INTERNATIONAL STANDARD

ISO 21226

First edition
2019-12

Soil quality — Guideline for the screening of soil polluted with toxic elements using soil magnetometry

Qualité du sol — Lignes directrices pour le criblage du sol pollué par des éléments toxiques en utilisant la magnétométrie du sol

Reference number
ISO 21226:2019(E)

ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Fax: +41 22 749 09 47
Email: copyright@iso.org
Website: www.iso.org

Published in Switzerland

Contents

Page

Foreword

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This document was prepared by Technical Committee ISO/TC 190, *Soil quality*, Subcommittee SC 3, *Chemical and physical characterization.*

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

At the time of publishing this document, the mapping of soil pollution status is generally based on geochemical methods that, despite development of new, more sophisticated and precise equipment, have apparent disadvantages, among them uncertainty, as usually there is no satisfactory information on the extent and range of pollution in the area. This results in the need of a large number of samples to be collected, followed by expensive and time-consuming chemical analysis.

Among anthropogenic soil pollutants, trace elements [potentially toxic elements (PTEs)] are the most problematic, widespread and persistent group that has accumulated in soil since the beginning of industrial revolution, mostly due to dry and wet deposition of particulates originating from emissions to the atmosphere. Due to the historical and persistent character of pollution, determination of soil quality, sources, extent and range of pollution requires large-area dense environmental monitoring network. In addition, identification of sources, pathways and extent of long-range transboundary transport of airborne trace elements creates serious technical problems and uncertainties. This has resulted in the development and broad application of soil magnetometry as easy-to-use, quick, inexpensive but sensitive and reliable screening geophysical technique based on the measurements of magnetic susceptibility in topsoil.

The method has not yet been standardized. For this purpose, a standard procedure, protocols and guidelines for the using soil magnetometry as a screening method are developed primarily to support the implementation of the two-stage optimized geophysical/geochemical method of measuring the soil spatial anthropogenic pollution with airborne trace elements from the dry and wet deposition, for further delineation of polluted soil areas to be adequately managed. The method provides data on the volume-specific magnetic susceptibility, κ, which reflects cumulative anthropogenic pollution of soil with trace elements, expressed as a PLI. The method is intended to serve as a screening and early warning system to be applied at any scale, from local to large regional one, also for the investigation of a long-range airborne element transport.

The application of this screening method alone does not allow determining the kind and concentrations of specific trace elements in soils. To carry out a more precise survey of the anthropogenic soil pollution with airborne trace elements, soil magnetometry as the screening geophysical “in situ” measurement technique (the 1st stage) is to be integrated with the classical geochemical methods (the 2nd stage) of the optimized procedure. Specifically, on the basis of geophysical methods used for screening, a relevant dense geochemical monitoring network can be applied in the areas of diagnosed elevated risk, thus reducing the number of samples and chemical analyses required.

Soil quality — Guideline for the screening of soil polluted with toxic elements using soil magnetometry

1 Scope

This document specifies methods for the measurements of magnetic susceptibility of soils (*κ*) as an indicator of potential soil pollution/contamination with trace elements associated with technogenic magnetic particles (TMPs) and describes related procedures, protocols and guidelines to be applied as a screening geophysical method of determination of soil pollution with trace elements. The results of measurements are used for preparing the maps of magnetic susceptibility of soils in the area of interest. From these maps, the areas of elevated and high magnetic susceptibility indicating high trace element total pollution load are discriminated for further identification of pollutants by geochemical methods.

This document is applicable to screening all TMPs-related anthropogenic emission sources including long-range transport of airborne elements, of which TMPs are carriers and indicators. Such emission sources comprise the majority of high-temperature industrial processes, where iron is present in any mineralogical form in raw materials, additives or fuels, is transformed into ferrimagnetic iron oxides (e.g. fossil solid and liquid fuels combustion, metallurgy, cement and ceramics industry, coke production, industrial waste landfills, land transport). This document is not applicable to screening anthropogenic emissions not associated with TMPs, e.g. organic pollutants or emissions from agricultural sources.

NOTE 1 Copper, zinc and other non-ferrous metal ores also contain iron (in many sulfides) as this element is abundant in almost all environments. During smelting, the iron occurring in sulfides is transformed into ferrimagnetic oxides (TMPs). However, in such cases, the proportion of TMPs and related PTEs is usually less than at coal combustion or iron metallurgy, for example, and not all PTEs are physically associated and transported by TMPs. Non-airborne elements are deposited in the close proximity of the emission source, while TMPs can be used in these cases as indicators of airborne elements and of the spatial distribution of the total element deposition from a smelter in the area.

In rare cases, some soils are developed on bedrock exhibiting geogenically high magnetism, which can cause false-positive results. This influence can, however, be easily indicated by measurements of magnetic susceptibility along soil profiles. This method is not applicable when the bedrock exhibits extremely high magnetic signals.

NOTE 2 Such cases are rare.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
topsoil
upper part of a natural soil that is generally dark coloured and has a higher content of organic matter and nutrients when compared to the (mineral) horizons below, excluding the humus layer

Note 1 to entry: For arable land, topsoil refers to the ploughed soil depth, while for grassland it is the soil layer with high root content.

3.2
subsoil
natural soil material below the *topsoil* (3.1) and overlying the parent material

Note 1 to entry: All or much of the original rock structure has been obliterated by pedogenic processes.

3.3
technogenic magnetic particles
different mineral forms of iron oxides exhibiting magnetic properties that are components of anthropogenic emissions from high-temperature technologic processes and are carriers of airborne trace elements

3.4
soil magnetometry
geophysical survey technique used for mapping spatial variations in the magnetic properties [mostly *magnetic susceptibility* (3.5)] of *topsoil* (3.1) and *subsoil* (3.2)

3.5
magnetic susceptibility
measure of the ability of a material to be magnetized expressed in SI magnetic units, which is proportional to the concentration of *technogenic magnetic particles* (3.3) in *topsoil* (3.1), indicating cumulative anthropogenic contamination of soil with trace elements

3.6
mass magnetic susceptibility
magnetic susceptibility (3.5) divided by density of sample material, measured in a laboratory when the mass of measured sample is known

3.7
frequency dependence of magnetic susceptibility
χ_{fd}
parameter revealing presence of superparamagnetic particles, being the result of natural (pedogenic or biogenic processes)

3.8
magnetic susceptibility mapping
development of 2D or 3D maps with the use of measured data of *magnetic susceptibility* (3.5) in the area of interest correlated with pollution load index

3.9
pollution load index
dimensionless index showing cumulative anthropogenic pollution of soil with trace elements used to validate results of *magnetic susceptibility* (3.5) screening

3.10
contamination factor
ratio of specific metal concentration in soil and its background value in soil

3.11
natural background concentration
concentration of a substance that is derived solely from natural sources (i.e. of geogenic origin) commonly expressed in terms of average, a range of values or a natural background value

Note 1 to entry: For the practical purposes of this document, this is mean element concentration in subsoil measured in soil cores collected from studied area.

3.12
soil core
core collected from an uppermost soil layer (min. 200 mm long and 35 mm in diameter)

3.13
boundary depth
depth in soil profile where *magnetic susceptibility* (3.5) stabilizes after decreasing from its maximum value, indicating the transition from the polluted layer to unpolluted part of soil profile

4 Symbols and abbreviated terms

PTE	potentially toxic trace element
TMP	technogenic magnetic particle
C_e	element concentration in a sample
$C_{Bl\text{-}e}$	baseline value for an element *e*
CF_e	contamination factor
PLI_{SITE}	pollution load index
κ	magnetic susceptibility
χ	mass magnetic susceptibility
χ_{fd}	frequency dependence of magnetic susceptibility

5 Fundamentals

5.1 Screening principle

Magnetic iron oxides are components of industrial and urban dusts emitted to the atmosphere and deposited on the soil surface. Anthropogenic emission sources of pollution containing technogenic magnetic particles (TMPs) comprise metallurgy, combustion of fossil fuels, coke industry, cement and ceramic industry, land transport, waste landfill sites and others.

Volume-specific magnetic susceptibility κ is directly proportional to the concentration of magnetic particles within the sensor penetration area and reflects cumulative anthropogenic contamination of soil with PTEs. High interdependence between the total historic dust dry and wet deposition, and magnetic susceptibility has been well confirmed. Magnetic susceptibility can be measured quickly and accurately in trace amounts as validated in Annex D. Magnetic susceptibility mapping of an area of interest based on the measurements of magnetic susceptibility in topsoil (soil surface and uppermost horizons), correlates with cumulative anthropogenic pollution with airborne trace elements expressed as pollution load index (PLI). Annex A describes the relation between magnetic susceptibility and trace element contamination taking place in topsoil.

5.2 Screening work processes

This screening method consists of two or three steps. All measurements may be performed either in the field only (two-step procedure), or as field and laboratory works (three-step procedure):

— field measurements and works;

— laboratory measurements;

— data mapping.

The next step is related to the use of screening measurement data maps with delineated potentially polluted areas for the targeted soil sampling within the proper geochemical analysis of soil pollution status:

— soil sampling for geochemical analysis.

5.3 Field measurements and works

Field measurements and works to be carried out are as follows:

— surface measurements of magnetic susceptibility of topsoil;

— in situ measurements of magnetic susceptibility along soil profiles (optional);

— topsoil core sampling for laboratory measurements of magnetic susceptibility along soil profiles.

5.4 Laboratory measurements

Magnetic susceptibility is measured along soil profiles in a laboratory.

5.5 Data mapping

Data mapping to be completed are as follows:

— magnetic susceptibility mapping of the area;

— delineation of contaminated sites for further geochemical analysis.

5.6 Soil sampling for geochemical analysis

Soil sampling is necessary, in case geochemical analysis is additionally arranged. See 7.5.

6 Apparatus

The following equipment and devices are used.

6.1 Field equipment

6.1.1 Field magnetic susceptibility loop sensor.

6.1.2 GPS.

6.1.3 Datalogger coupled with GPS or laptop.

6.1.4 Topsoil core sampler.

6.1.5 Plastic tubes for the topsoil core sampler.

6.1.6 Hammer.

6.1.7 Field core magnetic susceptibility meter (optional).

6.1.8 Laptop coupled with a field core magnetic susceptibility meter (optional).

6.2 Laboratory equipment

6.2.1 Dual-frequency laboratory magnetic susceptibility sensor.

6.2.2 Laboratory core magnetic susceptibility meter.

6.3 Data mapping

6.3.1 Visualization, contouring and surface modelling software.

NOTE Software used for terrain modelling, bathymetric modelling, landscape visualization, surface analysis, contour mapping, 3D/2D surface mapping, gridding and volumetrics.

7 Procedures

7.1 Measurement network

The main purpose of surface measurements of magnetic susceptibility is the determination of spatial distribution of pollution with trace elements. Basic measurements of magnetic susceptibility (κ) in the area of interest are performed in the field in a possibly regular network that is designed as discussed in Annex B.2. The grid density is selected depending on the size of an area to be screened, and the availability of preliminary information concerning possible sources and extent of anticipated pollution, but no less than 1/7 to 1/10 of the surveyed area, at the distance ratio DR approximately 1:1 to 1:2 between basic measurement points.

In the areas of identified elevated magnetic susceptibility, additional measurements should be performed close to about every third basic point, at the considerably smaller distance ratio DR approximately 1:5 to 1:10.

Within delineated areas of magnetic susceptibility higher than the average for the area, dense measurements should be carried out. The measurement points may be sited in irregular distances.

7.2 Measurements of magnetic susceptibility at the topsoil surface

Magnetic susceptibility (κ) at the topsoil surface is measured in the field with a portable hand magnetic susceptibility loop sensor in network points. The geographic position of each measurement point is recorded with GPS as is shown in the scheme in Annex B.1. Within about 2 m radius around the GPS position, at least 11 measurements (odd number) of magnetic susceptibility shall be taken. The soil surface shall be available for a sensor, thus a thick vegetation or litter in the measurement point should be racked aside.

The time needed for a single measurement is approximately 1 s.

The measurement results can be downloaded from a datalogger coupled with GPS and are ready for analysis. The downloaded table for a single measurement includes coordinates and measured values of soil magnetic susceptibility.

NOTE Extraordinary high values of magnetic susceptibility (outliers) can be caused by the occasional occurrence in topsoil layer of metallic artefacts. The possible impact of artefacts is eliminated by the rejection of the highest and the lowest values from the measured set of results when calculating mean value for a single point.

7.3 Measurements of vertical magnetic susceptibility distribution

7.3.1 General

The main purpose of measurements of magnetic susceptibility (κ) along the topsoil profile is: (a) determination of vertical distribution of anthropogenic pollution of the soil with trace elements that could be caused by different accumulation in organic horizons or by vertical migration of TMPs; (b) detection of possible influence of magnetic properties of a bedrock; (c) evaluation of the background magnetic susceptibility values;

Measurements of magnetic susceptibility along the soil profiles can be performed in two ways:

— by taking topsoil cores in the field and sending to the laboratory for magnetic susceptibility analysis;

— by in situ measurement of magnetic topsoil profile (optional).

The choice of field or laboratory measurements depends on the convenience, the need of obtaining instant information for further measurement performance and availability of equipment.

7.3.2 Topsoil core sampling

The topsoil core samples should be taken in the parts of the area showing the highest magnetic susceptibility (κ). Additionally, for a reference at least one core sample from the area of the lowest, and also of the moderate magnetic susceptibility shall be taken. The number of sampling points should be specified individually with regard of representativeness.

Cores are taken in the field in plastic tubes with the use of soil core sampler hammered into the soil layer. Plastic tubes, after checking the core status, shall be protected from core destabilization within the tube by capping from both sides with neutral caps, marked and wrapped tightly into thin plastic foil for the protection from moisture loss.

7.3.3 Field measurements

In situ measurements are more time-consuming, and slow down the measurement campaign; they preferably need dry weather for convenient performance. These measurements should be carried out if the results are required for a further proper design and conducting spatial field measurements.

The automatic “in situ” measurement of magnetic topsoil profile can be performed with the use of a core magnetic susceptibility meter for field measurements along the soil profile to detect vertical distribution of pollutants and horizons of pollutant accumulation. These data in the form of tables and graphs presenting magnetic susceptibility values vs layer depth are available instantly at the laptop coupled with the meter.

NOTE 1 A core magnetic susceptibility meter for automated in situ measurements is not indispensable equipment. The same results can be obtained with the use of a laboratory analysis of core samples taken in the field.

NOTE 2 In case of in situ measurements, the diameter of core sampler is compatible with core magnetic susceptibility meter.

7.3.4 Laboratory measurements

Soil cores taken in the field in plastic tubes with the use of soil core sampler are measured in a laboratory using a laboratory magnetic susceptibility sensor.

7.3.5 Topsoil magnetic profile analysis

Topsoil magnetic susceptibility profiles are analysed to determine:

a) origin of elevated magnetic susceptibility (anthropogenic or natural);

NOTE In the case of an anthropogenic origin of elevated magnetic susceptibility.

b) vertical distribution of pollutants resulted from;

1) Anthropogenic accumulation in organic horizon;

2) Vertical redistribution of iron minerals and pollutants in pore solution;

3) Geogenic magnetic susceptibility of bedrock that is usually visualized by the increase with the depth. In this case, false-positive errors of soil magnetometry may indicate higher anthropogenic soil pollution of the area with trace elements. Make a decision with respect to the applicability of the method in the screened area.

c) background magnetic susceptibility values.

7.4 Magnetic susceptibility mapping and data analysis

7.4.1 Data processing

Of the measured magnetic susceptibility data set for each measurement point, the highest and the lowest values shall be rejected, and the mean value calculated (with standard deviation).

7.4.2 Magnetic susceptibility surface mapping

The mean values of magnetic susceptibility shall be used as input data into a visualization, contouring and surface modelling computer program in order to obtain 3D or 2D contour maps of magnetic susceptibility distribution in the analysed area.

7.4.3 Data analysis

In the map, the areas within the contours of the highest magnetic susceptibility values indicate elevated or high trace element concentrations. These areas should be selected for further geochemical analysis in order to detect specific pollutants and evaluate the level of soil pollution.

In general, magnetic susceptibility values:

— in the range within 0 to 30×10^{-5} SI magnetic units, considered to indicate low pollution with trace elements;

— in the range within 30×10^{-5} to 70×10^{-5} SI magnetic units, indicating moderate pollution with trace elements;

— in the range within 70×10^{-5} to 100×10^{-5} SI magnetic units, indicating elevated pollution with trace elements;

— above 100×10^{-5} SI magnetic units, indicating high pollution with trace elements.

7.5 Soil sampling for geochemical analysis

Topsoil core samples within a delineated high pollution area taken at the screening stage are ready for geochemical analysis.

If more detailed geochemical analysis is required, a network with a denser grid within delineated high-pollution area should be developed and additional core samples taken in accordance with a procedure described in 7.3.2.

8 Screening report

The following information shall be documented in such a way that it is immediately available on request. In the following list, at least, the items marked with an asterisk (*) shall be included in the screening report. An example of the report form is provided in Annex C:

a) a reference to this document, i.e. ISO 21226:2019;

b) name and characterization of a screened site*;

c) date of measurements*;

d) weather conditions during measurements*;

e) graphic scheme of a screened site with a measurement network*;

f) a complete identification of the topsoil surface measurement positions (coordinates) in the grid*;

g) measured topsoil surface magnetic susceptibility values (κ) for the given measurement position;

h) values rejected and the calculated mean values of surface magnetic susceptibility with standard deviation*;

i) computed contour 2D or/and 3D maps of surface magnetic susceptibility distribution with full control over all map parameters*;

j) measurement method of magnetic susceptibility along soil profile*;

k) computed contour 2D maps of surface magnetic susceptibility distribution with identification of the soil profile measurement positions (coordinates) in the network*;

l) measured soil profile magnetic susceptibility values (κ) for the given measurement position;

m) the calculated mean values of topsoil and subsoil magnetic susceptibility with standard deviation*;

n) background magnetic susceptibility values*;

o) any deviation from measurement methods and the reason for these deviations together with all circumstances that have influenced the results*;

p) computed magnetic susceptibility distribution graphs along soil profiles*;

q) delineated areas of elevated/high trace element contamination*;

r) a list of soil core samples ready for geochemical analysis*;

s) a network for additional core samples for geochemical analysis;

t) any guidance resulted from surface magnetic susceptibility distribution maps and topsoil magnetic profile analysis.

Annex A
(informative)

Relation between magnetic susceptibility and trace element contamination of topsoil

A.1 General

The sources of contamination contributing to total loads of elements in soil and their mobility differ temporally and spatially are of different character and origin. Environmental fate and behaviour of trace elements depends upon the character of emission and soil properties: they may be a subject of a long-range transport and affect remote areas far from the emission source. The extent and character of emissions and their impact may undergo temporal and spatial alterations, and thus may differ substantially from the actual cumulative extent of soil pollution.

The spatial variability of soil pollution from wet and dry deposition of trace elements is high, in particular in urban, industrial and post-industrial areas, but due to long-range transport of pollutants (LRTP) also in areas far from anthropogenic activity. Therefore, a relatively dense measurement network is required for identification of polluted areas and ones concerned about pollution risk, where adequate actions should be undertaken. The use of an efficient, fast, simple, and cost-effective screening method for identifying such areas and conducting in diagnosed polluted areas a relevant geochemical monitoring in the network of a required density at the next stage would substantially reduce the time, the costs, the number of samples and chemical analyses but increase precision.

Extensive research conducted in the world for over two decades proved that magnetic susceptibility of soil, which is an easily measurable geophysical parameter and directly related to the concentration of magnetic particles in soil, can be used as an indicator of cumulative soil pollution with trace elements from dry and wet deposition.

Most of magnetic particles occurring in topsoil are of anthropogenic origin. Technogenic magnetic particles (TMPs) are generated in practically all high temperature technological processes involving trace metals, where different iron minerals, present in raw materials, fuels and additives are transformed into highly magnetic iron oxides. Magnetic iron oxides are components of industrial and urban dusts emitted to the atmosphere and deposited on the soil surface. Anthropogenic emission sources of pollution containing Technogenic Magnetic Particles (TMPs) comprise combustion of fossil fuels, coke industry, metallurgy, cement and ceramic industry, land transport, waste landfill sites and others. TMPs are common components of urban dusts and aerosols[1].

This feature makes possible to use TMPs as tracers of anthropogenic pollution with trace metals, as their presence, even in trace amounts, in soils can be easily detected by magnetic measurements. Magnetic susceptibility (κ) has been shown to be a reliable parameter for estimating impact on soil of dry and wet deposition of potentially toxic trace elements (PTEs) from industrial and urban sources[2][3]. Moreover, TMPs are known to serve as carriers of trace elements[1]. Magnetic particles and trace elements may also be produced independently by the same process and simultaneously emitted[4]. Besides magnetic iron oxides are efficient sorbents of trace elements. In many extensive studies conducted worldwide for over two decades, a high correlation between PTEs and magnetic parameters was observed[4][5][6][7][8][9].

TMPs and PTEs are enriched in the uppermost 100 mm of soil in undisturbed lands, where the highest concentrations of trace elements are commonly observed. Also cultivated agricultural soils and industrial/ post-industrial lands are well suitable for magnetic methods to indicate of PTE pollution. Magnetic susceptibility has appeared as a valuable tool for identification of a long-range transport of pollutants which in many cases plays an important role in the environmental pollution with PTEs.

A large number of studies conducted so far confirm reliability of soil magnetometry as an indicator of soil contamination with trace elements from dry and wet deposition. This shows its potential for use in routine standardized soil quality monitoring.

A.2 Magnetic susceptibility (*κ*) and pollution load index (PLI)

A.2.1 Relation between magnetic susceptibility κ and trace element deposition

Volume-specific magnetic susceptibility *κ* is directly proportional to the concentration of magnetic particles within the sensor penetration area and reflects the cumulative anthropogenic contamination of soil with PTEs. Studies conducted so far confirmed high interdependence between the total historic dry and wet deposition and magnetic susceptibility. It can be measured fast and accurately in trace amounts. Magnetic mapping by measurements of magnetic susceptibility in topsoil (soil surface and uppermost horizons) correlates with cumulative pollution with potentially toxic elements (PTEs).

Magnetic susceptibility does not differentiate specific trace elements but reflects a retrospective cumulative load of airborne trace elements in soil originating from dry and wet deposition of anthropogenic emissions. Of different trace elements, 15 are known to have airborne properties and are proven long-range migrants: V, Cr, Ni, Cu, Zn, As, Se, Mo, Cd, In, Sn, Sb, Hg, Tl and Pb. All these elements (except In) are considered to be potentially toxic (PTEs).

These elements, in different proportions related to concentration in emissions and differences in airborne properties, constitute cumulative anthropogenic pollution of soils. There is not much information concerning distribution of trace elements in anthropogenic emissions during the entire period of industrial revolution and the development of motorization. However, PTE concentrations in the surface layer of ombrotrophic peat bogs in southernmost Norway, which receive pollutant loads entirely from wet and dry deposition and are strongly affected by long range transport of pollutants, follow the order: Zn, Pb > Cu, As, V, Ni, Se > Cd, Cr, Sn, Sb, Mo > Hg, In, Tl. This trace element distribution suggests the combustion of fossil fuels and traffic to be significant sources of soil pollution in the area with PTEs. A fine particulate matter PM2.5 is an important part of anthropogenic emissions, the main carrier of TMPs and airborne anthropogenic trace elements and a source of dry and wet deposition of pollutants onto soil. The contemporary trace element distribution in PM2.5 originating from different locations, mostly in cities in 16 countries of the world (nine European countries, Canada, USA, Japan, Singapore and China), shows a high Fe content and a prevalence of the trace element sequence of Zn > Pb > Cu > Ni > As > Cd with a changeable position of V and Cr. Domination of Pb over Zn happens in rare cases[10]. The cease from using leaded gasoline resulted in the farther position of Pb in the elemental sequence in PM2.5 from locations with high traffic, while petrol lead was the main source of Pb in long-range transported aerosols for at least a few decades in the middle part of the 20th century.

The content of airborne trace elements in soils constitutes a resultant of many decades of impact of anthropogenic emissions changing with the development of industry, new technologies, economic and historical situation. Therefore, the current status of land use and anthropogenic emissions in the area might be highly misleading. Soil magnetometry provides a fingerprint of actual trace element pollution status of soil.

A.2.2 Contamination factor

To correlate magnetic susceptibility of soil with the state of soil pollution for validation purposes, contamination factors CF_e for airborne “technogenic” elements can be calculated from the equations proposed by Tomlinson et al., 1980[11] for parameters indicating cumulative load: contamination factor CF_e and Pollution Load Index (PLI):

Contamination factor is given in Formula (A.1):

$$CF_{\mathrm{e}} = \frac{C_{\mathrm{e}}}{C_{\mathrm{Bl\text{-}e}}} \tag{A.1}$$

As a baseline value CF_{Bl-e} for an element e, the following values may be used:

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

b) a mean value of the lowest concentrations of the element detected in the surveyed site (in case of lacking soil cores).

A.2.3 Pollution Load Index

Pollution load index can be calculated as a point value (for a single sampling site), as shown in Formula (A.2):

$$PLI_{\mathrm{SITE}} = \sqrt[n]{CF_{\mathrm{Zn}} \cdot CF_{\mathrm{Pb}} \cdot CF_{\mathrm{Cd}} \cdot \mathrm{K}\,\mathrm{K} \cdot CF_{\mathrm{n}}} \tag{A.2}$$

or spatially for a selected area represented by similar values of magnetic susceptibility shown in Formula (A.3)

$$PLI_{\mathrm{AREA}} = \sqrt[m]{PLI_{\mathrm{SITE}_1} \cdot PLI_{\mathrm{SITE}_2} \cdot \mathrm{K} \cdot PLI_{SITE_m}} \tag{A.3}$$

A.2.4 Validation of correlation and robustness

Correlation and robustness of geophysical screening should be examined routinely within a QA/QC procedure after subsequent geochemical testing of PTE concentrations in the network based on the results of magnetic susceptibility measurements in the area. In such a case, 3D or 2D contour maps of pollution load index distribution in the analysed area should be developed in accordance with the procedure described in 7.4 and compared for correlation with 3D or 2D contour maps of magnetic susceptibility in the area (See Annex D).

In another case, the comparison can be performed on the basis of independent measurements of magnetic susceptibility and geochemical measurements of trace element concentrations in soil in separate networks. In such a case, owing to the lack of interdependence, the most objective and visible results are obtained and the tests are organized to aim primarily at the validation and robustness of geophysical and integrated geophysical-geochemical methods in specific cases and applications.

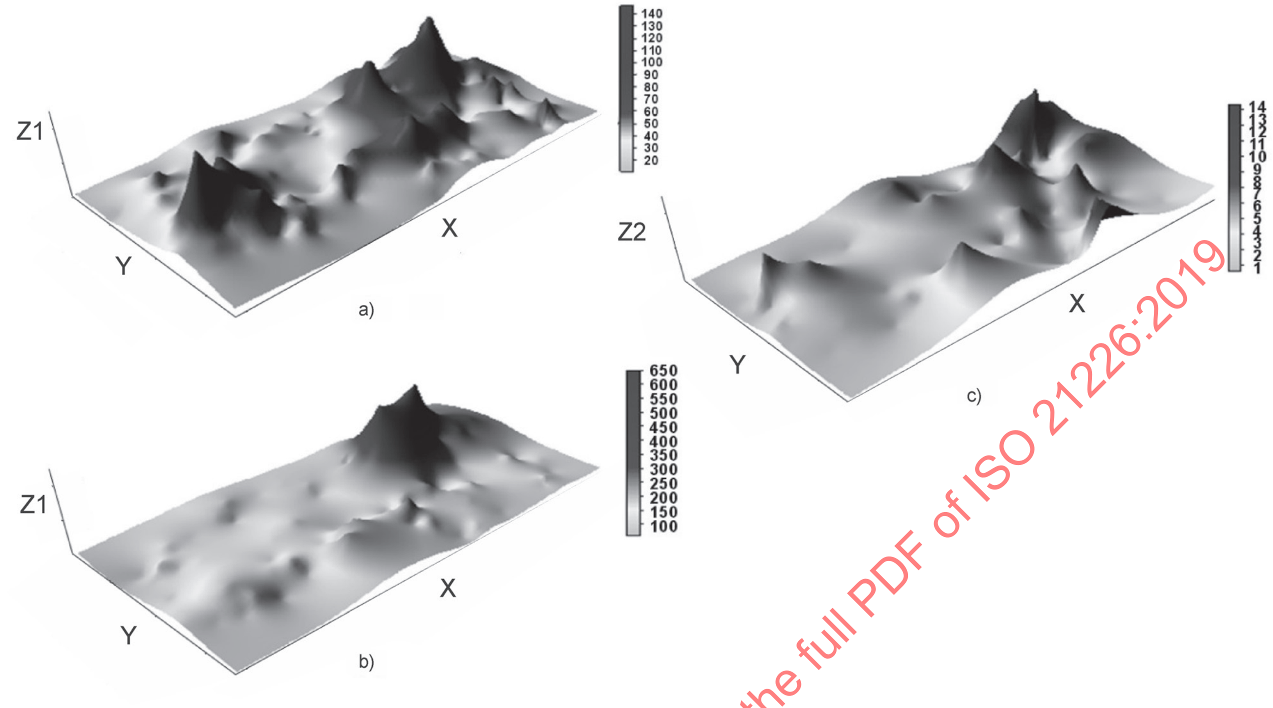
As a validation proof, the results of independent comparative studies are shown in Figures A.1 and A.2 (a, c, d, e and f). The results of subsequent geochemical measurements based on geophysical screening are shown in Figure A.2:

— "a" shows the "true pollution distribution". The PLI index is based on the regular network of 100 points;

— "b" shows the PLI distribution based on 30 points of targeted soil sampling (on the basis of magnetic screening);

— "c-f" show the PLI distribution based on 30 points of random soil sampling by four independent persons.

Figure A.3 demonstrates validation studies for a large area (18 415 km^2) performed in parallel in the same grid 4 × 4 km^2 by two independent teams: one conducted geophysical measurements of magnetic susceptibility κ and the other collected and analysed soil samples geochemically. In the investigated target area, the pollution level is mostly moderate. Some spots, however, show lower or higher pollution due to trace elements originating from different external and internal sources (industrial and transport emissions, spatial anthropogenic activity and in some places of a geogenic character). The results of measurements of magnetic susceptibility show high correlation with PLIs for groups of three (Zn, Cd and Pb) through five (Ni, Cu, Zn, Cd and Pb), 11 (V, Ni, Cu, Zn, As, Mo, Cd, W, Hg, Tl and Pb), 13 (V, Cr, Ni, Cu, Zn, As, Mo, Cd, W, Hg, Tl, Pb and U) and 15 elements in the soils of the area (V, Cr, Mn, Fe, Ni, Cu, Zn, As, Mo, Cd, W, Hg, Tl, Pb and U).



Key

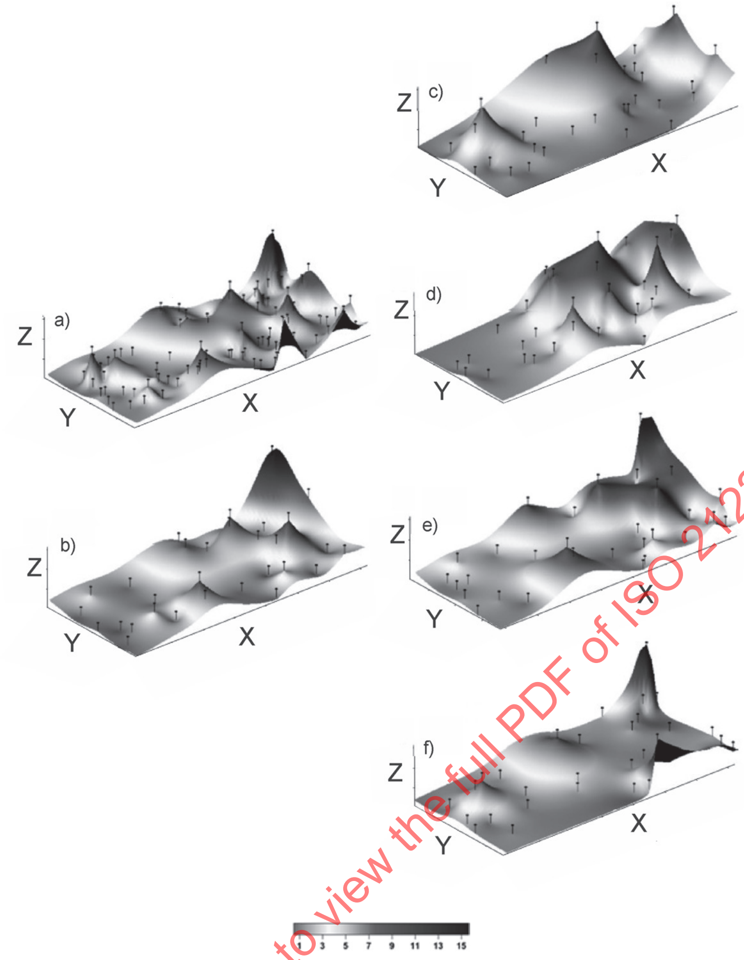
X longitude

Y latitude

Z1 magnetic susceptibility (κ)

Z2 pollution load index (PLI)

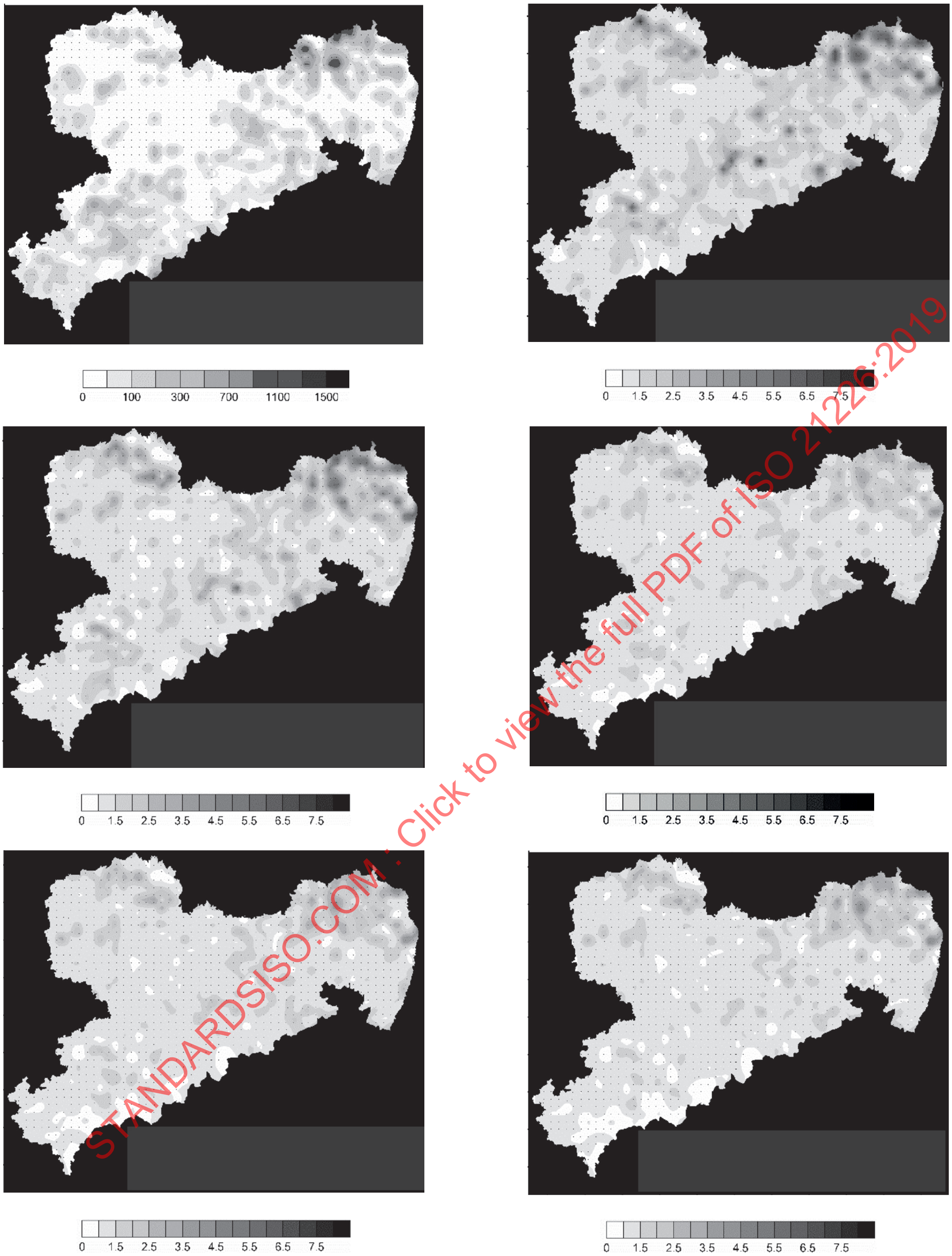
Figure A.1 — Method validation: Spatial distribution of magnetic susceptibility (*κ*) obtained by different tools: a) based on 180 measurements on the soil surface; b) based on 90 measurements in the uppermost 10 cm of soil vertical profiles; and c) Pollution Load Index (PLI) based on 61 chemical analyses (Area in the vicinity of Schwarze Pumpe power plant, Germany)



Key

⊺	sample location
X	longitude
Y	latitude
Z	pollution load index (PLI)
	Grayscale shows PLI.
a) - f)	see text

Figure A.2 — Method validation. PLIs: a) based on 100 chemical analyses (real pollution distribution) and c), d), e), and f) based on 30 points of random soil sampling by 4 independent persons; b) based on 30 points of targeted soil sampling (on the basis of magnetic susceptibility screening) (Area in the vicinity of Schwarze Pumpe power plant, Germany)



Key

top left	magnetic susceptibility (κ)
top right	PLI 3 elements (Zn, Cd and Pb)
center left	PLI 5 elements (Ni, Cu, Zn, Cd and Pb)
center right	PLI 11 elements (V, Ni, Cu, Zn, As, Mo, Cd, W, Hg, Tl and Pb)
bottom left	PLI 13 elements (V, Cr, Ni, Cu, Zn, As, Mo, Cd, W, Hg, Tl, Pb and U)

bottom right PLI 15 elements (V, Cr, Mn, Fe, Ni, Cu, Zn, As, Mo, Cd, W, Hg, Tl, Pb and U)

Grayscale top left shows magnetic susceptibility (κ), all other show PLI.

Further explanation see text.

Figure A.3 — Method validation. 2D map of 18 415 km2 area measured/sampled in a regular grid of 4 × 4 km at 1 168 points. Magnetic susceptibility vs PLI for three, five, 11, 13 and 15 elements determined geochemically at the same points (2014)

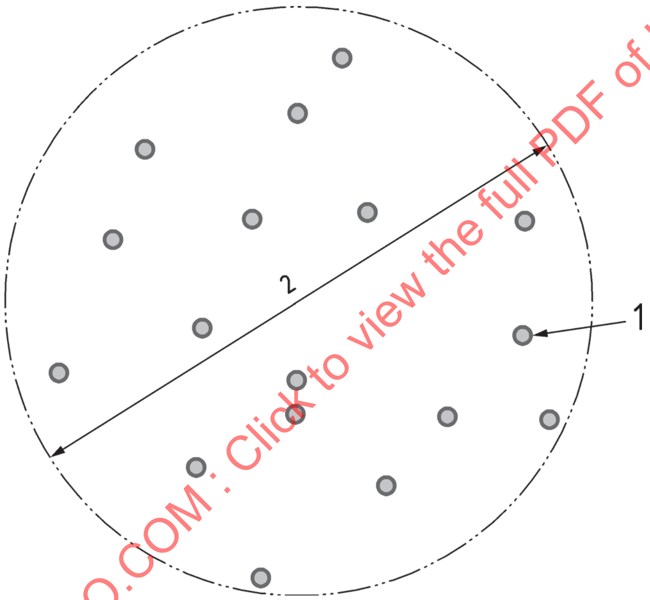
Annex B
(informative)

Measurement performance according to 7.1 and 7.2

B.1 Measurement performance at the single network measurement point

Magnetic susceptibility (κ) at the topsoil surface is measured in network points. Geographic position of each measurement point is recorded with GPS. The scheme of measurement performance at a single measurement point is given in Figure B.1.

At least 11 measurements of magnetic susceptibility shall be taken within about 2 m radius around the GPS position on a soil surface available for a sensor.



Key

1 single measuring spots within the network point

2 diameter of 2 m around the network point

Figure B.1 — Measurement performance at a network point

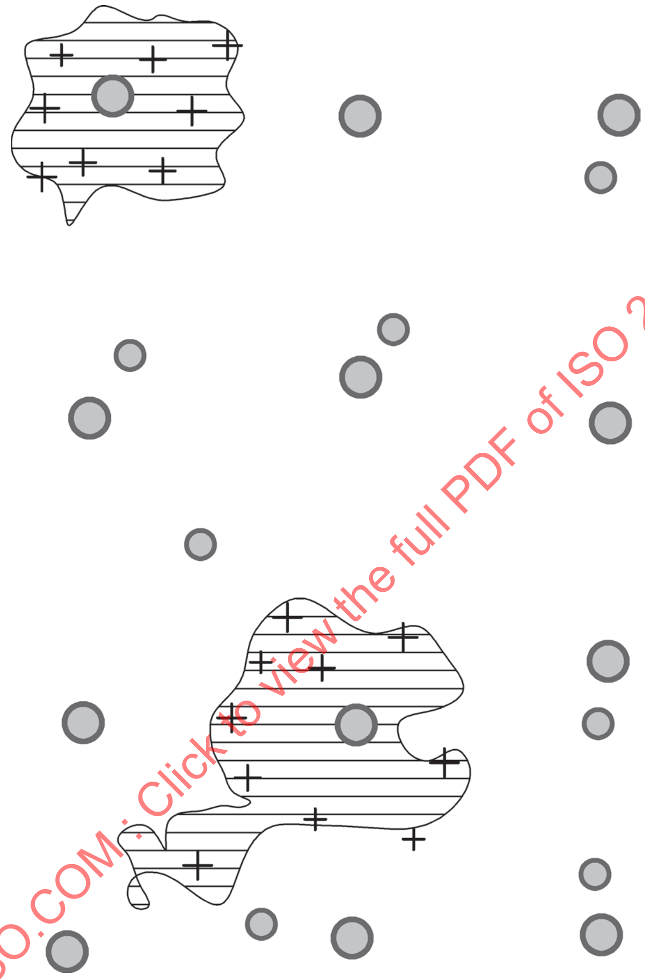
B.2 Design of a measurement network

Measurements of magnetic susceptibility in an area of interest are performed in a preliminary designed network following the three-stage procedure outlined in Figure B.2.

Stage 1: Basic measurements are to be conducted in a possibly regular major network. The grid density depends on the size of an area to be screened, the availability of preliminary information concerning possible sources and extent of anticipated pollution but no less than 1/7 to 1/10 of the surveyed area, at the distance ratio DR approximately 1:1 to 1:2 between major (basic) measurement points. The number of major measurement points: from several scores to several thousand, depending on the size of the area.

Stage 2: In the areas of identified elevated magnetic susceptibility, additional measurements shall be performed close to about every third major (basic) point, at the considerably smaller distance ratio DR approximately 1:5 to 1:10.

Stage 3: Within delineated areas at risk, of magnetic susceptibility higher than the mean value for the entire area, dense measurements shall be carried out. The measurement points may be sited in irregular distances.



Key

- basic measurement points in the regular network covering the entire area
- measurement points in an additional network in the areas of the elevated magnetic susceptibility
- measurement points in the delineated potential polluted areas (hot spots)
- hot spot

Figure B.2 — Design of the three-stage measurement network

Annex C
(informative)

Example of a screening report to record measurement results according to 9

The user of this document may make use of this present form.

The measurements were performed according to ISO 21226.

— Name of the screened site;

— Category of the screened site;

a) forest;

b) arable land;

c) grasslands;

d) post-industrial area;

e) urban area;

f) other.

— Site description (obligatory information);

a) forest - type of forest, predominant forest stand, age of trees, undergrowth, slope of the site (flat, slope < 5 %, slope > 5 %), other important available information;

b) arable land - state of the field (e.g. stubble field, ploughed field, sowed field - type of crop), slope of the site (flat, slope < 5 %, slope > 5 %) other important available information;

c) grassland - height of the grass, slope of the site (flat, slope < 5 %, slope > 5 %), other important available information;

d) post-industrial land - type of former industry, type of waste landfill/dumping site, kinds of artefacts present in topsoil, other important available information;

e) urban area - type of site (park, lawn, roadside), kinds of artefacts present in topsoil, other important available information;

f) others - slope of the site (flat, slope < 5 %, slope > 5 %), other important available information.

— Dates of measurements;

a) start;

b) end;

c) total duration (days);

d) weather conditions during the measurements: numbers of days with:

e) dry conditions;

f) wet conditions (rain, drizzle, after rain, fog);

g) frost.

— Graphic scheme of the screened site with a measurement network;

— Protocol on surface measurements (see Table C.1).

Table C.1 — Protocol on surface measurements

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							

— Graphic presentation of a computed contour 2D map of surface magnetic susceptibility distribution (with information about software used);

— Graphic presentation of a computed contour 2D map of surface magnetic susceptibility distribution with soil core location network;

— Measurement method of magnetic susceptibility of soil cores:

a) in situ;

b) laboratory:

— Protocol on soil core collection:

Table C.2 — Technical parameters of soil cores used (length and diameter)

Core no.	Mean surface κ value × 10^{-5} SI	Geographical position of a core			Remarks
		Latitude	Longitude	Altitude	
.../A					
.../B					

Table C.3 — Protocol on soil core measurements

Core no. **…/A** Depth	**κ value** × 10^{-5} SI	**Core no.** **…/B** Depth	**κ value** × 10^{-5} SI
0 cm		0 cm	
1 cm		1 cm	
2 cm		2 cm	
3 cm		3 cm	
4 cm		4 cm	
5 cm		5 cm	

— Graphic presentation of vertical magnetic susceptibility along soil profiles;

— Protocol on calculation of the most important parameters related to vertical distribution of κ values in a soil profile (see Table C.4).

Table C.4 — Protocol on calculation of the most important parameters related to vertical distribution of κ values in a soil profile

Core no. **…/A**	**Maximum** **κ value in topsoil** (× 10^{-5} SI)	**Depth of maximum κ value** (cm)	**Boundary depth** (cm)	**Mean κ value of topsoil**[a] (× 10^{-5} SI)	**± sd**	**Mean κ value of subsoil**[b] (× 10^{-5} SI)	**± sd**
Core no. …/B							

[a] Calculated as a mean κ value above the boundary depth.

[b] Calculated as a mean κ value below the boundary depth.

— Graphic presentation of a computed contour 2D map of the maximum κ value distribution in a soil profile (optional);

— Graphic presentation of a computed contour 2D map of the mean κ value distribution in a soil profile (optional);

— Protocol on core sampling for chemical analysis (see Table C.5).

Table C.5 — Protocol on core sampling for chemical analysis

Core no.	**Depth of sampled layer** (cm)	**Mean** **κ value of sampled layer** (× 10^{-5} SI)	**Mass magnetic susceptibility of soil sample** (× 10^{-8} m^3 kg^{-1})	**Mean mass magnetic susceptibility of soil sample** (× 10^{-8} m^3 kg^{-1})	**± sd**	**Frequency dependence of magnetic susceptibility** (%)

— Graphic presentation of the network for additional core samples for geochemical analysis (optional, if necessary);

— Any deviation from measurement methods and the reason for the deviations together with all circumstances that have influenced the results*;

— Other remarks.