table 3. Recommended soil amendments for in-situ immobilization of heavy metals

Amendment	Mode of action	Evidence and application rate	Points to consider
Biochar: carbon-rich solid produced by heating biomass (crop residues, nutshells, wood etc.) under oxygen-limited conditions	Porous structure and reactive surface groups bind metals	A global meta-analysis found metal bioavailability reduced by about 40 % in soil and 22 % in plants, with large differences between metals[1)] Best results at 1.1–3 % of soil mass.	Choose biochar with a surface area above 100 $m^2 g^{-1}$, neutral to alkaline pH and pyrolysis above 500°C. Soil properties affect the result more than the crop does.
Zeolite: natural crystalline aluminosilicate mineral from volcanic deposits (e.g. Hungary, Italy); clinoptilolite is the most common	High cation-exchange capacity binds positively charged metal ions	Two studies at 5 % zeolite: copper −31 to −36 %, lead −23 to −39 %, zinc −6.5 to −28 %, cadmium −5.5 %. Acid, alkaline or thermal treatment raises the capacity (alkaline: +10–20 %).	Binds negatively charged pollutants poorly. Natural material varies and may itself contain impurities, including pollutants.
Chitosan: biopolymer derived from shellfish waste or fungal cultures	Amine and hydroxyl groups bind a wide range of metals	Promising, especially as chitosan-modified biochar.	Biodegrades in soil, so bound metals can be released again. Use only in combination with a stable sorbent such as biochar.

Biochar and zeolite are generally available in large quantities and can be relatively inexpensive, depending on local market conditions. Biochar can also contribute to long-term carbon storage in soil and, under appropriate conditions, support carbon dioxide removal from the atmosphere.

When purchasing soil amendments, local administrations should request the following information from suppliers:

Raw material or origin and production conditions (for biochar, including pyrolysis temperature).

Product analysis results, including the content of PTEs and other relevant contaminants.

Key properties, including pH, specific surface area, and cation exchange capacity (CEC).

Recommended application rates and incorporation depth, adapted to the soil properties and

contamination conditions at the specific site.

Calculating the fertilization needs

Fertilization should be based on crop nutrient requirements, taking into account the nutrients already available in the soil. Adequate nutrient supply is essential for maintaining crop yields and ensuring the economic viability of non-food agriculture. However, excessive fertilization can contribute to water pollution and, in the case of nitrogen, emissions of harmful gases such as nitrous oxide (N_2O) and ammonia (NH_3).

Nitrogen

The recommended nitrogen application rate is determined in three steps:

- Determine the annual nitrogen requirement of the crop. The expected yield should be estimated based on the average yield over the previous five years, where such data are available.
- According to the PoLaRecCE recommended procedure, if the mineral nitrogen (N_{min}) content measured in the 0–60 cm or 0–90 cm soil profile exceeds 40 kg N ha^{-1}, reduce the nitrogen application rate by the amount exceeding this threshold.
- If the soil has a high nitrogen mineralization potential, indicated by high EUF-Norg values or high soil organic matter content, consider a further reduction in the nitrogen application rate.

Table 4 lists the annual nutrient needs of typical crops suitable also for non-food use. National regulations implementing the EU Nitrates Directive, including nitrogen application limits and prohibited fertilization periods, as well as any additional restrictions applicable to Natura 2000 sites, must always be respected.

Table 4. Annual nutrient needs of typical crops at medium yield potential

Crop	N [kg N ha^{-1} y^{-1}]	P_2O_5, class C [kg ha^{-1} y^{-1}]	K_2O, class C [kg ha^{-1} y^{-1}]
Silage maize	140–160	90	225
Silage sorghum	140–160	95	375
Grain maize	120–140	85	200
Grain sorghum	120–140	85	210
Canola (rapeseed)	120–140	65	90
Sugar beet	110–140	85	320
Wheat	110–130	55	80
Triticale	90–110	55	80
Rye	80–100	55	80
Sunflower	40–60	75	200

Crop	N [kg N ha^{-1} y^{-1}]	P_2O_5, class C [kg ha^{-1} y^{-1}]	K_2O, class C [kg ha^{-1} y^{-1}]
Cover crops without legumes	40-80	50	180
Field pea, field bean	0-60	65	100
Soybean	0-60	65	120
Cover crops with legumes	0-40	25	80

Phosphorus and potassium

The recommended phosphorus and potassium application rates are determined in three steps:

Determine the soil nutrient content class separately for phosphorus and potassium, based on the results of the CAL analysis (Table 5).

Obtain the recommended phosphorus and potassium application rates for soil nutrient content class C from Table 4.

Multiply each application rate by the corresponding correction factor for the soil nutrient content class (Table 6).

Table 5. Content classes for P and K in mg kg^{-1} (CAL method)

Class	Supply	P, arable	P, grassland	K, light soil (clay < 15 %)	K, medium soil (clay 15-25 %)	K, heavy soil (clay > 25 %)
A	Very low	< 26	< 26	< 50	< 66	< 83
B	Low	26-46	26-46	50-87	66-112	83-137
C	Adequate	47-111	47-68	88-178	113-212	138-245
D	High	112-174	69-174	179-291	213-332	246-374
E	Very high	> 174	> 174	> 291	> 332	> 374

Table 6. Correction factors for the class-C values in Table 5

Class	P_2O_5 factor	K_2O factor
A	1.5	1.5
B	1.25	1.25
C1 (lower part of C)	1	1
C2 (upper part of C: P 90-110; K 148-178 light, 177-212 medium, 205-245 heavy soil)	0.5	0.5 for cereals and potatoes; 0.75 for other crops
D	0.5 only on light soils (clay < 15 %), as subsurface banding	0.5 (D1); 0 for cereals (D2)
E	No fertilization	0

Monitoring, communication and long-term management

Immobilization reduces the mobility and bioavailability of metals but does not remove them from the soil. Therefore, appropriate land-use restrictions should be documented, and regular environmental monitoring should be conducted according to the site-specific monitoring plan to ensure the long-term effectiveness of immobilization. Chitosan, in particular, is biodegradable, and its gradual decomposition may lead to the remobilization of previously bound metals. Table 7 summarizes five key monitoring parameters, together with the recommended measurement frequency and the purpose of each parameter, to support the preparation of a site-specific monitoring plan.

Table 7. Monitoring plan for immobilized sites under non-food use

Parameter	Frequency	Purpose
Mineral nitrogen (N_{min})	Every year before planting	Sets the nitrogen rate
Phosphorus and potassium (CAL)	At intervals set by national guidelines	Adjusts P and K rates as content classes change
Soil pH	With each nutrient sampling	Falling pH makes metals more mobile and triggers the P correction
Plant-available metal fractions	Before application, then at agreed intervals	Shows whether the amendment is still effective
Metals in the harvested biomass	At each harvest	Confirms that the biomass is fit for its end use

Successful implementation depends on the cooperation of several actors. Table 8 summarizes their roles.

Table 8. Actors and their roles

Actor	Role
Regional environment authority	Contaminated-site register; approval of the risk-management concept
Municipality	Land-use planning, local coordination and communication with residents
Landowners and farmers	Implement the measures; keep field records
Agricultural advisory service	Prepares and reviews fertilization plans
Accredited laboratory	Analyses of soil, plants and amendments
Research partners	Trial design and interpretation of results
Biomass buyers	Secure the end use and its quality requirements

Communication

- Inform local residents at an early stage about the type and extent of contamination, the associated risks, the planned remediation measures, and any restrictions on future land use.
- Ensure the commitment and active involvement of the local administration in communication and public awareness activities from the beginning. Experience from the PoLaRecCE project shows that effective communication with local communities requires the support and cooperation of the local administration.
- Publish environmental monitoring results regularly, using clear and accessible language that can be easily understood by local residents.

Financing

- First, check the availability of national and regional funding programmes supporting the remediation and management of contaminated sites.
- The EU Soil Monitoring Law recognizes the polluter-pays principle. Where the responsible polluter cannot be identified or held liable, public funding, including available EU funding instruments, may be considered in accordance with applicable national and EU regulations.
- Non-food agricultural activities on remediated or degraded land may be eligible for agricultural support schemes. Eligibility conditions and available funding opportunities should be verified with the relevant national paying agency.

Checklist for administrations
The following checklist summarizes the tasks of the five steps.

Before you start

☐ Site checked against the national contaminated-site register

☐ Competent authority has confirmed that immobilization with non-food use is acceptable

☐ Landowners, farmers and the municipality have agreed to take part

Steps 1 and 2: Assessment

☐ Contamination assessment commissioned (metals, total and available fractions, extent)

☐ pH, clay content and organic matter measured

☐ N_{min} sampled before planting

☐ P and K analysed with the CAL method; P corrected if pH < 6

Step 3: Amendment and crop

☐ Amendment chosen on the basis of the metals and the soil properties

☐ Product analysis received, including the amendment's own contaminant content

☐ Non-food crop chosen and biomass buyer identified

☐ Disposal route for combustion ash or residues planned

Step 4: Fertilization

☐ N rate calculated and reduced for N_{min} above 40 kg N ha^{-1}

☐ P and K rates calculated with the correction factors of the content classes

☐ Nitrates Directive and Natura 2000 limits checked

Step 5: Long-term management

☐ Land-use restriction documented

☐ Monitoring plan agreed, with responsibilities and budget

☐ Residents informed; results published regularly

Glossary

A list of notions/terms specific to this document with short explanations

Notion	Description
AAS	Atomic absorption spectroscopy, a laboratory method to measure elements such as potassium
Biochar	Carbon-rich solid produced by heating biomass under oxygen-limited conditions
CAL method	Calcium-acetate-lactate extraction of plant-available P and K (ÖNORM L 1087)
CEC	Cation-exchange capacity: the amount of positively charged ions a material can hold
Chitosan	Biodegradable biopolymer derived from chitin
EUF	Electro-ultrafiltration, a method to extract readily available nutrients, including organic N
ICP-OES	Inductively coupled plasma optical emission spectroscopy, a laboratory method to measure many elements at once
In-situ immobilization	Binding contaminants in the soil where they are, instead of removing the soil
N_{min}	Mineral nitrogen (nitrate plus ammonium) available to plants
NET	Negative emission technology: removes CO_2 from the atmosphere and stores it
NIR	Near-infrared spectroscopy, used for fast soil scans
PTM	Potentially toxic metal
Zeolite	Porous aluminosilicate mineral with a high cation-exchange capacity

Bibliography

[1] Payá Pérez, A.; Rodríguez Eugenio, N. Status of Local Soil Contamination in Europe: Revision of the Indicator “Progress in the Management Contaminated Sites in Europe”; Copenhagen, 2018.