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PoLaRecCE

magnetometry for rapid assessment of soil pollution

SUBJECT * MERGEFORMAT Best available practices and on-site techniques for environmental site assessment and soil recovery

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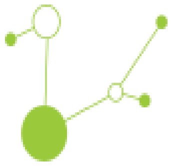

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Executive summary

Deliverable 2.1.1 of the PoLaRecCE project is related to Activity 2.2, which focuses on the development of toolboxes for environmental site assessments. Its purpose is to provide guidelines for the use of soil magnetometry as a simple, fast, cost-effective, yet reliable geophysical screening method. This technique is based on measurements of magnetic susceptibility (κ) in topsoil and soil cores, in accordance with the ISO 21226:2019(E) standard [1]. Soil magnetometry is applied as a preliminary method for assessing the degree of soil contamination with potentially toxic elements (PTEs). PTEs represent one of the most problematic categories of anthropogenic soil pollutants. These include, among others, chromium, manganese, iron, cobalt, nickel, copper, zinc, arsenic, selenium, molybdenum, cadmium, mercury, and lead. They have been accumulating in soils continuously since the onset of the industrial revolution, primarily due to dry and wet deposition of airborne particles from atmospheric emissions [2]. Given both historical and ongoing emissions, as well as the persistent nature of these pollutants, determining soil quality—as well as the sources, scale, and extent of contamination—requires continuous environmental monitoring.

This document is written in clear language intended for end-users and includes explanatory boxes for easier understanding, along with proper citations for further reading.

1. Introduction

1.1. Objectives

The objective of Deliverable 2.1.1 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 [1].

1.2. Scope

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. These findings highlight its potential for use in standardized, routine soil quality monitoring.

1.3. Relations to other documents

A short description of how this document relates to other documents developed within the project.

In the PoLaRecCE project, this Deliverable 2.1.1 is linked to Activity 2.2, which includes all activities for the development of toolboxes for environmental site assessment (D 2.1.1, D 2.1.2 and D 2.1.3).

1.4. Intended Audience

This document is intended for local and regional administration, advisors and policymakers involved in soil management, farmers and land owners.

1.5. Usage guidelines

As a training material for end-users, this document has been written in an easy-to-understand language, supported by explanatory schemes. However, proper references are provided to allow those interested to further explore the topic.

2. Soil magnetometry as a method for determining soil condition

2.1. 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): 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; 2) **geostatistical evaluation and processing** of magnetic data to generate a map of the spatial distribution of κ values and to locate magnetic anomalies; 3) **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; 4) **chemical analysis** of heavy metals in core samples collected from magnetic ‘hot spots’—areas with the highest probability of pollution by PTEs.

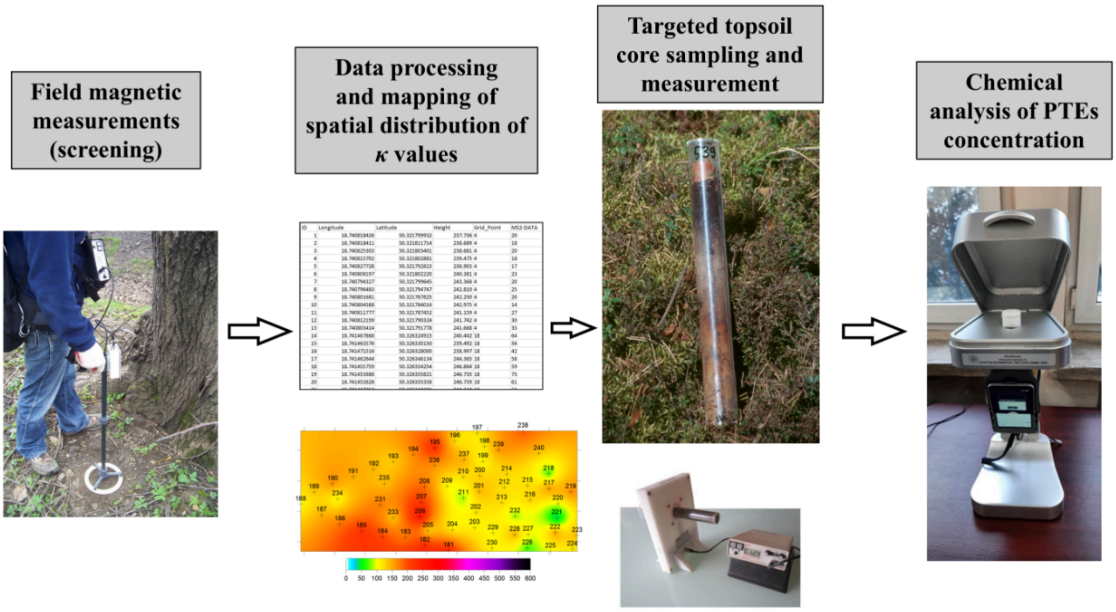


Figure 1 Four steps procedure of soil magnetometry (ISO21226:2019)

2.1.1. 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.

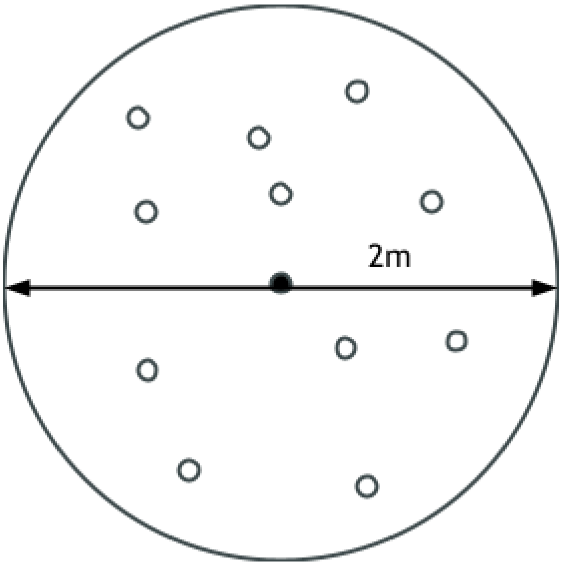


Figure 2 Scheme of field measurement of magnetic susceptibility (κ) values in sample point

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

2.1.2. 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).

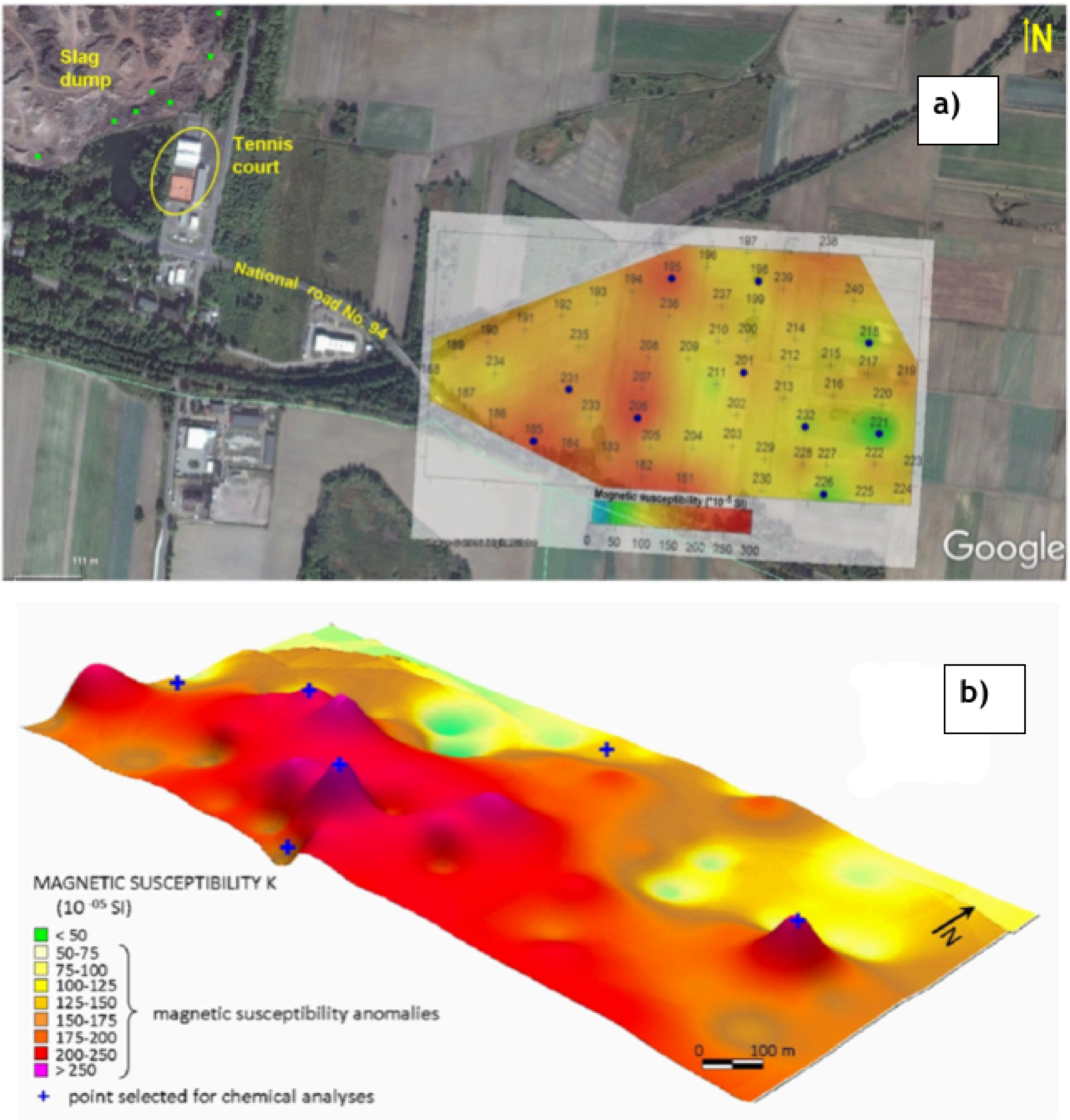


Figure 4. Examples of maps of spatial distribution of magnetic susceptibility values: a) example of 2D map [4], example of 3D map [6].

2.1.3. 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.

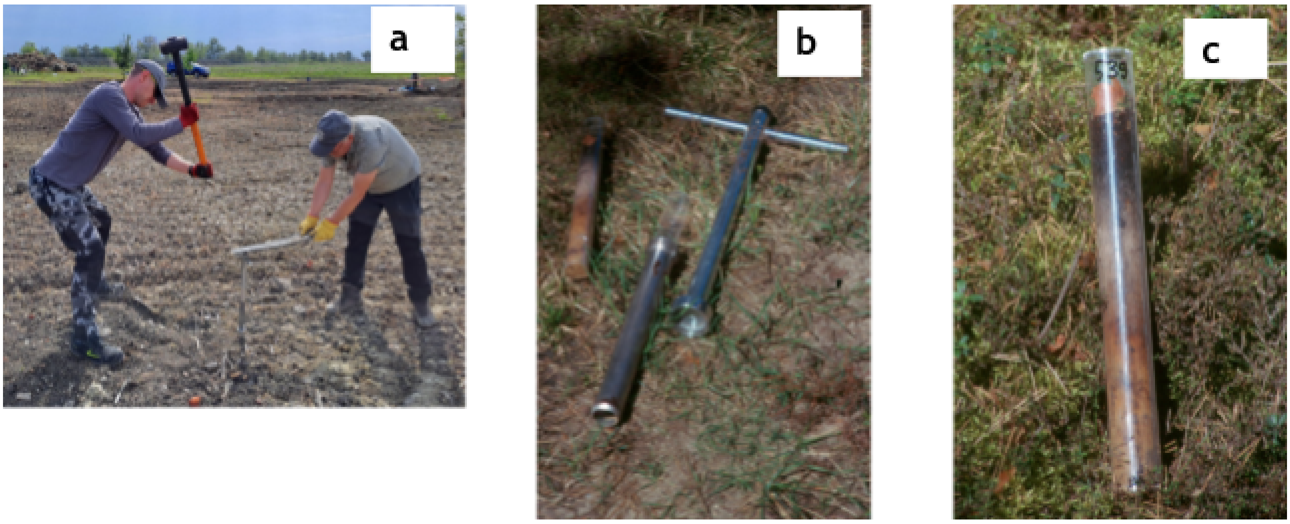


Figure 5 Topsoil core sampling: a) core sampling, b) two parts of Humax core sampler, c) topsoil core.

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).

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

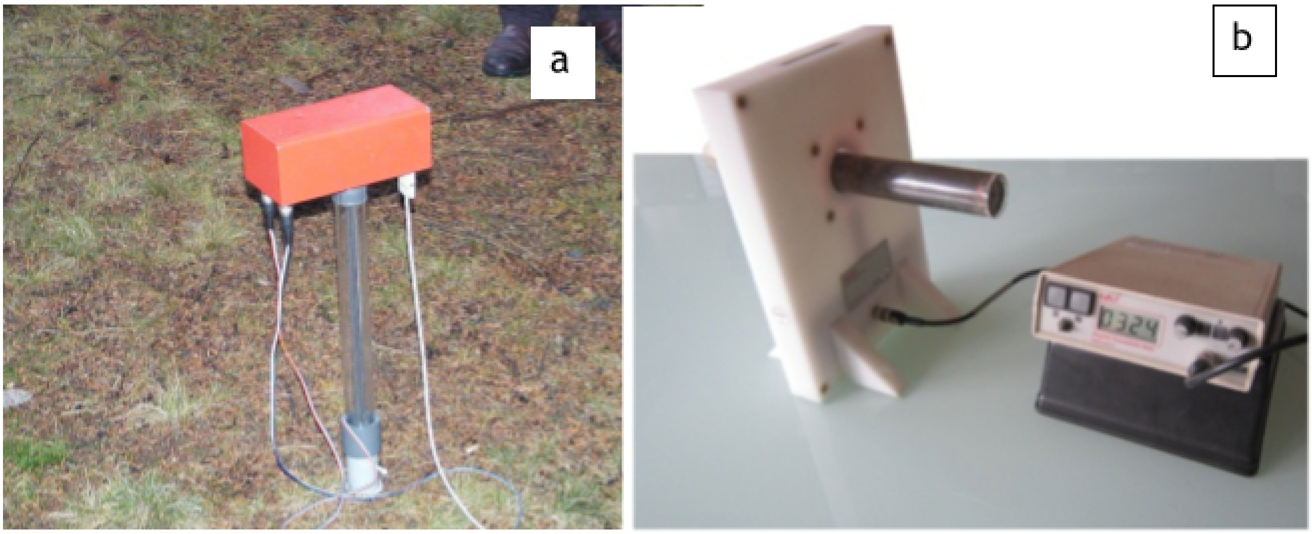


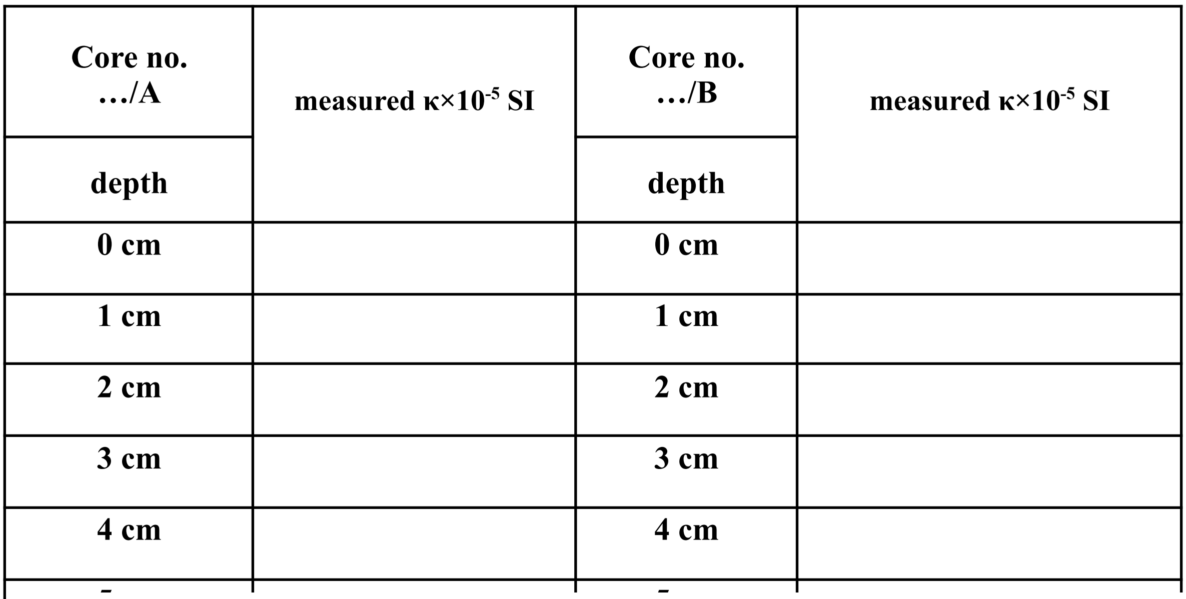
Figure SEQ Figure * ARABIC 6 Measurement of vertical distribution of κ value along the topsoil cores: a) automatic field measurement; b) laboratory measurement.

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 κ×10^{-5} SI**	**Core no. …/B**	**measured κ×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**	

Figure SEQ Figure * ARABIC 7 Measurement protocol from the laboratory measurement of vertical distribution of κ valies in topsoil cores.

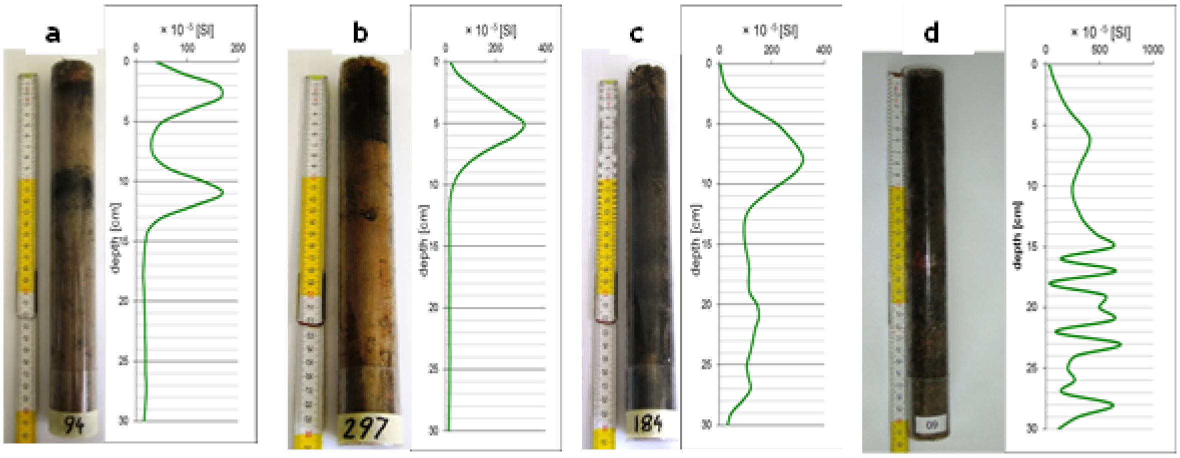


Figure 8. Examples of different topsoil cores and vertical distribution of κ values: a) core with buried organic horizon from polluted areas; b) typical core from polluted area developed on sundy soil; c) core from polluted area developed on chernoziem; d) core from urbanosol developed on anthropogenic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

2.1.4. 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) [7]. 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).

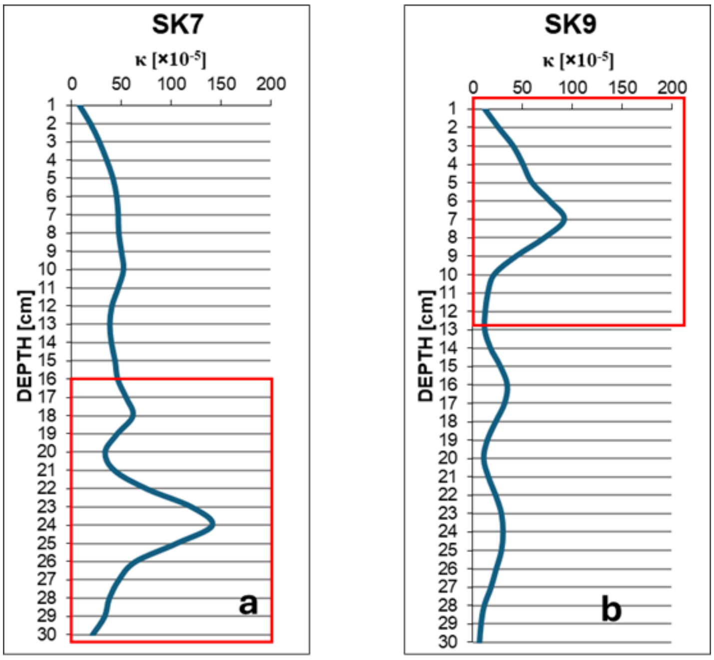


Figure 9. Examples of distribution of magnetic susceptibility values: a) natural (most probably pedogenic) occurrence of magnetic particles; b) accumulation of TMPs as a result of deposition.

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

3. 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:

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

$$\sqrt[n]{CF_{Zn} \times CF_{Pb} \times CF_{Cd} \times \cdots \times CF_n}$$

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:

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

where $\mathbf{C_{el}}$ is the measured concentration of elements at the sampling point and $\mathbf{C_{background}}$ 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).

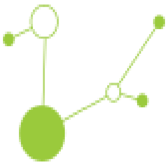
4. Applicability and limitations in using soil magnetometry.

The ISO 21226:2019(E) standard specifies the procedure for measuring the magnetic susceptibility of soils (κ or x) 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.

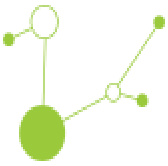
This method is applicable for screening all anthropogenic emission sources related to TMPs, including the long-range transport of airborne elements, for which TMPs serve as carriers and indicators. Such emission sources include the majority of high-temperature industrial processes, where iron is present 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

Bibliography

[1] ISO. 2019. ISO 21226:2019: Soil Quality—Guideline for the Screening of Soil Polluted With Toxic Elements Using Soil Magnetometry. International Organization for Standardization.

[2] Magiera T., Zawadzki J., Szuszkiewicz M., Fabijańczyk P., 2018. Impact of an iron mine and a nickel smelter at the Norwegian/Russian border close to the Barents Sea on surface soil magnetic susceptibility and content of potentially toxic elements; Chemosphere 195, 48-62.

[3] Magiera, T.; Jabłońska, M.; Strzyszcz, Z.; Rachwał, M., 2011. Morphological and mineralogical forms of technogenic magnetic particles in industrial dusts. Atmos. Environ., 45, 4281–4290.

[4] Rachwał M., Wawer M., Magiera T., Steinnes E., 2017. Integration of soil magnetometry and geochemistry for assessment of human health risk from metallurgical slag dumps; Environmental Science and Pollution Research.

[5] Magiera, T., Łukasik, A., Zawadzki, J., & Rösler, W., 2019. Magnetic susceptibility as indicator of anthropogenic disturbances in forest topsoil: A review of magnetic studies carried out in Central European forests. Ecological Indicators, 106, 105518.

[6] Magiera, T., Rachwał, M., Łukasik, A., 2013b. Soils of urban forests and parks of the Upper Silesia region. In: Charzyński, P., Hulisz, P., Bednarek, R. (Eds.), Technogenic Soils of Poland. Polish Society of Soil Sciences, Toruń, pp. 301–319.

[7] Magiera, T., & Szuszkiewicz, M., 2025. Combination of Portable X-Ray Fluorescence With Soil Magnetometry as an Effective Tool for Distinguish Different Pollution Sources. Land Degradation & Development.