

# World Soil Information Service (WoSIS) — Procedures for standardizing and coding soil analytical method descriptions (Version 2025)

ISRIC Report 2025/01

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# Contents

Contents .....	3
Preface .....	5
Summary .....	6
1. Introduction.....	7
2. Quality aspects related to laboratory data .....	7
2.1 Context .....	7
2.2 Laboratory error .....	8
2.3 Standardization of soil analytical method descriptions .....	10
3. Criteria for standardizing soil analytical method descriptions.....	11
3.1 Background .....	11
3.2 Guiding principles .....	12
3.3 Coding of analytical procedures and method options.....	13
4. Description of method options for soil properties standardized in WoSIS .....	15
4.1 Chemical properties.....	16
4.1.1 Soil pH .....	16
4.1.2 Cation exchange capacity.....	17
4.1.3 Calcium carbonate equivalent .....	20
4.1.4 Gypsum .....	21
4.1.5 Electrical conductivity .....	22
4.1.6 Soluble salts .....	22
4.1.7 Organic matter.....	23
4.1.8 Organic carbon .....	24
4.1.9 Total carbon.....	25
4.1.10 Total nitrogen .....	26
4.1.11 Phosphorus .....	27
4.1.12 Micronutrients and trace metal elements .....	28
4.2 Physical properties.....	30
4.2.1 Coarse fragments .....	30
4.2.2 Soil texture.....	31
4.2.3 Bulk density.....	33
4.2.4 Water retention.....	34
4.2.5 Hydraulic conductivity.....	36
5. Concluding remarks.....	37
Acknowledgements .....	38
Appendix – Examples of option tables for describing soil analytical methods.....	39
References.....	43

## List of Tables

Table 1. Soil properties standardized in WoSIS and units of measurements.....	12
Table 2. Coding of method options for pH KCl measured according to five different procedures.....	15
Table 3. Method options for coding arsenicum (As) measured in soil. ....	29
Table 4. Example of method options for coding cation exchange capacity.....	39
Table 5. Example of methods options for coding electrical conductivity. ....	41
Table 6. Mapping WoSIS codes to GLOSIS codes (example for pH-KCl).....	42

## List of Figures

Figure 1. Particle size class limits used in various countries. ....	14
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## Preface

The ISRIC - World Soil Information foundation, legally registered as the International Soil Reference and Information Centre, has a mission to serve the international community as custodian of global soil information. We are striving to increase awareness and understanding of soils in major global issues.

We have updated the procedures for WoSIS (World Soil Information Service), our centralized enterprise database to safeguard and share soil profile data upon their cleaning and standardization. Everybody may contribute data for inclusion in WoSIS. However, data providers must indicate how their data may be distributed through the system. This may be 'please safeguard a copy of our dataset in your data repository', 'you may distribute any derived soil data but not the actual profile data' or 'please check and help us to standardize our data in WoSIS, there are no restrictions on use (open access)'. This can be indicated using a Creative Commons license.

Conditions for use are managed in WoSIS together with the full data lineage to ensure that data providers are properly acknowledged. In accord with these conditions, the submitted data are quality-assessed and standardized, with the ultimate aim to make them 'comparable as if assessed by a single given (reference) method'. The most recent set of standardized soil profile data served from WoSIS, commonly referred to as *wosis\_latest*, may be accessed freely through our Soil Data Hub. Further, on an irregular basis, we provide static snapshots of the data for consistent citation purposes.

In its capacity as World Data Center (WDC) for Soils, ISRIC also serves its data products to the global user community through auxiliary portals, including those of the International Science Council (ISC) World Data System (WDS), GEOSS (Global Earth Observing System of Systems) and DataONE.

WoSIS is the result of collaboration with a steadily growing number of partners and data providers, whose contributions we gratefully acknowledge. New releases of WoSIS-derived products, that consider a broader range of quality-assessed soil data, will gradually be released by us for the shared benefit of the international community and national stakeholders.

Ir H. van den Bosch

Director, ISRIC - World Soil Information

## Summary

This report describes general principles for standardizing and coding soil observations/properties considered in WoSIS (WorldSoilInformation Service); ultimately, the standardized data are served to users following FAIRdata principles. Data for nominally similar soil properties, collated from disparate sources, are grouped according to major features of the corresponding analytical methods; that is, the properties are grouped according to 'operational definitions' i.e. a given combination of 'property-procedure-method options'. For example, major features for defining soil pH are the extractant solution (water or salt solution), and in case of salt solutions the salt concentration (molarity), as well as the soil/solution ratio. A further descriptive element may be the type of instrument used for the actual laboratory measurement.

The following chemical and physical properties are currently considered during the standardization process:

- a) Chemical properties: organic carbon, total carbon, total carbonate equivalent, total nitrogen, phosphorus, soil pH, cation exchange capacity, and electrical conductivity. To which have been added, in 2025, the following: Calcium (Ca), Magnesium (Mg), Potassium (K), Sodium (Na), Aluminum (Al), Hydrogen (H<sup>+</sup>), Acidity (Al<sup>3+</sup> + H<sup>+</sup>) and Sulfur (S), as well as Arsenicum (As), Boron (Bo), Bromine (Br), Cadmium (Cd), Chrome (Cr), Copper (Cu), Iron (Fe), Lead (Pb), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Selenium (Se), Zinc (Zn), as well as soluble salts (anions and cations) for saline soils.
- b) Physical properties: soil texture (sand, silt, and clay), bulk density, coarse fragments, water retention, and hydraulic conductivity.

Full data harmonization in a global context, the ultimate objective of WoSIS, will first become feasible once results of extensive proficiency testing programs become freely available and a common set of 'international' reference methods has been accepted as the common standard by the international soil community; such would provide the basis for method validation between laboratories with their actual/adjusted method. Results of such 'harmonization' transformations should be managed in a separate set of databases tables.

# 1. Introduction

The World Soil Information Service, or WoSIS in short, is a server database for handling and managing multiple soil datasets in an integrated manner, subsequent to proper data screening and cleansing, standardization, and ultimately full harmonization. A key element is that the system allows for inclusion of soil data shared by third parties, while keeping track of the data lineage (provenance) and possible restrictions for use (licenses). The terms of these licenses will determine which set of quality-assessed and standardized data (known as *wosis\_latest*<sup>1</sup>) can be served to the international community. These data in combination with spatial environmental co-variate layers can then be used, for example, to generate soil property maps using digital soil mapping (e.g., Poggio *et al.* 2021; Turek *et al.* 2023). Subsequently, these maps can be used to address global challenges such as climate change, food security, and the degradation of land and water resources at continental and (sub)regional scale.

This report builds upon Appendix C and D of the former procedures manual<sup>2</sup> (Ribeiro *et al.* 2020). It complements the technical part of the ‘2023 Procedures Manual’ which follows ISO 25828 domain model conventions (De Sousa 2023). Section 2 focusses on quality aspects related to soil laboratory data. Section 3 provides criteria for standardizing disparate soil analytical method descriptions (as described in the corresponding standard operation procedures). Section 4 presents the method options for each combination of ‘property and procedure’ as implemented in the new WoSIS data model. Concluding remarks on the way forward are made in Section 5. Method option tables for cation exchange capacity (CEC) and electrical conductivity are presented in the Appendix as examples; similar lists for all properties will gradually become queryable through an evolving [dashboard](#).

## 2. Quality aspects related to laboratory data

### 2.1 Context

WoSIS is being populated using soil data produced for diverse types of studies; the corresponding data were sampled and analyzed in a range of laboratories according to a wide range of methods. By implication, the quality of the standardized/harmonized data in WoSIS will be determined by the quality of all preceding steps of data processing. Typically, a quality management system comprises measures necessary to arrive at a predefined and constant quality at agreed costs (based on user specific requirements for use). For instance, (certified) laboratories develop/use protocols for each sub-process, use validated methods for laboratory investigations, and participate in round robin tests to monitor their performance over time with respect to certified

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<sup>1</sup> [https://data.isric.org/geonetwork/srv/eng/catalog.search#/search?any=wosis\\_latest](https://data.isric.org/geonetwork/srv/eng/catalog.search#/search?any=wosis_latest)



or consensus reference materials (van Reeuwijk and Houba 1998; WHO 2011; US-EPA 2015; GLOSOLAN 2023).

ISRIC, for example, published reference methods for soil analysis as a step towards standardization of analytical methods in soil laboratories (van Reeuwijk 2002). These methods cover the range of analytical methods required for soil characterization according to the Revised FAO Legend (FAO 1988) and the World Reference Base (IUSS Working Group WRB 2022). Similarly, the Natural Resources Conservation Service of the United States Department of Agriculture publishes a Soil Survey Laboratory Methods Manual (Soil Survey Staff 2022a), which is the reference source for the National Cooperative Soil Survey Soil Characterization Database (USDA-NCSS 2021) and widely referred to internationally as reference. Alternatively, Australia has its own set of reference laboratory tests (Rayment and Lyons 2011) and, for example, uses different particle size class limits for defining the 'silt' fraction. More recently, within the framework of the Global Soil Partnership (GSP), GLOSOLAN (2022b) are developing a new set of standard operation procedures for worldwide application that may provide the basis for future data harmonization.

Although adoption of uniform reference methods at different laboratories contributes to a common quality level, it does not rule out that the quality of individual data held in compiled datasets such as WoSIS, which draws on a wide range of source data, may differ in quality as discussed below.

## 2.2 Laboratory error

Important quality characteristics for any measured data are the random and systematic error (Magnusson and Örnemark 2014). Random errors in experimental measurements are caused by unknown and unpredictable changes in the experiment; such changes may occur in the measuring instruments or in the environmental conditions. Systematic errors in experimental observations usually come from the measuring instruments themselves. Both error components will contribute to a varying extent to the total error. In practice, however, in reports and publications these essential laboratory error characteristics generally are not presented along with the actual data produced. In such cases, error characteristics can only be extracted afterwards from quality management systems or estimated in special experimental designs. Laboratories participating in inter-laboratory studies such as ring tests or round robin tests receive feedback on their quality performance with the particular methods by comparing their results with those from other participants. Examples are WEPAL (2022), the Wageningen Evaluating Programme for Analytical Laboratories, the Australasia inter-laboratory proficiency programme (ASPAC) (Rayment and Peverill 2002), the North American Proficiency Testing Programme (NATP 2015) and GLOSOLAN (2023). These programs often are certified according to ISO/IEC 17043. However, they do not consider the influence of differences in sampling procedure and pretreatment at individual laboratories as these programs use pretreated and homogenized materials. Further, the reference materials need to be relevant/representative for the soil types analyzed at a given laboratory. Ross *et al.* (2015), for example, in studying the inter-laboratory variation in the chemical analysis of acidic forest soil reference samples from eastern North America, stressed the importance of using sample materials representative for the (types of)



samples in the batches processed. When a new, or revised, analytical method is introduced, laboratories should do a validation study to compare the quality performance with other (similar) methods, previous versions of the method and materials with reference and consensus results (e.g., Bispo *et al.* 2021; ICP Forests 2021).

An extended guide to the validation of methods, consistent with international standards such as ISO/IEC 17025, is given by EURACHEM (2014). It includes validation and verification methods as well as a number of performance characteristics including random and systematic error, limits of detection, and limit of quantification. For laboratory methods, the latter two characteristics are used to indicate the limit below which the detection of an analyte becomes problematic, respectively the lowest level of analyte that can be determined with acceptable performance. Unfortunately, many laboratories do not include these measures in their quality statements with the data they distribute even though detailed validation reports may be available. These aspects complicate the processing of soil information obtained from different data providers in databases such as WoSIS, hence sometimes necessitating adoption of pragmatic solutions when processing the source data.

Adequate quality management in a laboratory is a prerequisite for reliable results and ‘data fit for intended use.’ However, it should be noted that the contribution of laboratory error is not necessarily the major component of the total error in derived interpretations; spatial variability can contribute even more (Goodchild and Gopal 1989; Goodchild 1994; Heuvelink 2014; Wadoux and Heuvelink 2023). An indication for the presence of other error sources can be found in the difference between the nugget in a variogram and the smaller values for lab error from validation and comparable experiments (Heuvelink 1996).

While cost-efficient and cost-effective procedures for field sampling are often well described (De Gruijter *et al.* 2006; Louis *et al.* 2014; Brus 2022), less attention is paid to quality requirements for laboratory investigations. They are often copied from previous and similar studies by applying the same methods. If for practical reasons alternative methods have to be selected, it should be remembered that numerous soil properties are based on ‘operational definitions’ (Soil Survey Staff 2022a) and may apply only for specific user groups. That is, the property is best described by the details of the applied laboratory method. An example is the ‘pH of the soil,’ which needs information on sample pretreatment, soil/solution ratio and description of solution (e.g., water, KCl 1M) to be fully understood. Similarly, in WoSIS soil properties are defined by the analytical methods and the terminology used, based on customary practice in soil science. As noted before, if highest laboratory accuracy is important it should be included in the selection criteria as well.

Two other examples where the description of soil analytical methods is particularly important for selection of alternative methods are cation exchange capacity (CEC) and available phosphorus. The capacity of a soil to adsorb and exchange cations from exchange sites depends importantly on the actual pH and the ionic strength of the solution. However, the need for a sufficiently detailed description of analytical methods is particularly reflected in the case of so-called plant ‘available phosphate’, where the choice of the appropriate laboratory methods is largely determined by soil pH as a proxy for soil mineralogy and soil type (Elrashidi 2010). Hence, ‘vague’ descriptions for available-P methods are essentially useless, unless used in a specific context such

as a (local) fertilizer recommendation scheme. Correlation studies have shown that only in specific cases (i.e., soils and intended use) useful region-specific conversions can be made for available-P values determined according to different analytical methods, such as P-Olsen, P-Bray, modified P-Morgan and Mehlich III (Mallarino 1995; Grandt *et al.* 2010; Breure *et al.* 2022; Gu *et al.* 2024), making international harmonization of results of such methods cumbersome or possibly at best ‘broad brush’. Examples of such efforts include the work of Ciampalini *et al.* (2013) in Tunisia, Gu *et al.* (2024) at regional level, and Maire *et al.* (2015) at the global level.

According to GlobalSoilMap (2015) there is generally no universal equation for converting from one analytical method to another in all situations. Within the framework of the Global Soil Partnership (Baritz *et al.* 2014), for example, this would imply that each regional node would need to develop and apply node-specific conversions (towards the adopted standard methods and soil types), building on comparative analyses of say archived samples (Jankauskas *et al.* 2006; Sadoski and Ivanova 2020; Hu *et al.* 2021). The solid work of the Global Soil Laboratory Network (GLOSOLAN), established by the Global Soil Partnership in 2017, deserves particular attention in this respect (see Batjes 2023).

## 2.3 Standardization of soil analytical method descriptions

Lacking detailed quantitative information on the quality of the soil analytical data held in the diverse source databases shared for use in WoSIS, it was necessary to develop a qualitative way to describe the analytical methods in a flexible, yet comprehensive and consistent way. For all source data, as indicated earlier, it is assumed that the quality requirements of the (first) user are met, and basic quality checks and screening have taken place and soil-relevant options in the method are applied in the source laboratory. This allows users of WoSIS to make their own judgement on the quality of individual data, for instance by the assumption that selected data have comparable quality characteristics or an acceptable (inferred) quality compared to their requirements.

For practical reasons, the options selected for describing laboratory methods in WoSIS are assigned on the basis of the descriptions provided in the respective (database) sources. This implies that information interpreted from the original report (source materials) is used here. At a later stage, in principle, some refinements may be possible if the original data can be consulted again; realistically, such would be the task of the original data providers. Such a mechanism would be realizable once an inter-operable, federated system is in place as foreseen for GLOSIS, within the framework of the Global Soil Partnership (de Sousa *et al.* 2021).

The WoSIS approach for the qualitative description of analytical methods can be seen as complementary to method descriptions used in reports from proficiency tests. In these cases, results from participants are coded to provide details of the methods applied within a particular grouping, such as the determination of ‘soil organic carbon’ content (WEPAL 2022). As explained above, the spread of the results within a given grouping can provide an indication for the spread in a compiled database.

Soil property ‘pH KCl’ will be used as example here. The selected ‘method options’ are sample

pretreatment, the soil/solution ratio, the molarity of the KCl solution, and the measurement technique. Further, it is important to know if the observations are the result of direct laboratory measurements or whether they are derived from spectral data, which would introduce additional uncertainty (Shepherd *et al.* 2022; Safanelli *et al.* 2025). It is assumed here that each laboratory, for the particular soils investigated, uses a shaking method and an equilibrium time long enough for the measurement to get a stable reading. These conditions may differ per soil type and (pair of) electrode(s) used, but these are considered of minor importance for differentiating methods in the WoSIS database. Once an option is identifiable, based on the available (source) information, the appropriate option/value can be added (i.e., 0.1, 0.5, 1 M). Such a grouping allows users of the database to select subsets that are analyzed according to comparable analytical methods, and thus may be considered as having equal quality for a specific use. When necessary, values/options not yet considered in the ‘method options’ table can be added; a web interface for making such insertions is under development (Luis Calisto, *pers. comm.*).

In addition to the method description according to the standardized coding system, values can be allocated for the inferred confidence in the conversion; this qualitative assessment is based solely on the information embedded in the ‘summarized’ method descriptions as provided in the various source databases. As indicated, these descriptions were often generalized by the data providers themselves from a more detailed source, such as ‘their’ laboratory manual. Importantly, the present confidence flags should not be seen as a measure for the quality of a particular laboratory. The criteria for coding ‘standardized analytical methods’ in WoSIS, as developed so far, are presented in Section 4.

As indicated, the present approach can accommodate data sets that are derived from proximal sensing methods. Soil sensing methods rely strongly on traditional laboratory methods for their calibration as expressed in region-specific soil spectral libraries (Viscarra Rossel *et al.* 2016; Shepherd *et al.* 2022) with the accompanying statistical models. Spectrally-derived data can be flagged in WoSIS using the method option ‘spectral’ (Boolean) with reference to the corresponding property and analytical method (e.g., ‘CEC\_pH7\_spectral’.) Ideally, the underpinning spectral library and statistical prediction model applied should be succinctly characterized in the WoSIS method option tables too, in view of the associated uncertainties (van Leeuwen 2024; Viscarra Rossel *et al.* 2024). Overall, data derived from traditional laboratory analysis are more reliable, though more costly, than those derived from spectrometry (Shepherd *et al.* 2022).

### 3. Criteria for standardizing soil analytical method descriptions

#### 3.1 Background

This section explains WoSIS conventions for describing and coding soil analytical method

descriptions. First, the guiding principles are explained in Section 3.2, then the methodology in Section 3.3, and subsequently the approach for describing possible method options (Section 3.4). A concise description of the approach adopted for each analytical method/procedure under consideration here (Table 2) is provided in Section 4.

All measurement values in WoSIS are expressed using SI units or non-SI units accepted for use with the International Systems of Units.

*Table 1. Soil properties standardized in WoSIS and units of measurements.*

Soil property	Standard units <sup>a</sup>
Bulk density	kg/dm <sup>3</sup>
Calcium carbonate equivalent	g/kg
CEC (and exchangeable bases, acidity)	cmol(c)/kg
Coarse fragments	100 cm <sup>3</sup> /cm <sup>3</sup>
Electrical conductivity	dS/m
Organic carbon	g/kg
pH	Unitless
Phosphorus	mg/kg
Sand, silt, and clay fractions	g/100g
Total carbon	g/kg
Total Nitrogen	g/kg
Extractable elements (e.g. K, Pb and Zn)	mg/kg
Soluble salts (for saline soils)	cmol/l
Water retention gravimetric (at given tension) <sup>b</sup>	g/100g
Water retention volumetric (at given tension) <sup>b</sup>	cm <sup>3</sup> /100cm <sup>3</sup>
Hydraulic conductivity (saturated and unsaturated)	cm/s(econd)

<sup>a</sup> Conversions: g kg<sup>-1</sup> or permille (1 = 0.1%); vol% is equivalent to 100 x cm<sup>3</sup> cm<sup>-3</sup>; wt % is equivalent to 100 x g g<sup>-1</sup>; kg dm<sup>-3</sup> is equivalent to g cm<sup>-3</sup> or Mg m<sup>-3</sup>; dS m<sup>-1</sup> is equivalent to mS cm<sup>-1</sup>, originally mmho cm<sup>-1</sup>, at 25°C; cmol(c) kg<sup>-1</sup> is equivalent to meq 100 g<sup>-1</sup>. Layer depth (top resp. bottom) expressed in cm, measured from the surface, including organic layers and mineral covers (see Batjes *et al.* 2024).

<sup>b</sup> Water holding capacity may be calculated as the amount (volume) of water held between 1/3 bar and 15 bar according to USDA conventions (Soil Survey Staff 2022a).

## 3.2 Guiding principles

In WoSIS, the description of analytical results considers key aspects of methods that are widely used in soil laboratories for the particular soil property. These are tabled along with available method options with a concise description for each option, as further described in Section 4.

Laboratory results in publications and reports are generally labeled with information that can be found in laboratory manuals, yet the full information is seldom provided in the databases themselves. It is assumed here that all source data (as shared for consideration in WoSIS) have passed routine quality control procedures at the source laboratory and a rigorous check by the first user. If during that process the decision was taken to include or exclude a special treatment, the assumption in WoSIS is that the original decision was made correctly (i.e., that the given option was deliberately left out from the selected criteria). Examples for this are washing out of water-soluble salts in the method for the determination of the CEC, and use of non-dried materials in case of samples with volcanic ash. It is also assumed that when a laboratory method has characteristics that restrict its application to specific soil types, these have been duly pondered upon by the source laboratory. In principle, such checks form an integral part of quality management procedures in a laboratory (van Reeuwijk and Houba 1998).

As indicated, WoSIS is populated with data coming from many sources that consider different laboratory standards and approaches. Therefore, the number of method options for each soil property has been limited to a practical level keeping in mind the intended use of the standardized data served from WoSIS i.e. mainly for broad scale applications, see Poggio *et al.* (2021) and Turek *et al.* (2023). For more detailed analyses at (sub)national level the ‘local or national’ databases should be consulted.

### 3.3 Coding of analytical procedures and method options

Soil analytical procedures are described using a sequential approach. First, the soil property matching the label of the source data to be entered in WoSIS needs to be selected. This must be done with utmost care: some soil property ‘labels’ in the source database can include information on the laboratory method applied; these are ‘operational’ definitions, for example ‘CEC-NH<sub>4</sub>OAc’.

Once the appropriate soil property (e.g., electrical conductivity) is identified, the method (or procedure) of analysis is identified and the corresponding *method options* need to be characterized using the relevant option table (see Appendix for examples). The method options that best describe the particular laboratory method are identified and coded. This step may be ‘tricky’ when incomplete information has been provided in the source metadata; in such situations it may be necessary to contact the original data provider for additional information<sup>2</sup>.

Alternatively, for some datasets it may be unrealistic to aim for a full characterization of the analytical methods. In such cases, a lower confidence level can be assigned based on an evaluation of all method options (from high (1) to low (3)). This step, however, is not shown in the option tables themselves (i.e., only visible to the database manager).

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<sup>2</sup> In case a low confidence rating is specified in the standardized data sets, national data providers are encouraged to help ISRIC WDC-Soils updating the corresponding descriptions as they may have access to more detailed sources, such as the actual laboratory manuals.

Results of many soil laboratory analyses are expressed with reference to a base, known as ‘fine earth fraction’ of a soil sample. This fraction is prepared during sample pretreatment at the source laboratory upon air drying. Next, part of the air-dried material is sieved. The actual sieve size determines both the upper limit for the fine earth fraction and the lower limit for the coarse fraction. Most countries use 2 mm as the upper limit for the fine earth fraction (Soil Survey Staff 2022a). Alternatively, in the former Soviet Union and satellite countries, laboratories used 1 mm for this (Katschinski 1956). Analytical results expressed with respect to the <1 mm and <2 mm fractions as base are essentially different and difficult to harmonize unless large data sets are available for the comparisons (Sadovski and Ivanova 2020). Such aspects need special attention when international datasets are to be fully harmonized, for example using transformation or pedotransfer functions (Rousseva 1997; Nemes *et al.* 1999; Esmaeelnejad *et al.* 2016; Makó *et al.* 2017; Takahashi *et al.* 2020; van Leeuwen *et al.* 2024), and should be considered in international laboratory intercomparison programmes such as undertaken by GLOSOLAN.

Sub-divisions (i.e., name and class size limits) within the defined coarse and fine earth fractions can vary markedly between countries as shown in Figure 1 (Nemes *et al.* 1999; GlobalSoilMap 2015). Further, as observed by Loveland (2016), interchangeability of sub fractions is restricted by differences in quality of say the pipette-method, hydrometer method, and the grainsize distribution determined using diffraction (e.g., Elfaki *et al.* 2016; Faé *et al.* 2019). Harmonizing such disparate textural data to a common standard remains an important challenge (e.g., GlobalSoilMap 2015; Moeys 2018; Sadovski and Ivanova 2020; Corral-Pazos-de-Provens *et al.* 2022), also for SoilGrids predictions.

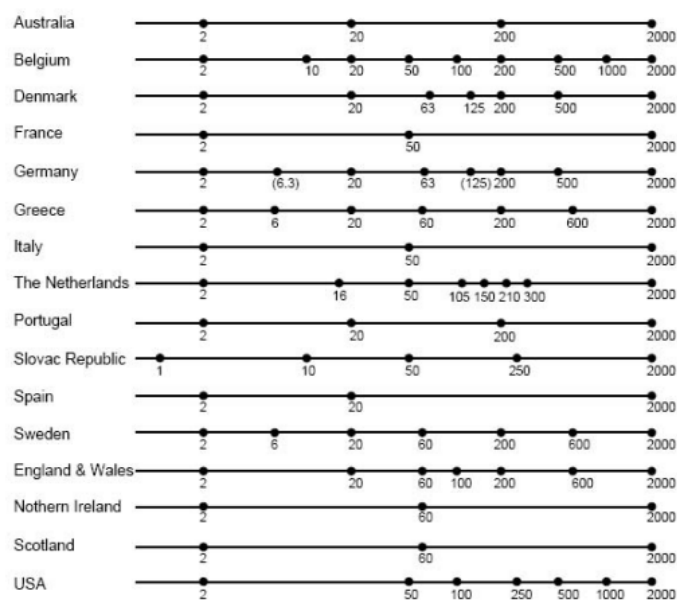


Figure 1. Particle size class limits used in various countries.

## 4. Description of method options for soil properties standardized in WoSIS

This section describes the method options for all soil properties presently considered in the WoSIS standardization workflow. Additions to the preceding list of properties, as described in Batjes and van Oostrum (2023), include soluble salts (section 4.1.6), gypsum (section 4.1.4), and a range of micronutrients and heavy metals (section 4.12). Soil properties considered in this section are divided into chemical and physical properties, and not listed in any particular order within these two categories.

The versatility of the WoSIS approach for standardizing and coding soil analytical method descriptions, in a global context, is illustrated in Table 2. Five different reference methods for pH KCl, namely ISO 10390:2005 (ISO 2021), USDA (Soil Survey Staff 2022a), ISRIC (van Reeuwijk 2002), WEPAL (2022) and GLOSOLAN (2021) are described by their main features. On the basis of this information, similarly measured observations can be selected.

*Table 2. Coding of method options for pH KCl measured according to five different procedures.*

Key	Method				
	ISO <sup>a</sup>	ISRIC <sup>b</sup>	USDA <sup>c</sup>	WEPAL <sup>d</sup>	GLOSOLAN <sup>e</sup>
Pretreatment	<2 mm	<2 mm	<2 mm	<2 mm	<2 mm
Solution	KCl	KCl	KCl	KCl	KCl
Concentration	1 M	1 M	1 M	1 M	1 M
Ratio	1 : 5	1 : 2.5	1 : 1	1 : 5	1 : 5
Ratio base	v/v	w/v	w/v	v/v	w/v
Instrument	Electrode	Electrode	Electrode	Electrode	Electrode

<sup>a</sup> ISO 10390:2005 specifies an instrumental method for the routine determination of pH using a glass electrode in a 1:5 (volume fraction) suspension of soil in water (pH in H<sub>2</sub>O), in 1 mol/l potassium chloride solution (pH in KCl) or in 0.01 mol/l calcium chloride solution (pH in CaCl<sub>2</sub>) (ISO 2021); this coding example is for pH KCl.

<sup>b</sup> ISRIC: Method 4-1 for pH-KCl (van Reeuwijk 2002).

<sup>c</sup> USDA: Method 4C1a2a3 (Soil Survey Staff 2022a).

<sup>d</sup> WEPAL Wageningen Evaluating Programs for Analytical Laboratories (WEPAL 2022). WEPAL is an accredited world-leading organizer of proficiency testing programs in the fields of plants, soil, sediments and organic waste. Participants in the International Soil-Analytical Exchange programme receive four times a year, four samples to be analyzed for comparison of results. Participants describe the applied extraction / digestion, and the method of detection of the particular element of their method applied.

<sup>e</sup> Considers the pH of the soil measured in either water, CaCl<sub>2</sub>, or KCl systems; this coding is for pH KCl (GLOSOLAN 2021).

In the future, an attempt may be made to align the dedicated WoSIS codes and terminology to those being considered for the emerging GLOSIS system (Batjes *et al.* 2019; Palma *et al.* 2024) and associated community codelists (van Genuchten 2022). An example, for pH-KCl, is provided in the Annex in Table 6.



## 4.1 Chemical properties

### 4.1.1 Soil pH

#### *Background*

The soil solution reflects the composition of the soil. Therefore, the pH and electro-conductivity of a standardized soil water mixture are often used for the first discrimination of soils and soil layers. The difference in pH measured in a soil/water extract and extract with 1 M KCl (pH delta value) for instance is an indication for the potential acidity. This 'delta pH' should be measured with equal conditions for both measurements. For some analytical methods, the pH determines the sample pretreatment for that method (i.e., presence of carbonates) or is a criterion for additional analyses. pH in saturated paste of soil, for example, is used in cross-checking salinity data (Rhoades *et al.* 1999).

#### *Method*

Methods for the determination of the pH of soil samples are characterized using seven method options:

- *Sample pretreatment* : Refers here to the upper size limit adopted by a laboratory to define the 'fine earth fraction.' Two physical pretreatments are widely used internationally for this: a) sieve crushed, dried soil material through a 1 mm sieve, and b) idem, but using a 2 mm sieve. By implication, these values will determine the corresponding lower limit for the 'coarse fraction.'
- *Solution*: To determine the pH of a soil sample,  $H^+$  ions need to be brought into solution. Distilled water and solutions with low ionic strength are used to stimulate this process. 'Stronger' salt solutions are needed to force exchange of i.e.,  $Al^{3+}$ . Measurements in a saturated paste are aimed to represent the natural environmental conditions (Pansu and Gautheyrou 2006).
- *Ratio*: pH methods consider different 'soil / solution' ratios. The specific ratio determines the composition of the supernatant solution, leading to different pH values. More ions can dissolve in a larger volume until maximum solubility is reached for the particular combination of exchanged and dissolved ions. Agitation time and method of shaking, as well as place of measurement (i.e., 'in the rest' or 'actively stirred' portion) have to be standardized in a laboratory to establish consistent measurement conditions. To obtain reliable measurements for pH  $H_2O$  in soils with high organic matter content, usually a higher water: soil ratio is used (Pansu and Gautheyrou 2006). Measurements in which electrodes are in contact with the sediment, may show a 'suspension' effect; this effect can modify results by +/- 1 pH unit.
- *Ratio base*: Results can be expressed on a weight or volume basis; as such, ratios can be expressed as weight / volume (w/v) and volume / volume (v/v).

- *Concentration*: Solutions with a high salt concentration enforce ion exchange processes. For instance, a 1 M KCl solution is used to release hydrogen ions and  $\text{Al}^{3+}$  ions from the exchange complex. With 1 M NaF,  $\text{OH}^-$  is released in the solution and  $\text{Al}^{3+}$  complexed; the observed increase in pH is an indication for ‘active aluminum’ (van Reeuwijk 2002).
- *Instrument* : In the laboratory, usually the pH is measured with a pH-meter. The (combination of) electrode(s) and their maintenance are controlled by the laboratory; they are checked before the measurement starts with calibration of the instrument. As the position of the electrode in the solution is considered most important, the type of electrode used is not considered a key-criterion here. pH test strips and hand-held pH meters are also used to measure soil pH in the field; however, such pH values may differ widely from those recorded under standard laboratory conditions.
- *‘Monitoring’*: This term is used here solely with respect to observing (monitoring) changes in oxidizable sulfur compounds over time for which changes in soil pH are measured until equilibrium is reached, providing a measure for ‘sulfidic soil materials’ (Soil Survey Staff 2022a). Such conditions commonly occur in intra-tidal zones adjacent to oceans.
- *Spectra*: This flag can be set to *true* or *false*. It shows whether the analyses were performed directly in the laboratory or whether they were derived from spectral analyses, a spectral calibration library and estimation service (e.g. Partida *et al.* 2025; Safanelli *et al.* 2025).

#### 4.1.2 Cation exchange capacity

##### Background

Micro- and macro-nutrients and heavy metals are held and released into the soil solution from exchange sites associated with clay and organic matter fractions; cations are held by the negative charges at the exchange sites. The electric charge that can develop at these sites varies with clay mineralogy, type of organic matter and the pH (Dixon *et al.* 1977). The cation exchange capacity (CEC) is an estimate of the total amount of cations held at these exchange sites, at a pre-defined pH (e.g., ‘pH7 buffer’). The ‘effective CEC’ is the CEC determined at the pH of the soil.

Salts present in the soil are considered a separate resource of ions and have to be removed by washing prior to analyses of the saturation status of the exchange complexes. If present in considerable amounts, sodium and calcium from carbonates, and gypsum can dominate the saturation of the exchange sites. Part of these soil components may dissolve in the solutions used (pH 8.2 to 8.5) preventing complete saturation of exchange sites in the lab methods as described below.

Usually, before the determination of the CEC, the amount and type of exchangeable bases are determined first. These ‘exchangeable bases’ are Calcium, Magnesium, Sodium and Potassium. From these, the bases saturation can be calculated as the ratio of exchangeable bases and the cation exchange capacity (at pH 7).

## Method

Various methods are used to determine CEC. In practice, these methods are selected considering available lab facilities, soil types to be investigated and specific (research) requirements. CEC methods are described here according to their major features; detailed information about specific methods, including their limitations, may be found in the underpinning laboratory manuals. In the standardization process for WoSIS, CEC methods are first subdivided on the basis of the technique applied (i.e., direct and approximate (indirect) methods).

- *Sample pretreatment* : This feature indicates whether data are reported for a fine earth fraction defined as having an upper limit of 1 mm (Katschinski 1956) or 2 mm (most common).
- *Technique*: As a preceding step to the determination of the total amount of cations that can be held in soil often the actual saturation of the exchange sites with basic cations is determined. This amount is known as ‘exchangeable bases.’ Typically, these cations are exchanged by a (buffered) solution with a cation occurring in the soil (e.g.,  $\text{NH}_4^+$  which is not considered a ‘base cation’). If exchangeable acidity (sum of exchangeable Hydrogen and Alumina) is also needed, the actual saturation of the exchange complex with cations can be estimated (indirect method), although minor fractions of manganese and iron are ignored in the method. These techniques with summation (of groups of) exchangeable cations are considered here as indirect methods for the determination of the CEC.
- *Reported pH*: The release of cations from and the saturation of the exchange sites depend on the charge of the exchange surfaces, as determined by clay mineralogy and type of organic matter. These charges will vary with the pH of the exchange solution (e.g., buffer) as applied in the laboratory method. This effect is particularly for soils with variable charge components (e.g., volcanic materials) and high organic matter content. Conversely, soils with a permanent charge show only small differences in CEC with increasing lab pH (Dixon *et al.* 1977; Gillman 2007). The ‘CEC’ is often determined at pH 7 that is with use of solutions buffered at pH 7; this CEC value then is considered representative for most agricultural soils. If the CEC at field pH is needed, then unbuffered solutions are used for saturation.
- *Exchange solution*: 1 M KCl and 1 M  $\text{NH}_4\text{Cl}$  are considered un-buffered solutions; they can be used for the determination of exchangeable acidity in soils with pH less than 5.5. Alternatively, the potentially available acidity is determined by extraction with a solution buffered at pH 8.2 such as  $\text{BaCl}_2$ ; the change in acid ‘consumption by the buffer’ is measured by back titration of the solution. This amount (i.e., potential acidity) is generally higher than the amount of field exchangeable acidity.
- The total amount of cations that can be held in soil can also be calculated in a *direct* way: the soil sample is saturated by applying an excess of a suitable index cation with subsequent determination of the excess or replacement of the index cation by another cation (see *direct methods* below).
- *Replacement solution*: Once the exchange sites are saturated, the excess of the solution

used for the exchange is washed out. In a next step the index cation is brought into solution by a replacement solution (buffered) at the particular pH. This is used for instance in the well-known CEC methods with  $\text{BaCl}_2$  – Triethanolamine (TEA) for ( $\text{Ba}^{2+}$ ) buffered at pH 8.2, and  $\text{NH}_4$ -acetate/ $\text{Na}$ -acetate at pH 7 and similar methods. This (washing and) replacement step can be omitted if the amount of index cation removed from the (buffered) index cation solution is estimated. For instance, if solutions with Ag-Thiourea (+) unbuffered or buffered from 4.0 to 8.0 are used.

- *Index cation*: The index cation criterion further specifies the method for the determination of the CEC. The index cation can be a cation from a buffer solution, or a cation added to the buffer solution. The latter group of cations are not common in soils or cations with a high selectivity. Their selection may depend on the clay minerals and type of organic matter present in a given sample. For some of these cations sophisticated instruments like flame atomic absorption and inductively coupled plasma spectrometers are needed for quantification.

CEC can be determined using *direct* and *indirect* methods as described below:

- *Direct methods*: These are used to achieve complete saturation of exchange sites at a particular pH, buffered solutions that contain a cation with high selectivity are used to saturate all exchange sites. The cation can be regarded as an index cation if the cation is used to quantify the exchange sites. The index cation can be a cation from a buffer component (i.e.,  $\text{Na}^+$  or  $\text{NH}_4^+$ ). Cations that can be considered absent in the soil (i.e.,  $\text{Ba}^{2+}$ , Ag-thiourea, and  $\text{Li}^+$ ) or have been exchanged in previous treatments (i.e.,  $\text{Na}^+$ ) can also be index cations. To improve exchange often solutions with a high concentration of the index cation and replacing cation have to be used. The selection of an index cation is not only based on the selectivity of the ions at the exchange sites, but also on the instrumentation available for quantification.
- To enhance the saturation with an index cation, samples can be pre-leached with a buffered solution as well. The small amount of buffer solution and cation(s) left improves the selectivity of the analysis.
- Further information may be found elsewhere (Baize 1993; Pansu and Gautheyrou 2006; GLOSOLAN 2022a; Soil Survey Staff 2022a).
- *Indirect method* (CEC by approximation): Cations that may be present on the exchange sites can be subdivided into three groups. Through summation of the cations in these three groups, the cation exchange capacity can be approximated in an indirect way. In most agricultural soils, the exchangeable bases Calcium, Magnesium, Sodium and Potassium dominate. In case of soil with a  $\text{pH} < 5$  part of the exchange sites will be saturated with Alumina and Hydrogen. Iron and Manganese are often the most prominent in the 'rest group.' The cation exchange capacity can be approximated by summation of these groups of cations (Pansu and Gautheyrou 2006; Soil Survey Staff 2022a).

Exchangeable bases and exchangeable acidity can be determined in buffered and unbuffered solutions. If determined in unbuffered solutions the CEC at (field) soil pH is approximated. It should be noted that the CEC based on summation of individual cations may be less accurate than values for CEC determined using a *direct* determination.

### 4.1.3 Calcium carbonate equivalent

#### *Background*

Carbon in soils can be subdivided into organic carbon and inorganic carbon. Inorganic carbon is present in various mineralogical materials such as carbonates (e.g.,  $\text{CaCO}_3$ ,  $\text{MgCO}_3$ ,  $\text{CaMg}(\text{CO}_3)_2$ ). A convenient solution in the laboratory is to express results for inorganic carbon forms as if originating from calcium carbonate, i.e., as 'Total Calcium Carbonate Equivalent.' Most soils with a pH less than 7 do not contain any significant amounts of carbonates (GLOSOLAN 2020).

Inorganic carbon can be quantified by dissolution of carbonates in acid and titration of residual acid, or measurement of evolved  $\text{CO}_2$  by volume, pressure, or absorption on a solid or precipitation in a solution. Instrumental methods use sensors for  $\text{CO}_2$  in purified streams of evolved gases with acid treatment or burning at elevated temperatures. An alternative is to measure the weight loss with burning at selected temperatures. For a detailed description of available options see Soil Survey Staff (2022a).

#### *Method*

Analytical methods to determine calcium carbonate equivalent in soils are described using the following method options.

- *Sample pretreatment* : Analyses are for the fine earth fraction using the limits defined by the source laboratory, which is <1 mm or <2 mm.
- *Reaction*: Quantification of carbonates often is based on dissolution in acids. The choice of the acid depends amongst others on the expected amount of carbonates, and the subsequent detection technique. The concentrations should be strong enough to get dissolution in a reasonable time but exclude the risk of and error by acid fumes.
- *Temperature*: At higher temperature dissociation of acids and so dissolution of carbonates increases. Possible options are described in the feature table, for example 'dissolution of carbonates by sulphuric acid [ $\text{H}_2\text{SO}_4$ ]'.
- *Detection*: Where substantial amounts of carbonates are present, titrimetric methods for the excess of acid after dissolution or the volume of  $\text{CO}_2$  evolved at dissolution can be used. Evolved  $\text{CO}_2$  can also be quantified by increased pressure in a fixed volume. Alternatives are gravimetric methods with precipitation of  $\text{CO}_2$  or weight loss from the sample. If the evolved stream of gases is purified, sensors sensitive to carbon forms can be applied as well. These instrumental methods (element analyzers) usually are applied

only with smaller amounts of (inorganic) carbon / carbonates in the sample (Soil Survey Staff 2022a).

- *Calculation*: Many laboratories for soil analyses do not have methods that can discriminate inorganic C that originates from various sources. Most methods are based on acid consumption with dissolution of carbonates, or quantification of CO<sub>2</sub> evolved. An indirect method is the subtraction of total organic carbon (TOC) from total carbon (TC). These forms are for instance determined by element analyzers with and without prior acid treatment for removal of carbonates. In all cases the quantified amounts have to be converted to the same molecular amounts of CaCO<sub>3</sub>.

#### 4.1.4 Gypsum

##### *Background*

Gypsum is widely found in soils under arid and semi-arid climates due to its semi-soluble nature. It is present in soils in the form of calcium sulphate dihydrate (CaSO<sub>4</sub>·2H<sub>2</sub>O). Many countries are using their own routine methods for analyzing gypsum content (see FAO 1990; Álvarez *et al.* 2022; Soil Survey Staff 2022a). However, such standardized methods and criteria cannot be used for all kinds of soils, and it is not clear to what extent results are comparable (Yaghmaeian Mahabadi and Givi 2008). For example, according to Herrero *et al.* (2009), routinely drying at 105° C and pulverizing samples for laboratory analyses makes all analytical results uncertain because gypsum becomes anhydrite and/or bassanite at this temperature. Alternatively, Álvarez *et al.* (2022), recently reported that the most accurate results are obtained with methods based on the loss of gypsum water upon heating when gypsum content is > 4%, and with the turbidimetric method in case of lower amounts of gypsum. The acetone method (US Salinity Laboratory Staff 1954) is used as the reference method in the main classification systems such as USDA Soil Taxonomy (Soil Survey Staff 2022b) and the World Reference Base for Soil Resources (IUSS Working Group WRB 2022).

Gypsum and calcium carbonates can interfere with some laboratory measurements including cation exchange capacity (Section 4.1.2) and particle-size distribution (Section 4.2.2).

##### *Methods*

- *Sample pretreatment* : The analyses apply to fine earth fraction as defined in the source laboratory (i.e. <1 mm (Katschinski 1956) or <2 mm.)
- *Technique*: Common methods include the turbidimetry, thermogravimetry, and acetone method. For the latter (US Salinity Laboratory Staff 1954), gypsum is dissolved by shaking the sample with water. It is then selectively precipitated from the extract by adding acetone. This precipitate is re-dissolved in water and the Ca concentration is determined as a measure for gypsum. This method also extracts anhydrite.
- *Spectral*: This flag can be set to *true* or *false*. It shows whether the analyses were performed directly in the laboratory or whether they were derived from spectral analyses, a spectral

calibration library and estimation service (e.g. Partida *et al.* 2025; Safanelli *et al.* 2025).

#### 4.1.5 Electrical conductivity

##### *Background*

The electrical conductivity (EC) of a soil extract is a measure for the salt content in the solution (salinity of soil). EC is a measurement that correlates with soil properties that affect crop productivity, including soil texture, cation exchange capacity (CEC), drainage conditions, organic matter level, salinity, and subsoil characteristics. The saturation extract (EC<sub>e</sub>) is considered to give a better representation of actual soil conditions with respect to plant environments (Soil Survey Staff 2022a).

##### *Method*

Electrical conductivity is described using four method options:

- *Sample pretreatment* : The analyses apply to fine earth fraction as defined in the source laboratory (i.e. <1 mm (Katschinski 1956) or <2 mm.)
- *Solution*: Electrical conductivity is measured in soil extracts prepared with distilled or demineralized water (i.e., with very low electro conductivity).
- *Ratio*: The amount of salts that can be dissolved depends on the soil / water ratio used (e.g., 1:1 or 1:5). These ratios are often predefined in soil classification systems and soil fertility evaluating schemes. With smaller ratios, EC can easily be determined in the supernatant solution after sedimentation of coarser materials. Saturated paste solutions are close to the soil solution. Often the pH H<sub>2</sub>O and EC are measured in the same soil extract (soil/water ratio).
- *Instrument* : EC is measured using an electro conductivity electrode. This can be done in the laboratory and in the field using hand held instruments (Rhoades *et al.* 1999; Soil Survey Staff 2022a).

#### 4.1.6 Soluble salts

##### *Background*

The term soluble salts, as applied to soils, refers to major dissolved inorganic solutes. Soil salinity is described and characterized in terms of the concentrations (or, occasionally, the content) of soluble salts (US Salinity Laboratory Staff 1954; Soil Survey Staff 2022a). Generally, the content of soluble salts is only measured in ‘salt-affected-soils’ and particularly when the EC<sub>e</sub> ≥ 4 dS m<sup>-1</sup>. Such soils are most common in arid and semi-arid regions.

Agronomically, salt composition and distribution in the soil profile affect plant response, i.e. through osmotic stress, specific ion effects, and nutritional imbalances (Rhoades *et al.* 1999). Quantifying and mapping soil salinity is difficult due to its large spatial and temporal variability



(e.g., Fernandez-Buces *et al.* 2006; Ivushkin *et al.* 2019). Accurate field evaluations require sampling at various field locations and various depths and over time to take into account the crop species to be grown.

## Methods

Analytical methods for soluble salts are described using two options.

- *Sample pretreatment* : The analyses apply to fine earth fraction as defined in the source laboratory (i.e. <1 mm (Katschinski 1956) or <2 mm.)
- *Technique*: Soluble salts are measured in soil extracts prepared with distilled or demineralized water (i.e., with very low electro conductivity), see Rhoades *et al.* (1999). The soluble salts (anions and cations) considered here are  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ ,  $\text{Na}^+$ ,  $\text{CO}_3^{2-}$ ,  $\text{HCO}_3^-$ ,  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$ .

### 4.1.7 Organic matter

#### Background

Soil organic matter has been defined as the organic fraction of the soil exclusive of undecayed plant and animal residues. It has been used synonymously with ‘humus’. For laboratory analyses, however, the soil organic matter generally includes only those organic materials that accompany soil particles in the fine earth fraction (Soil Survey Staff 2022a). Organic matter content can be determined directly by ignition (400 °C) after which the loss in weight of the soil sample is taken as a measure of the organic matter content. The latter can be used to derive the organic carbon content (see Section 4.1.8).

#### Method

- *Sample pretreatment* : This feature indicates how a laboratory has defined the upper limit for the fine earth fraction, as discussed earlier: <1 mm or <2 mm. These values also set the lower limit for the coarse fraction.
- *Detection*: Weight loss on ignition (LOI), which involves ignition at 400 °C in a furnace, is used as a measure for the content of organic matter present in the fine earth fraction.
- *Calculation*: No conversion factor is applied for soil organic matter (i.e., LOI values are reported as is). According to Soil Survey Staff (2022a), the percent organic matter lost on ignition (400 °C) can be used in place of *indirect* organic matter estimates of SOC loss by the Walkley-Black organic C method.

*Note*: Generally, it is assumed that soil organic matter contains 58 % C hence the commonly used conversion factor of 1.724 times the amount of soil organic carbon (van Bemmelen 1890). The actual conversion factor, however, may be up to 2.0 for topsoil's and even 2.5 for subsoils depending on the type of soil organic matter (Pribyl 2010; Minasny *et al.* 2020; Shamrikova *et al.* 2022). An appropriate factor should be used to convert soil

organic matter (SOM) content to content of soil organic carbon (SOC):  $\text{SOC (g/kg)} = 1/\text{factor} * \text{SOM (g/kg)}$ ; this factor should be indicated in the corresponding method option table, when possible.

#### 4.1.8 Organic carbon

##### Background

Carbon in soils is divided over several fractions and components. Major fractions are organic and inorganic carbon. Inorganic carbon is present in mineralogical materials such as carbonates. Cells of microorganisms, plant and animal residues at various stages of decomposition, stable 'humus' synthesized from residues, and nearly inert and highly carbonized compounds, such as charcoal, graphite, and coal (Nelson and Sommers 1982, p. 347), all contain organic carbon. Organic materials coarser than 2 mm are considered residues. The 'fine earth' fraction is the basis for the laboratory analyses for soil carbon.

The preferred method for determining 'total organic and inorganic carbon,' or total carbon (see Section 4.1.10), should consider an element analyzer that allows for controlled temperature and detection based on CO<sub>2</sub> evolution. Other methods often require a correction for lower recovery (Lettens *et al.* 2007). Alternatively, the content of organic carbon can be derived from LOI analysis of organic matter content as described in Section 4.1.7.

##### Method

Methods used for the determination of organic carbon are described using six method options.

- *Sample pretreatment*: This feature indicates how a laboratory has defined the upper limit for the fine earth fraction, as discussed earlier: <1 mm or <2 mm. These values also set the lower limit for the coarse fraction.
- *Pretreatment*: Carbon in the fine earth fraction can be determined by oxidation and quantification of CO<sub>2</sub> released. If the sample also contains carbonates (i.e., inorganic carbon) this fraction can liberate CO<sub>2</sub> as well. This inorganic fraction can be removed by acid treatment (without oxidation power) prior to the actual determination of organic carbon.
- *Reaction*: Organic carbon can be determined by wet or dry oxidation (ISO-10694 1995; van Reeuwijk 2002; Soil Survey Staff 2022a). For wet oxidation, mixtures of bichromate and sulphuric acid are frequently used. Determination can be based on excess bichromate or CO<sub>2</sub> development. Methods based on CO<sub>2</sub> detection need sample pretreatment to remove carbonates. CO<sub>2</sub> is also liberated with dry oxidation and quantified in element analyzers.
- *Temperature*: In both wet and dry oxidation methods the completeness of the reaction depends on the temperature. The heat of reaction during wet oxidation should be sufficient to induce substantial oxidation of organic materials (i.e., a high recovery fraction for organic carbon, see GLOSOLAN 2019)). Thermal decomposition of

bichromate may occur when external heating cannot be limited and controlled during wet oxidation. Dry oxidation requires a furnace with controlled temperature of over 900 °C.

- **Detection:** Excess of bichromate can be determined by back-titrating with  $\text{Fe}^{3+}$ . Alternatively, the organic carbon content can be calculated from the amount of chromic ions ( $\text{Cr}^{3+}$ ) formed using colorimetric techniques. Wet oxidation methods with detection based on excess bichromate are hampered by interferences from charcoal,  $\text{Fe}^{2+}$ ,  $\text{Mn}^{2+}$  where present. In a furnace, with extra oxygen and catalysts added to complete oxidation to  $\text{CO}_2$  and purification of the gas stream evolved, total C (organic C and inorganic C) can be detected. Gas chromatography, coulometric methods and/or infrared-based methods can be used to quantify  $\text{CO}_2$  evolution. Inorganic carbon should preferably be removed by prior acid treatment.
- **Calculation:**

Dry oxidation: Total carbon (TC) is defined as the sum of total organic carbon (TOC) and total inorganic carbon (TIC), where TIC is derived from the calcium carbonate equivalent or from a direct determination (as measured for basic soils). Methods to assess TIC by prior treatment with acid or separate determination are covered in Section 4.1.3.

Wet oxidation: Methods based on the original method of Walkley and Black (1934) often involve incomplete oxidation (Lettens *et al.* 2007; Soil Survey Staff 2022a) and consider a recovery factor. This factor is based on the assumption that 77% of the total carbon present is determined during the analyses. However, in practice, the actual factor will depend on the type of soil organic matter present in the sample and soil type (Grewal *et al.* 1991; Lettens *et al.* 2007). Use of a correction factor that is not representative for the soil material under consideration will introduce a systematic error. Only few methods with wet-oxidation, with or without external heating, claim 100% recovery (for all soil types); for a critical review see Pribyl (2010).

#### 4.1.9 Total carbon

##### Background

Carbon in soils can be divided in an organic and inorganic fraction. Inorganic carbon is present in carbonate minerals such as calcite ( $\text{CaCO}_3$ ) and dolomite ( $\text{MgCO}_3$ ). Organic carbon is found in organic materials such as plant residues, humus, and charcoal. Total carbon (TC) is defined as the sum of total organic carbon (TOC) plus total inorganic carbon (TIC, expressed as Calcium carbonate equivalent). From an analytical point of view, TOC and TIC are defined measurement categories, also referred to as ‘sum parameters’, whereas each part can contain several substances in varying proportions (Hilke 2015).

##### Method

Analytical methods for total carbon are described using two options.

- *Sample pretreatment* : Analyses are for the fine earth fraction using the limits defined by the source laboratory. This can be <1 mm or <2 mm, which may be seen as the present international standard for defining the coarse fraction.
- *Calculation*: When small amounts of inorganic carbon are present, total carbon can be estimated by dry combustion at higher temperature using an elemental analyzer (Kuhlbusch *et al.* 2009; Soil Survey Staff 2022a). However, in practice inorganic carbon is removed first after which the organic carbon fraction is determined. Larger amounts of inorganic carbon usually are usually determined after dissolution of the mineral fraction with acids and release of CO<sub>2</sub>. Results are expressed as total carbonate equivalent. Total carbon can be calculated using a range of methods for both inorganic and organic carbon.

#### 4.1.10 Total nitrogen

##### *Background*

Nitrogen (N) in soils is present as NO<sub>3</sub><sup>-</sup> and NH<sub>4</sub><sup>+</sup> with negligible amounts as NO<sub>2</sub>; together they form the mineral N-fraction. N in organic matter forms the organic fraction. N<sub>2</sub>O and N<sub>2</sub> are present as gases. Due to microbial activity and other soil processes, the size of the different fractions will vary with time and management conditions (including sample pre-treatment). The individual N-fractions present at the time of sampling are estimated by extractions. For the determination of Total Nitrogen, two methods are commonly used: combustion and digestion. A detailed account is provided in soil laboratory manuals (van Reeuwijk 2002; Soil Survey Staff 2022a).

##### *Method*

Analytical methods to determine Total Nitrogen are divided over four techniques and described using three more method options.

- *Sample pretreatment* : Analyses are for the fine earth fraction as defined by the source laboratory, that is <1mm (Katschinski, 1956) or <2 mm.
- *Technique*: Traditional determinations for Total Nitrogen can be grouped into two categories: combustion of organic matter in a furnace (Dumas) and digestion with acid treatment and heating (Kjeldahl). NIR/MIR spectroscopic methods allow for non-destructive determinations of Nitrogen, yet these methods need to be calibrated against conventional wet-chemistry measurements (Shepherd *et al.* 2022).
  - *Digestion*: Since the introduction of the Kjeldahl method for the determination of N, the method has been modified to accelerate the method and include all forms of nitrogen in soils. Salts like Potassium or Sodium-sulphate are added to sulphuric acid to raise the boiling point of the digestion mixture. A catalyst (i.e., CuSO<sub>4</sub>) is used to accelerate the reactions. An addition of KMnO<sub>4</sub> or HClO<sub>4</sub> may be needed to complete the digestion.

To include  $\text{NO}_3$  and  $\text{NO}_2$ , the Kjeldahl digestion is preceded by an oxidation step with i.e.,  $\text{H}_2\text{O}_2$ . After excess  $\text{H}_2\text{O}_2$  is removed,  $\text{NO}_3$  is coupled with salicylic acid in the sulphuric acid medium. Some methods use sodium thiosulfate to reduce the formed nitro-compounds into amino compounds. Fixed  $\text{NH}_4^+$  is liberated with HF-treatment and combined into the Kjeldahl digestion.

- **Combustion:** In the Dumas combustion method, Nitrogen is oxidized with copper(I) oxide in a stream of  $\text{CO}_2$  or with  $\text{O}_2$ , in an elevated temperature furnace at 900-1350 °C. The flushed gas stream is purified and after conversion of  $\text{NO}_x$  to  $\text{N}_2$  total Nitrogen is estimated.
- **Detection:** With sodium hydroxide, Nitrogen as  $\text{NH}_3$  is released from the Kjeldahl digest and distilled into a solution of boric acid and titrated. For quantification by semi-automatic systems, the digest is diluted, and an aliquot used for the colorimetric determination of phosphorus by nitroprusside reaction at 660 nm.

Modern element analyzers use thermal conductivity for quantification. Other systems measure  $\text{N}_2$  manometrically after absorption of  $\text{CO}_2$ .

#### 4.1.11 Phosphorus

##### Background

Phosphorus is one of the major plant nutrients in the soil and one of the most complex. It is a constituent of plant cells, essential for cell division and development of the growing tip of the plant. Therefore, it is vital for seedlings and young plants. Phosphorus quickly binds with iron and aluminum in the soil and becomes unavailable to plants, especially when soil pH  $\text{CaCl}_2$  is below 5.0. Phosphorus deficiency is common in many tropical soils (Fairhurst *et al.* 1999).

Soil-P is one of the most cumbersome properties to measure and interpret (Soil Survey Division, 2014). The pH of a soil is a useful criterion for selecting the appropriate extractant for 'extractable-P' (Elrashidi 2010). Such extractants differ in pH, buffer capacity, and ionic strength which makes them selective for certain P types and fractions. As a result, measures of extractable P for a given soil sample (soil type) as obtained using different methods, such as P-Olsen (for basic soils), P-Bray (for acid soils) and P Mehlich 3 generally are not interchangeable .

##### Method

Analytical methods to determine total Phosphorus are divided over thirty-three techniques and described using three more method options.

- **Sample pretreatment :** Analyses are for the fine earth fraction as defined by the source laboratory, that is <1mm (Katschinski, 1956) or <2 mm.
- **Technique:** To determine total phosphorus, sample material has to be decomposed with acids and oxidizing reagents and destructed at high temperature. Fractions of this total phosphorus can be determined by selective extractants (e.g., Bray and Kurtz 1945;

Olsen *et al.* 1954; Levy and Aschlesinger 1999; Elrashidi 2010). Spectroscopic methods like MIR/NIR may be used, but these non-destructive methods need calibration against conventional laboratory methods to allow for interpretation of the P-measurements.

As indicated, the 'chemistry' of the analytical methods is complex due to the different (types) of components in the extractant. Soil legacy data thus can best be grouped first using the source (name) of the extractant (e.g., P-Olsen, P-Bray 2, or Mehlich III), and subsequently considering key features of the extractant as given in the description.

- *Decomposition (for Total P)*: For total P methods, the sample has to be decomposed by treatments with destructive and oxidizing capacities. Several mixtures of acids can be used. In the same process organic matter is oxidized.
- *Detection*: For quantification of Phosphorus, the colorimetric 'molybdate blue' and 'molybdate yellow' method are considered standard methods. Organic matter in the extract may give an interference by its colour and so has to be removed. Adsorption to charcoal and oxidation of dissolved P are frequently used. These treatments of the extract and the acids used towards the end of the method may influence the fractionation of phosphate in the extract. Ascorbic acid is often preferred over  $\text{SnCl}_2$  as a reductant for colour development in the Molybdate-blue method.

#### 4.1.12 Micronutrients and trace metal elements

##### *Background*

The extractable elements considered here include Arsenicum (As), Boron (Bo), Bromine (Br), Cadmium (Cd), Chromium (Cr), Copper (Cu), Iron (Fe), Lead (Pb), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Selenium (Se), and Zinc (Zn). Out of these, arsenic, nickel, cadmium, chromium, copper, lead, mercury, zinc are heavy metals. Many of these elements occur in soils under natural conditions. Soils may become contaminated by the accumulation of heavy metals and metalloids through emissions from the rapidly expanding industrial areas, mine tailings, disposal of high metal wastes, leaded gasoline and paints, land application of fertilizers, animal manures, sewage sludge, pesticides, wastewater irrigation, coal combustion residues, spillage of petrochemicals, and atmospheric deposition (Wuana and Okieimen 2011).

Procedures for standardizing analytical methods for a wide range of micronutrients and/or trace metal elements were developed on the basis of a literature survey (Sims 1989; Benton Jones 1990; Alva 1993; Mallarino 1995; Bibiso *et al.* 2015; Soil Survey Staff 2017; Haefele *et al.* 2024). Note that words like trace metal, heavy metal, trace element only characterize chemical elements according to their nature and abundance. As such, they do not provide any information concerning their possible toxicity for biota, which will depend on their abundance, availability and speciation as well as physiological roles in the species under study (Duffus 2002; Pourret *et al.* 2021). Many of the elements considered here are essential in plant life but when their concentrations become too high they can become toxic. Alternatively, nutrients such as

cobalt, strontium, vanadium, silicon and nickel enhance soil health but deficiency itself will not stop plant growth (Wuana and Okieimen 2011).

The most common methods for determining the concentration of trace metal elements in soil is via total elemental analysis, but for plant growth and productivity the elements need to be present in plant-available forms (e.g. Kihara *et al.* 2017; Soil Survey Staff 2022a; Marschner and Rengel 2023). Note that the elements Calcium (Ca), Magnesium (Mg), Potassium (K) and Sodium (Na) have also been discussed in section 4.1.2 on ‘CEC determination’ under exchangeable bases.

Indicative, ‘plausible ranges’ for the above elements —both for mineral and organic samples— based on a long-term monitoring programme are presented in ICP Forests (2020, p. 25). As the number of measurements for these observations increases in WoSIS, such plausibility limits will gradually be added/updated in the corresponding tables.

## Method

Analytical methods for micronutrients/metals salts are described using the following options.

- *Sample pretreatment*: The analyses apply to fine earth fraction as defined in the source laboratory (i.e. <1 mm (Katschinski 1956) or <2 mm.)
- *Technique*: For each element under consideration here, the ‘property – procedure - method option(s)’, as commonly used to characterize the respective observations are listed. For example, the element arsenicum ‘extracted with Aqua regia or similar (determines total of element present in soil)’ with observation code ‘AS\_EXTTOT’ or arsenicum ‘extracted with Mehlich 1 solution, a weak acid soil extraction procedure (formerly known as Double Acid or North Carolina method)’ with observation code ‘AS\_EXTME1’, respectively ‘AS\_EXTME3’ for an extraction with the ‘Mehlich 3 solution, a weak acid soil extraction procedure’ (Table 3).
- *Spectral*: This flag can be set to *true* or *false*. It shows whether the analyses were performed directly in the laboratory or whether they were derived from spectral analyses, a spectral calibration library and estimation service (e.g. Partida *et al.* 2025; Safanelli *et al.* 2025).

Table 3. Method options for coding arsenicum (As) measured in soil.

Key	Code	Value	AS_EXTTOT	AS_EXTME1	AS_EXTME3	AS_EXTDTPA	AS_EXTMORG
sample pretreatment	1	sieved over 1 mm sieve	yes	yes	yes	yes	yes
sample pretreatment	2	sieved over 2 mm sieve	yes	yes	yes	yes	yes
Technique	1	Extracted with Aqua regia or similar (determines total of element present in soil)	yes	no	no	no	yes
Technique	2	Extracted with Mehlich 1 solution, a weak acid soil extraction procedure (formerly known as Double Acid or North Carolina method)	no	yes	no	no	no
Technique	3	Extracted with Mehlich 3 solution, a weak acid soil extraction procedure	no	no	yes	no	no



Technique	4	Extracted with AB-DTPA (ammonium bicarbonate-diethylenetriaminepentaacetic acid) solution	no	no	no	yes	no
Technique	5	Extracted with 'universal' Morgan solution, a weak acid soil extraction procedure	no	no	no	no	yes
Spectral	1	False	yes	yes	yes	yes	yes
Spectral	2	True	yes	yes	yes	yes	yes

## 4.2 Physical properties

### 4.2.1 Coarse fragments

#### Background

As indicated, the solid part of the soil mass is subdivided by sieving into a fraction smaller and a fraction larger than 2 mm; these fractions are often denoted as the fine earth and coarse earth fraction. Data sets from the former Soviet Union and its satellites, however, often use 1 mm as upper the limit (Katschinski 1956) for the fine earth fraction.

The amount of coarse fragments is needed in calculations that consider the total soil mass as reference. Internationally, different systems are used for naming subclasses within the coarse fraction, using a range of class limits and names (Nemes *et al.* 1999; FAO 2006; ISO/TC 190 2016; ANSIS 2023).

Alternatively, the fine earth fraction is most relevant for soil processes. This fraction provides the base material for most soil physical, chemical, and mineralogical analyses; see section on particle size distribution and analysis (sand, silt, and clay fractions).

#### Method

Methods for the determination of mass of coarse fragments are described using the following method options:

- *Sample pretreatment* : This feature indicates whether data are reported with reference to an upper limit of 1 mm or 2 mm for the fine earth fraction.
- *Size*: The coarse fraction can be subdivided into several subclasses. Typically, their respective amounts can best be estimated or weighed in the field or laboratory.
- *Type*: The coarse fraction can comprise several types of materials which can be described according to their size and nature, as e.g., determined by their resistance against disintegration in water or sodium-hexametaphosphate. During sample pretreatment, pedogenetic materials have to be carefully removed from the sample and treated as a separate sub fraction. Breaking up of such materials may lead to the release of smaller ferromanganese and calcium carbonates (and barium sulphate or gypsum concentrations)

nodules.

- *Estimates*: There are two ways to express the amount of coarse fragments (i.e., volume (V) basis and weight (W) basis). For conversions from V to W the bulk density is required. In the absence of such data, default data for bulk density ( $1.45 \text{ g cm}^3$ ) and mineral particle size density ( $2.65 \text{ g cm}^3$ ) are often assumed (Soil Survey Staff 2022a).
- *Base*: The amount of respective coarse fractions can be expressed as part of the whole soil or related to e.g., the fine earth fraction or other fractions determined.

## 4.2.2 Soil texture

### *Background*

The particle size distribution (PSD) in soils is important in a wide range of agricultural, geological, and technical and engineering studies. It influences soil properties such as the workability, water holding capacity and drainage, and the capacity to hold (micro) nutrients as a reservoir for plant growth. For most laboratory investigations samples are first passed through a sieve to determine the 'fine earth' fraction (van Reeuwijk 2002; Soil Survey Staff 2022a); the upper limit of 2 mm is widely used for this. Alternatively, in the former Soviet Union and its satellite countries, the upper limit for fine earth fraction has been set at 1 mm (Katschinski 1956).

The 'coarse fraction' is always defined with reference to the upper limit of the 'fine earth fraction' in the corresponding scheme. Whole soil refers to all particle-size fractions, including boulders with maximum horizontal dimensions less than those of the pedon. In general, the term soil texture is used to describe the fine-earth fraction (Soil Survey Staff 2022a). At one time, the term rock fragments was differentiated from the term coarse fragments, which excluded stones and boulders with diameters  $>250 \text{ mm}$  (Soil Survey Staff 1975). The rationale for this distinction was that particles  $<250 \text{ mm}$  were generally regarded as part of the 'soil mass' as they affect moisture storage, infiltration, runoff, root growth, and tillage (Soil Survey Staff 1951).

Soil particles in the fine earth fraction can be subdivided into fractions of distinct size classes. In most cases, the following (nominal) classes are defined: 'sand,' 'clay,' and an intermediate class named 'silt.' However, the actual size limits for these classes can vary between countries and laboratories, for example an upper limit for the 'silt' fraction given as 0.020, 0.050, 0.060 or 0.63 mm (see Figure 2). Such fractions, in turn, can be subdivided to provide additional detail (e.g., fine silt and very fine silt); again, subclasses are defined using different size limits and (local) names, complicating overall standardization and harmonization efforts (Loveland and Whalley 2000).

In view of the above, in WoSIS descriptive criteria for 'sand,' 'silt,' and 'clay' are presented in one single feature table. During laboratory analyses, these fractions are often determined simultaneously using the same sample.

## Method

Analytical methods for the determination of the sand, silt, and clay (size) fraction in soil samples are described using three options for the sand and silt size fraction, and four for the clay size fraction. When the exact fraction sizes are not reported in the source metadata, of necessity the inferred class limits are sometimes inferred (with a flag for lower confidence).

- *Sample pretreatment*: Refers here to the upper size limit adopted by a laboratory to define the 'fine earth fraction.' Two physical pretreatments are used internationally: a) sieve crushed, air dry soil material through a 1 mm sieve (Katschinski 1956), and b) idem, but using a 2 mm sieve (Soil Survey Staff 2022a). By implication, these values will determine the corresponding lower limit for the 'coarse fraction,' as well as the actual 'base' to which results of soil chemical analyses apply.
- *Size*: Fractions for a given particle size distribution should be distinguished according to their size and not according to their allocated names as used in different (inter)national systems. This practice facilitates logical grouping of size fractions in WoSIS according to the particle size distribution schemes as adopted in the various source databases.
- *Treatment* : Soil particles are often bound into aggregates by cementing materials such as organic matter, calcium carbonate and iron oxides. Such aggregates are broken up during the pretreatment step of the analytical method. For example, hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) is used to remove organic matter by oxidation. HCl, HAc (acetic acid) or buffer solutions (Na acetate) are used to remove carbonates in basic pH soils ( $\text{pH} > 7$ ). Ultrasonic treatment is needed for samples that contain kaolinite, micas (e.g., illite and muscovite) and allophanic materials; the energy generated by the vibrations is transferred into the suspension and breaks the cohesion of the aggregates. In some laboratories, sesquioxides are removed in an optional deferration step. Many of these treatments are soil type specific. When such (pre)treatments and dispersion methods are excluded from the laboratory method, measurement will be for 'water dispersible' or 'natural clay' (see below).
- *Dispersion*: During the dispersion of clay size particles, effects of the electric charges at the exchange surfaces have to be controlled carefully (Soil Survey Staff 2022a). A clay suspension is most stable when the particles have large electrical double layers which is the case with monovalent cations and diluted solutions (Bolt and Bruggenwert 1978). Chemisorption of phosphate at pH values far from the isoelectric point, can also reduce repulsion forces by charges on the clay surface. Therefore, a mixture of sodium hexametaphosphate buffered at pH 10 by  $\text{Na}_2\text{CO}_3$  (also known as 'Calgon' type) is frequently used as dispersant. Alternative dispersants include ammonia and soda. Well-dispersed soil solutions remain 'turbid' for a longer time than those that have not been submitted to any pretreatment.
- *Instrument*: Subsequent to pretreatment and dispersion of the fine earth fraction, this fraction is divided into so-called sand, silt, and clay fractions (see above discussion about class size limits and naming issues). In the '<2 mm' scheme, the sand fraction is separated from the silt and clay fraction by sieving; for example, using 0.050 or 0.063 mm as the

lower limit. Typically, the silt and clay fractions are determined after sedimentation in a cylinder based on Stokes' law, which assumes silt and clay particles to be perfect spheres. The rate of sedimentation depends amongst others on the radius, shape, density of the different particles, density of the liquid used for dispersion, and temperature (Soil Survey Staff 2022a). Detailed descriptions of possible error components in results from particle size analyses can be found elsewhere (Loveland 2016).

The main instruments for particle size analysis include:

- *Pipette method*: In the (Robinson) pipette method the relevant (i.e.,  $<0.050$  or  $0.063$  mm) fraction is sampled at a predefined depth and time after sedimentation started. The actual depth is calculated from Stokes' law for a specific settling time interval, size fraction and temperature. The pipette method is considered to be the reference method.
- *Hydrometer*: This method (often referred to as Bouyoucos hydrometer method) is commonly used as an alternative to the 'pipette' method. It is based on the density of the suspension, which is a function of the concentration and kind of particles present (after a certain time of settling). Results are considered to be less reliable than those obtained using the pipette method.
- *Laser diffraction (beam)*: These methods for grain size analyses are based on the measurement of the intensity of diffracted laser beams of near infrared / infrared light on suspended particles. The scattered light is detected at an angle (often  $90^\circ$ ) of the incident beam. The number of detectors used, determines the number of fractions in the measurement range. With a high number of detectors, this results in a 'continuous' spectrum. Wavelength, size, refractive index of surface of particles are principal factors in the calibration of the instrument. Results may differ from those obtained with the pipette method for the same samples (Loveland and Whalley 2000; Pieri *et al.* 2006; Buurman and Van Doesburg 2007).
- *Field hand estimates*: Trained personnel with field experience in a specific region or with specific soil types may estimate the clay content in a semi quantitative way by 'hand, finger' sensing. Texture classes assigned from field texture and laboratory particle size analyses are not always equivalent, especially where the clay content is considered to be high (Minasny *et al.* 2007; Richer-de-Forges *et al.* 2023).

### 4.2.3 Bulk density

#### *Background*

Bulk density provides a measure for soil compaction. It is defined as the ratio of the mass of oven dried solids to the total or bulk volume. In contrast to particle size density, soil bulk density includes both the volume of solids and pore space. Pore space depends on the soil's extensibility and so the volume of soil changes almost dynamically with soil water content. Bulk density is needed to convert data from weight to a volume basis and *vice versa*.

## Method

Sampling techniques for bulk density are determined by the natural setting of the solid soil components and the pores. Therefore, the moisture condition has to be defined at the time the bulk density is estimated. Measurements can be based on weight and volume.

Methods for determining bulk density are described using four method options:

- *Sample type*: In one group of methods, a sample is taken by pressing cores with known volume (rings) into the soil. Other methods use clods taken in the field; after sealing, the volume of the coated clod is measured by submerging into water (nowadays, this can also be done using 3D scanning). Alternatively, in some cases, clods are reconstituted from soil material <2 mm (Soil Survey Staff 2022a). If soil coherence is too weak to prepare a clod or take a soil core, the volume of excavated soil is measured instead.
- *Measurement condition*: The moisture condition of the sample determines whether swelling or shrinking has taken place (e.g., air dried, rewetted).
- *Base*: The bulk density of a soil sample is the ratio of the mass of solids to the total or bulk volume. The total volume includes both solids and pore space. Bulk density is usually reported for the '<2 mm' soil fabric, the mass and volume of rock fragments are subtracted from the total mass and volume (Soil Survey Staff 2022a).
- *Corrections*: Bulk density is calculated for soil materials <2 mm in g cm<sup>-3</sup> (i.e., fine earth fraction). Mineral materials larger than 2 mm and vegetal materials are removed from the sample. If the density of rock fragments is known or can be approximated, corrections can be included in the calculations of the bulk density (Soil Survey Staff 2014). Sometimes bulk density is expressed on the basis of the whole soil. Such measurements refer to all particle-size fractions, including boulders with maximum horizontal dimensions less than those of the pedon (Grossman and Reinsch 2002; Soil Survey Staff 2022a).
- *Calculation*: When not actually measured, bulk density can be based on expert knowledge. In such cases, 'calculation' is flagged as 'unknown.' (Such values are not served with *wosis\_latest*).

## 4.2.4 Water retention

### Background

The capacity of a soil to hold water (and air) depends on the amounts and types of organic matter, content of sand, silt, and clay, as well as soil structure or physical arrangement of the particles. Water and air are held in the inter-connected pore spaces between the solid materials. If all these spaces are filled with water, the soil is at its maximum water holding capacity. The corresponding volume of water can be gradually depleted by plant growth, transpiration,

evaporation, and drainage. Water is less readily released by and transported through smaller sized pores. In some soil types, such as shrink-swell clays, the water holding capacity can change with desorption or absorption of water (hysteresis effect).

In the laboratory, water holding capacity at predefined suctions is determined by suction or application pressure on a sample. A detailed account is provided in soil physics handbooks (Koorevaar *et al.* 1983; Jury *et al.* 1991) and laboratory manuals (Soil Survey Staff 2022a). Currently, members of the SOPHIE network are working on the standardization and harmonization of soil water retention methods (SOPHIE 2022; Guillaume *et al.* 2023).

The nature of the soil material may preclude some sampling types. For example, water retention for expanding clays is overestimated when sieved samples are used instead of natural soil fabric at tensions of 6, 10 and 33 kPa (Soil Survey Staff 2022a). Cores cannot be used when the soil material is not coherent enough, such as in very sandy soils.

When reporting values for water retention, it is important to note whether results are expressed on a w/w basis or w/v basis. Conventionally, with pF curves the moisture content is expressed in volume % (w/v) rather than weight % (w/w); conversion between these units require the availability of bulk density data (Soil Survey Staff 2022a).

## Method

Analytical methods for water retention are described using six options.

- *Tension*: The capacity of a soil to hold water is often expressed as the water content determined after equilibration of samples, from different depth layers, with water at various suction values (kPa). For practical reasons, high suction values are often controlled by tension in pressure pans. Desorbed or absorbed water between these equilibrium points and the initial saturated condition is measured on a mass basis (W). Water content at selected tension points can be expressed in different measurement units, as follows: 1 bar = 100 kPa (kilo Pascal); 1 bar = 1020 cm H<sub>2</sub>O ≈ 1000 cm H<sub>2</sub>O; 1 bar = 75.01 cm Hg; 1 bar = 0.9869 atm ≈ 1 atm.
- *Sample type*: Water holding capacity can be derived from: air dry soil material sieved (disturbed samples, fine earth fraction as defined in given laboratory e.g., '1 mm' or '<2 mm'); natural clods; reconstituted clods of soil material; and soil cores taken at a particular depth.
- *Treatment* : For desorption methods, irrespective of the initial moisture status, all samples are first saturated on a tension table by capillarity; subsequently, they are equilibrated at pre-defined water retention levels. Methods that involve wetting of oven dry soils may cause irreversible changes in pore size. To study changes resulting from wetting and drying, the gravimetric water content can be determined after a second equilibration.
- In the *absorption methods*, the sample is initially very dry and subsequently equilibrated at the pre-defined retentions levels without prior saturation.

- To facilitate desorption by tension or pressure in lab experiments samples have to be in close contact with a supporting surface. Silt or kaolin can be used as an intermediate layer to improve the contact of the sample with a ceramic or porous plate or, in a sandbox for multiple samples.
- Clods are generally sealed by a plastic lacquer (e.g., 'Saran F 310 resin'). A flat surface is cut to enhance contact on the ceramic plate or to allow clods to get wet on a tension table. At higher tension levels water is removed from the smallest pores by pressure. Here the original arrangement of soil materials is no longer important; bulk material (sieved <2 mm, air dry, e.g., removed from cores), is placed in retainer rings on the ceramic plate.
- *Desorption method*: Equilibrium values for water desorption can be set by a hanging water column or application of 'over pressure.' A hanging water column with a water manometer is used for lower retention levels (<250 kPa). Hanging water columns should not exceed a length of 10 meters unless vacuum conditions are created and controlled by an Hg-manometer at the 'open end' of the column. With the pressure method, multiple samples are placed on a ceramic plate in a 'pressure pan.' In a series of equilibrium points the above methods are often combined; also, there is an overlap in potential use of the respective desorption methods.
- *Device*: Within the range of equilibrium values for the determination of water holding capacity (e.g., from pF 1.5 to pF 4.2) several 'overlapping' devices can be applied. Saturation is achieved on a tension table at 5 cm tension (5 kPa) applied at the base of the sample. Other equilibrium points may be set in a pressure plate extractor, on a porous plate with burette to measure the volume of desorbed water, or in a kaolin bath. Tensiometers are used with the wind evaporation method.
- *Expression*: Water content may be expressed on a volume basis (volume of water per unit volume of moist soil), on a dry mass basis (mass of water per unit mass of soil solids), or on a wet mass basis (mass of water per unit mass of wet soil). Water holding capacity conventionally is expressed in volume % (weight per volume, w/v) rather than in weight % (weight per weight, w/w). To arrive at volume %, weight% has to be multiplied by bulk density. Where present, a correction needs to be applied for coarse fragments (Soil Survey Staff 2022a).

#### 4.2.5 Hydraulic conductivity

##### *Background*

Hydraulic conductivity is a measure for how fast water flows through the soil voids. It is a function of the texture, grain size and distribution, density, as well as the macrostructure of the soil. Measurement of hydraulic conductivity is time-consuming (Green *et al.* 1986; Soil Survey Staff 2022a), hence it is often determined using pedotransfer functions from more widely available soil parameters such as particle size and bulk density (van Genuchten 1980; Vereecken



*et al.* 1992; Wösten *et al.* 1995). However, the associated uncertainties can be large (van Alphen *et al.* 2001; Minasny and McBratney 2002; Loosvelt *et al.* 2011).

There are two broad approaches for determining hydraulic conductivity, an empirical and an experimental approach. The experimental approach either uses laboratory or field tests for which several methods are available (see [Wikipedia](#)), the results of which are not necessarily comparable. In this context, reference should be made to the ‘Soil program on hydro-physics via international engagement’ ([SOPHIE](#)) which has the ambition to provide a generally accepted degree of harmonization and standardization of soil hydro-physical properties (see Bakker *et al.* 2019).

### Method

Generally, two measures for hydraulic conductivity are reported in the source materials shared for consideration in WoSIS:  $K_s$ , saturated hydraulic conductivity and  $K_h$ , unsaturated hydraulic conductivity. These have been measured according to a range of field procedures. The methods of measurement themselves however are not specified in greater detail in WoSIS, as there are already well known, dedicated databases for soil hydrological properties such as HYPRES (Wösten *et al.* 1999; Nemes *et al.* 2001) and UNSODA (Nemes *et al.* 2001).

## 5. Concluding remarks

A larger selection of soil properties can now be standardized in WoSIS.

Actual ingestion of new datasets, however, will be largely dependent on the willingness/ability of data providers to share some of their soil data for consideration in WoSIS.

Once at least 30,000 measurements for a given soil observation (e.g. Ca\_EXTME3) have been standardized these will be served to the international community through *wosis\_latest* and possible new snapshots.

Full data harmonization to a common set of reference methods in WoSIS, using a range of validated pedotransfer functions, will first become feasible once:

- A common set of ‘international’ reference methods (e.g., ISO or GLOSOLAN standard operation procedures) has been accepted as the common standard by the international soil science community, and
- Results of globally distributed proficiency testing program become freely available. Such proficiency testing program would provide the basis for method validation between laboratories with their actual/adjusted method.

## Acknowledgements

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## Appendix – Examples of option tables for describing soil analytical methods in WoSIS

Coding procedures for CEC (cation exchange capacity) and electrical conductivity are given below as examples in Table 4 and 5, respectively. Method options for the soil properties that are served with *wosis\_latest* can be consulted using a(n evolving) [dashboard](#). Further, in Table 6, an example is provided for the ‘conversion’ between WoSIS codes and those considered in the concept scheme for the GLOSIS codelist.

*Table 4. Example of method options for coding cation exchange capacity.*

<b>Key</b>	<b>Code</b>	<b>Value</b>
sample pretreatment	0	not specified
sample pretreatment	1	sieved over 1 mm sieve
sample pretreatment	2	sieved over 2 mm sieve
Technique	0	not specified
Technique	1	determination by lab procedure
Technique	2	approximated by summation exchangeable cations
reported pH	0	not specified
reported pH	1	reported as (no buffer applied); field pH
reported pH	2	buffered at 7.0
reported pH	3	buffered at 8.0
reported pH	4	buffered at 8.1
reported pH	5	buffered at 8.2
reported pH	6	buffered at 8.3
reported pH	7	buffered at 8.4
reported pH	8	buffered at 8.5
exchange solution	0	not specified
exchange solution	1	not applied
exchange solution	2	1 M KCl
exchange solution	3	1 M NH <sub>4</sub> -acetate
exchange solution	4	1 M NH <sub>4</sub> -chloride
exchange solution	5	0.5 M Li-acetate
exchange solution	6	0.5 M BaCl <sub>2</sub> -TEA
exchange solution	7	0.1 M BaCl <sub>2</sub> -TEA
exchange solution	8	1 M Na-acetate
exchange solution	9	0.01 M Ag-thiourea
exchange solution	10	0.01 M Ag-thiourea + buffer

<i>Key</i>	<i>Code</i>	<i>Value</i>
exchange solution	11	0.25 M NH <sub>4</sub> Ac
exchange solution	12	0.1 M CaCl <sub>2</sub>
exchange solution	13	0.5 M Li-chloride
exchange solution	14	0.1 M Li-EDTA
exchange solution	15	Ba-acetate
exchange solution	16	BaCl <sub>2</sub>
Replacement	0	not specified
Replacement	1	not applied
Replacement	2	NaOH
Replacement	3	KCl
Replacement	4	NaCl
Replacement	5	KNO <sub>3</sub> Ca(NO <sub>3</sub> ) <sub>2</sub>
Replacement	6	NH <sub>4</sub> -acetate
Replacement	7	Ca-Acetate
Replacement	8	Mg(NO <sub>3</sub> ) <sub>2</sub>
Replacement	9	Mg(SO <sub>4</sub> ) <sub>2</sub>
Replacement	10	NH <sub>4</sub> Cl
Replacement	11	NaNO <sub>3</sub>
Replacement	12	10% NaCl + HCl
Replacement	13	CaCl <sub>2</sub>
Replacement	14	K-EDTA
Replacement	15	Na-acetate
index cation	0	not specified
index cation	1	not applied
index cation	2	NH <sub>4</sub> <sup>+</sup>
index cation	3	Na <sup>+</sup>
index cation	4	0.01 M Ag-Thiourea <sup>+</sup>
index cation	5	Ba <sup>2+</sup>
index cation	6	Li <sup>+</sup>
index cation	7	Mg <sup>2+</sup>
index cation	8	Ca <sup>2+</sup>
bases approximation	0	not specified
bases approximation	1	not applied
bases approximation	2	sum exchangeable bases (NH <sub>4</sub> Cl, unbuffered)
bases approximation	3	sum exchangeable bases (NH <sub>4</sub> OAc, buffered pH 7)
bases approximation	4	sum exchangeable bases (BaCl <sub>2</sub> -TEA pH 8.1)
bases approximation	5	sum of extractable Na, K, Ca, Mg (NH <sub>4</sub> Cl, 0.05M, unbuffered)
acidity approximation	0	not specified

<i>Key</i>	<i>Code</i>	<i>Value</i>
acidity approximation	1	not applied
acidity approximation	2	exchangeable acidity (KCl extract), (sum of) H, Al
acidity approximation	3	extractable / potential acidity (BaCl <sub>2</sub> - TEA, pH 8.2)
acidity approximation	4	(sum of) extractable H, Al (NH <sub>4</sub> Cl, 0.05M, unbuffered)
other exchangeable cations	0	not specified
other exchangeable cations	1	not applied
other exchangeable cations	2	(sum of) extractable Fe, Mn (NH <sub>4</sub> Cl, 0.05M, unbuffered)
Spectral	1	false
Spectral	2	true

Table 5. Example of methods options for coding electrical conductivity.

<i>Key</i>	<i>Code</i>	<i>Value</i>
sample pretreatment	0	not specified
sample pretreatment	1	sieved over 1 mm sieve
sample pretreatment	2	sieved over 2 mm sieve
Solution	0	not specified
Solution	1	water [H <sub>2</sub> O]
Ratio	0	not specified
Ratio	1	1:1
Ratio	2	1:2
Ratio	3	1:2.5
Ratio	4	1:5
Ratio	5	1:10
Ratio	6	1:50
Ratio	7	saturated paste
Ratio	8	slurry
ratio base	0	not specified
ratio base	1	weight / volume
ratio base	2	volume / volume
Instrument	0	not specified
Instrument	1	electrode
Instrument	2	electrode (field measured)
Spectral	1	False
Spectral	2	True

An example for the ‘conversion’ between codes used in WoSIS and those considered in the concept scheme for the GLOSIS codelist is presented in Table 6. It should be noted that the evolving GLOSIS codelist provides less detailed information than is presented in *wosis\_latest*. In the case of soil pH-KCl, for example, WoSIS can also provide information on the molarity of the solution and indicate whether an observation was made in the laboratory or derived from spectral data.

*Table 6. Mapping WoSIS codes to GLOSIS codes (example for pH-KCl).*

<b>wosis_code<sup>a</sup></b>	<b>key</b>	<b>value</b>	<b>codelist_code<sup>b</sup></b>
PHKC	ratio	1:1	pHKCl_ratio1-1
PHKC	ratio	1:2	pHKCl_ratio1-2
PHKC	ratio	1:2.5	pHKCl_ratio1-2.5
PHKC	ratio	1:5	pHKCl_ratio1-5
PHKC	ratio	1:10	pHKCl_ratio1-10
PHKC	ratio	1:20	pHKCl_ratio1-20

<sup>a</sup> Codes used in [WoSIS](#). <sup>b</sup> Codes from GLOSIS [codelist](#).

## References

- Alva AK 1993. Comparison of Mehlich 3, Mehlich 1, ammonium bicarbonate-DTPA, 1.0M ammonium acetate, and 0.2M ammonium chloride for extraction of calcium, magnesium, phosphorus, and potassium for a wide range of soils. *Communications in Soil Science and Plant Analysis* 24, 603-612. <https://doi.org/10.1080/00103629309368826>
- Álvarez D, Antúnez M, Porras S, Rodríguez-Ochoa R, Olarieta JR and Poch RM 2022. Quantification of Gypsum in Soils: Methodological Proposal. *Spanish Journal of Soil Science* 12 <https://www.frontierspartnerships.org/journals/spanish-journal-of-soil-science/articles/10.3389/sjss.2022.10669>
- ANSIS 2023. *Australian National Soil Information System*, Australian National Soil Information System, Canberra (AU). <https://ansis.net/>
- Baize D 1993. *Soil Science Analyses: A Guide to Current Use*. John Wiley & Sons, Chichester, 192 p.
- Bakker G, Heinen M, Gooren HPA, Groot WJMd and Peters PD 2019. *Hydrofysische gegevens van de bodem in de Basisregistratie Ondergrond (BRO) en het Bodemkundig Informatie Systeem (BIS); Update 2019*. , Wettelijke Onderzoekstaken Natuur & Milieu, Wageningen, 128 blz. p. <https://edepot.wur.nl/526509>
- Baritz R, Erdogan H, Fujii K, Takata Y, Nocita M, Bussian B, Batjes NH, Hempel J, Wilson P and Vargas R 2014. *Harmonization of methods, measurements and indicators for the sustainable management and protection of soil resources (Providing mechanisms for the collation, analysis and exchange of consistent and comparable global soil data and information)*, Global Soil Partnership, FAO, 44 p. <http://www.fao.org/3/a-az922e.pdf>
- Batjes NH 2023. *Options for harmonising soil data obtained from different sources* ISRIC - World Soil Information, Wageningen, 21 p. <https://dx.doi.org/10.17027/isric-wdc-6ztd-eb19>
- Batjes NH and van Oostrum AJM 2023. *WoSIS Procedures for standardizing soil analytical method descriptions (version 2023)*, ISRIC - World Soil Information, Wageningen, 46 p. <https://doi.org/10.17027/isric-1dq0-1m83>
- Batjes NH, Kempen B and van Egmond F 2019. *Tier 1 and Tier 2 data in the context of the federated Global Soil Information System (GLoSIS)*, FAO, 42 p. <https://doi.org/10.17027/isric-dcmkd4-g431>
- Batjes NH, Calisto L and de Sousa LM 2024. Providing quality-assessed and standardised soil data to support global mapping and modelling (WoSIS snapshot 2023). *Earth System Science Data*, 4735–4765. <https://doi.org/10.5194/essd-16-4735-2024>
- Benton Jones J 1990. Universal soil extractants: Their composition and use. *Communications in Soil Science and Plant Analysis* 21, 1091-1101. <https://doi.org/10.1080/00103629009368292>
- Bibiso M, Taddesse AM, Gebrekidan H and Melese A 2015. Evaluation of Universal Extractants for Determination of Some Macronutrients from Soil. *Communications in Soil Science and Plant Analysis* 46, 2425-2448. <https://doi.org/10.1080/00103624.2015.1081925>
- Bispo A, Arrouays D, Saby N, Boulonne L and Fantappiè M 2021. *Proposal of methodological development for the LUCAS programme in accordance with national monitoring programmes. Towards climate-smart sustainable management of agricultural soils (EU H2020-SFS-2018-2020 / H2020-SFS-2019)* EJP Soil, 135 p. [https://ejpsoil.eu/fileadmin/projects/ejpsoil/WP6/EJP\\_SOIL\\_Deliverable\\_6.3\\_Dec\\_2021\\_final.pdf](https://ejpsoil.eu/fileadmin/projects/ejpsoil/WP6/EJP_SOIL_Deliverable_6.3_Dec_2021_final.pdf)
- Bolt GH and Bruggenwert MGM 1978. *Soil Chemistry*. Elsevier Scientific Publishing Company, Amsterdam
- Bray RH and Kurtz LT 1945. Determination of total, organic, and available forms of phosphorus in soils. *Soil Science* 59, 39-46. [http://journals.lww.com/soilsci/Fulltext/1945/01000/Determination\\_of\\_Total,\\_Organic,\\_and\\_Available.6.aspx](http://journals.lww.com/soilsci/Fulltext/1945/01000/Determination_of_Total,_Organic,_and_Available.6.aspx)
- Breure MS, Van Eynde E, Kempen B, Comans RNJ and Hoffland E 2022. Transfer functions for phosphorus and potassium soil tests and implications for the QUEFTS model. *Geoderma* 406, 115458. <https://www.sciencedirect.com/science/article/pii/S0016706121005383>
- Brus J 2022. *Spatial sampling with R*. Chapman and Hall R/C, New York <https://doi.org/10.1201/9781003258940>
- Buurman P and Van Doesburg JDJ 2007. Laser-diffraction grain-size analyses of reference profiles. In: Arnalds O *et al.* (editors), *Soils of Volcanic Regions in Europe*. Springer-Verlag, Heidelberg, pp 451-468.
- Ciampalini R, Lagacherie P, Gomez C, Grünberger O, Hamrouni MH, Mekki I and Richard A 2013. Detecting, correcting and interpreting the biases of measured soil profile data: A case study in the Cap Bon Region (Tunisia). *Geoderma* 192, 68-76. <http://www.sciencedirect.com/science/article/pii/S0016706112002923>
- Corral-Pazos-de-Provens E, Rapp-Arrarás Í and Domingo-Santos JM 2022. Estimating textural fractions of the

- USDA using those of the International System: A quantile approach. *Geoderma* 416, 115783. <https://www.sciencedirect.com/science/article/pii/S0016706122000908>
- De Gruijter JJ, Brus DJ, Bierkens MFP and Knottters M (editors) 2006. Sampling for natural resource monitoring. Springer, Heidelberg, 338 p.
- de Sousa L, Kempen B, Mendes de Jesus J, Yigini Y, Viatkin K, Medyckyj-Scott D, Richie DA, Wilson P, van Egmond F and Baritz R 2021. *Conceptual design of the Global Soil Information System infrastructure*, Rome, FAO and ISRIC, Wageningen, Netherlands, 30 p. <http://www.fao.org/3/cb4355en/cb4355en.pdf>
- Dixon JB, Weed SB, Kittrick JA, Milford MH and White JL 1977. *Minerals in soil environments*. Soil Science Society of America, Madison (WI), 948 p.
- Duffus JH 2002. "Heavy metals" a meaningless term? . *Pure and Applied Chemistry* 74, 793-807. <https://doi.org/10.1351/pac200274050793>
- Elfaki JT, Gafer MA, Sulieman MM and Ali ME 2016. Hydrometer method against Pipette method for Estimating Soil particle size distribution in Some Soil Types Selected from Central Sudan. *International Journal of Engineering Research and Advanced Technology (IJERAT)* 2, 25-41. [https://www.researchgate.net/publication/297884732\\_Hydrometer\\_method\\_against\\_Pipette\\_method\\_for\\_Estimating\\_Soil\\_particle\\_size\\_distribution\\_in\\_Some\\_Soil\\_Types\\_Selected\\_from\\_Central\\_Sudan](https://www.researchgate.net/publication/297884732_Hydrometer_method_against_Pipette_method_for_Estimating_Soil_particle_size_distribution_in_Some_Soil_Types_Selected_from_Central_Sudan)
- Elrashidi MA 2010. *Selection of an appropriate phosphorus test for soils*, Soil Survey Laboratory, USDA, Lincoln (NE). [http://www.nrcs.usda.gov/Internet/FSE\\_DOCUMENTS/nrcs142p2\\_051918.pdf](http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051918.pdf)
- Esmaelnejad L, Siavashi F, Seyedmohammadi J and Shabanpour M 2016. The best mathematical models describing particle size distribution of soils. *Modeling Earth Systems and Environment* 2, 1-11. <https://doi.org/10.1007/s40808-016-0220-9>
- EURACHEM 2014. The fitness for purpose of analytical methods, EURACHEM. <https://www.eurachem.org/index.php/publications/guides/mv>
- Faé GS, Montes F, Bazilevskaya E, Añó RM and Kemanian AR 2019. Making Soil Particle Size Analysis by Laser Diffraction Compatible with Standard Soil Texture Determination Methods. *Soil Science Society of America Journal* 83, 1244-1252. <https://doi.org/10.2136/sssaj2018.10.0385>
- Fairhurst T, Lefroy R, Mutert E and Batjes NH 1999. The importance, distribution and causes of P deficiency as a constraint to crop production in the tropics. *Agroforestry Forum* 9, 2-8. <https://tinyurl.com/y64nbdfh>
- FAO 1988. *FAO-Unesco Soil Map of the World, Revised Legend, with corrections and updates (Reprint of World Soil Resources Report 60, FAO, Rome, 1988)*. World Soil Resources Report 60, FAO, Rome; reprinted with updates as Technical Paper 20 by ISRIC, Wageningen, 1997, 140 p. [http://www.isric.org/sites/default/files/ISRIC\\_TechPap20.pdf](http://www.isric.org/sites/default/files/ISRIC_TechPap20.pdf)
- FAO 1990. *Management of gypsiferous soils*, FAO, Rome. <https://www.fao.org/4/t0323e/t0323e00.htm#Contents>
- FAO 2006. *Guidelines for soil description (4th ed.)*, FAO, Rome, 97 p. <http://www.fao.org/docrep/019/a0541e/a0541e.pdf>
- Fernandez-Buces N, Siebe C, Cram S and Palacio JL 2006. Mapping soil salinity using a combined spectral response index for bare soil and vegetation: A case study in the former lake Texcoco, Mexico. *Journal of Arid Environments* 65, 644-667. <http://www.sciencedirect.com/science/article/B6WH9-4H877KF-1/2/e2d2a23248280404a68fae69280ab4bf>
- Gillman GP 2007. An analytical tool for understanding the properties and behaviour of variable charge soils. *Australian Journal of Soil Research* 45, 83-90. <http://www.publish.csiro.au/paper/SR06117>
- GlobalSoilMap 2015. *Specifications Tiered GlobalSoilMap products (Release 2.4)*, 52 p. <https://www.isric.org/documents/document-type/globalsoilmap-specifications-v24-07122015>
- GLOSOLAN 2019. *Standard operating procedure for soil organic carbon: Walkley-Black method (Titration and colorimetric method)*, GLOSOLAN / FAO, Rome, 27 p. <https://www.fao.org/3/ca7471en/ca7471en.pdf>
- GLOSOLAN 2020. *Standard operating procedure for soil calcium carbonate equivalent (Titrimetric method)*, GLOSOLAN / FAO, Rome, 16 p. <https://openknowledge.fao.org/server/api/core/bitstreams/109095f4-980f-4bde-b8a0-0cee1641ab32/content>
- GLOSOLAN 2021. *Standard operating procedure for soil pH determination*, GLOSOLAN / FAO, Rome, 23 p. <https://www.fao.org/3/cb3637en/cb3637en.pdf>
- GLOSOLAN 2022a. *Standard operating procedures for cation exchange capacity and exchangeable bases 1 N ammonium acetate, pH 7.0 method*, GLOSOLAN / FAO, Rome, 21 p. <https://openknowledge.fao.org/server/api/core/bitstreams/cfc7409a-422e-4daf-86e0-6364f3d5d0fa/content>
- GLOSOLAN 2022b. *Standard operating procedures (SOPs)*, GLOSOLAN / FAO. <https://www.fao.org/global-soil-partnership/glosolan-old/soil-analysis/standard-operating-procedures/en/>



- GLOSOLAN 2023. *GLOSOLAN best practice manual (on-line)*, FAO, GSP, Rome. <https://www.fao.org/global-soil-partnership/glosolan-old/soil-analysis/standard-operating-procedures/en/#c763834>
- Goodchild MF 1994. Sharing imperfect data. In: Singh A (editor), *Proceedings UNEP and IUFPPO international workshop in cooperation with FAO in developing large environmental databases for sustainable development*. UNEP/GRID, Sioux Falls, pp 102-110.
- Goodchild MF and Gopal S 1989. *The accuracy of spatial databases*. Taylor & Francis, London, 312 p.
- Grandt S, Ketterings QM, Lembo AJ and Vermeylen F 2010. In-Field Variability of Soil Test Phosphorus and Implications for Agronomic and Environmental Phosphorus Management. *Soil Sci. Soc. Am. J.* 74, 1800-1807. <http://dx.doi.org/10.2136/sssaj2008.0190>
- Green RE, Ahuja LR and Chong SK 1986. Hydraulic conductivity, diffusivity and sorptivity of unsaturated soils: field methods. In: SSSA (editor), *Methods of Soil Analysis, Part I. Physical and mineralogical methods*. Agronomy Monograph No. 9. American Society of Agronomy - Soil Science Society of America, Madison, pp 771-785. <https://doi.org/10.2136/sssabookser5.1.2ed.c30>
- Grewal KS, Buchanan GD and Sherlock RS 1991. A comparison of three methods of organic carbon determination in some New Zealand soils. *Journal of Soil Science* 42, 251-257. <https://doi.org/10.1111/j.1365-2389.1991.tb00406.x>
- Grossman RB and Reinsch TG 2002. Bulk density and linear extensibility, *Methods of Soil Analysis: Part 4 Physical Methods*, pp 201-208. <https://dl.sciencesocieties.org/publications/books/tocs/sssabookseries/methodsofsoilan4>
- Gu Y, Ros GH, Zhu Q, van Doorn M, Shen J, Cai Z, Xu M and de Vries W 2024. Potential use of phosphorus saturation degree as combined indicator for crop yield and leaching risks at regional scale. *European Journal of Agronomy* 161, 127347. <https://www.sciencedirect.com/science/article/pii/S1161030124002685>
- Guillaume B, Aroui Boukbida H, Bakker G, Bieganski A, Brostaux Y, Cornelis W, Durner W, Hartmann C, Iversen BV, Javaux M, Ingwersen J, Lamorski K, Lamparter A, Makó A, Mingot Soriano AM, Messing I, Nemes A, Pomes-Bordedebat A, van der Ploeg M, Weber TKD, Weihermüller L, Wellens J and Degré A 2023. Reproducibility of the wet part of the soil water retention curve: a European interlaboratory comparison. *SOIL* 9, 365-379. <https://soil.copernicus.org/articles/9/365/2023/>
- Haefele SM, Mossa AW, Gashu D, Nalivata PC, Broadley MR, McGrath SP and Thomas CL 2024. Mehlich 3 as an indicator of grain nutrient concentration for five cereals in sub-Saharan Africa. *Field Crops Research* 307, 109243. <https://www.sciencedirect.com/science/article/pii/S0378429023004367>
- Herrero J, Artieda O and Hudnall WH 2009. Gypsum, a Tricky Material. *Soil Sci Soc Am J* 73, 1757-1763. <http://soil.scijournals.org/cgi/content/abstract/soilsci;73/6/1757>
- Heuvelink GBM 1996. Identification of field attribute error under different models of spatial variation. *International Journal of Geographical Information Systems* 10, 921-935. <https://doi.org/10.1080/02693799608902117>
- Heuvelink GBM 2014. Uncertainty quantification of GlobalSoilMap products In: Arrouays D, N McKenzie, J Hempel, ARd Forges and A McBratney (editors), *GlobalSoilMap. Basis of the Global Spatial Soil Information System*. Taylor & Francis Group, London, UK, pp 335-240.
- Hilke I 2015. *General principles for the quantification of Total Organic Carbon (TOC) in environmental solid and liquid samples*. Technical Reports 30, Max-Planck-Institut für Biogeochemie, Jena (Germany), 20 p. [https://www.bgc-jena.mpg.de/www/uploads/Publications/TechnicalReports/30\\_2015\\_TechnicalReport\\_Hilke.pdf](https://www.bgc-jena.mpg.de/www/uploads/Publications/TechnicalReports/30_2015_TechnicalReport_Hilke.pdf)
- Hu B, Bourennane H, Arrouays D, Denoroy P, Lemerrier B and Saby NPA 2021. Developing pedotransfer functions to harmonize extractable soil phosphorus content measured with different methods: A case study across the mainland of France. *Geoderma* 381, 114645. <http://www.sciencedirect.com/science/article/pii/S0016706119324437>
- ICP Forests 2020. *ICP Forests monitoring Manual. Part XVI: Quality assurance and control in laboratories (ver 2020-1)*, Eberswalde, Germany, 46 p. [https://www.icp-forests.org/pdf/manual/2020/ICP\\_Manual\\_part16\\_2020\\_QAQC\\_Labs\\_version\\_2020-1.pdf](https://www.icp-forests.org/pdf/manual/2020/ICP_Manual_part16_2020_QAQC_Labs_version_2020-1.pdf)
- ICP Forests 2021. *ICP Forests monitoring Manual. Part X: Sampling and analysis of soil*, Eberswalde, Germany. <https://storage.ning.com/topology/rest/1.0/file/get/9995584862?profile=original>
- ISO-10694 1995. Soil quality — Determination of organic and total carbon after dry combustion (elementary analysis) (ISO 10694:1995(en)). <https://www.iso.org/obp/ui/#iso:std:iso:10694:ed-1:v1:en>
- ISO 2021. ISO 10390:2005: Soil quality -- Determination of pH, International Organization for Standardization. [http://www.iso.org/iso/catalogue\\_detail.htm?csnumber=40879](http://www.iso.org/iso/catalogue_detail.htm?csnumber=40879)
- ISO/TC 190 2016. ISO/TC 190 - Soil quality (standards catalogue), International Organization for Standardization.

- [http://www.iso.org/iso/iso\\_catalogue/catalogue\\_tc/catalogue\\_tc\\_browse.htm?commid=54328](http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_tc_browse.htm?commid=54328)
- IUSS Working Group WRB 2022. *World Reference Base for soil resources 2022 - International soil classification system for naming soils and creating legends for soil maps*, International Union of Soil Sciences, Vienna (Austria), 284 p. [https://www.isric.org/sites/default/files/WRB\\_fourth\\_edition\\_2022-12-18.pdf](https://www.isric.org/sites/default/files/WRB_fourth_edition_2022-12-18.pdf)
- Ivushkin K, Bartholomeus H, Bregt AK, Pulatov A, Kempen B and de Sousa L 2019. Global mapping of soil salinity change. *Remote Sensing of Environment* 231 <https://doi.org/10.1016/j.rse.2019.111260>
- Jankauskas B, Jankauskiene G, Slepeliene A, Fullen MA and Booth CA 2006. International comparison of analytical methods of determining the soil organic matter content of Lithuanian eutric Albeluvisols. *Comm. in Soil Science and Plant Analysis* 37, 707-720. <http://dx.doi.org/10.1080/00103620600563499>
- Jury AW, Gardner WR and Gardner WH 1991. *Soil Physics (5th ed.)*. Wiley, New York
- Katschinski NA 1956. Die mechanische Bodenanalyse und die Klassifikation der Böden nach ihrer mechanischen Zusammensetzung, *Rapports au Sixième Congrès International de la Science du Sol*. International Society of Soil Science, Paris (FR), pp 321-327. [http://iuss.boku.ac.at/files/vi\\_e\\_congres\\_international\\_de\\_la\\_sciences\\_du\\_sol\\_volume\\_b\\_paris\\_1956\\_compressed.pdf#page=323](http://iuss.boku.ac.at/files/vi_e_congres_international_de_la_sciences_du_sol_volume_b_paris_1956_compressed.pdf#page=323)
- Kihara J, Sileshi GW, Nziguheba G, Kinyua M, Zingore S and Sommer R 2017. Application of secondary nutrients and micronutrients increases crop yields in sub-Saharan Africa. *Agronomy for Sustainable Development* 37, 25. <https://doi.org/10.1007/s13593-017-0431-0>
- Koorevaar P, Menelik G and Dirksen C 1983. *Elements of soil physics*. Developments in Soil Science 13. Elsevier, Amsterdam, 228 p.
- Kuhlbusch TAJ, Borowiak A, Gelenscer A, Genberg J, Gladtko D, Maenhaut W, Pio C, Popovicheva O, Putaud JP, Paul, Quincey, Sciare J, Brink Ht, Viana M and Yttri KE 2009. *Measurement of Elemental and Organic Carbon in Europe*, Office for Official Publications of the European Communities Luxembourg, 114 p. <http://publications.jrc.ec.europa.eu/repository/bitstream/JRC54045/ecoc%20eur%20report%20240909.pdf>
- Letten S, Vos BD, Quataert P, van Wesemael B, Muys B and van Orshoven J 2007. Variable carbon recovery of Walkley-Black analysis and implications for national soil organic carbon accounting. *European Journal of Soil Science* 58, 1244-1253. <http://dx.doi.org/10.1111/j.1365-2389.2007.00916.x>
- Levy ET and Aschlesinger WH 1999. A comparison of fractionation methods for forms of phosphorus in soils. *Biogeochemistry* 47, 25-38. <http://dx.doi.org/10.1023/A:1006105420235>
- Loosvelt L, Pauwels VRN, Cornelis WM, De Lannoy GJM and Verhoest NEC 2011. Impact of soil hydraulic parameter uncertainty on soil moisture modeling. *Water Resources Research* 47 <http://www.scopus.com/inward/record.url?eid=2-s2.0-79952483403&partnerID=40&md5=eec7a5c66b1f9a6be15e13585100b41f>
- Louis BP, Saby NPA, Orton TG, Lacarce E, Boulonne L, Jolivet C, Ratié C and Arrouays D 2014. Statistical sampling design impact on predictive quality of harmonization functions between soil monitoring networks. *Geoderma* 213, 133-143. <https://www.sciencedirect.com/science/article/pii/S0016706113002541>
- Loveland P 2016. Particle size analysis: What does it mean? *The Auger* Dec. 2016, 25-25. <http://soils.org.uk/auger>
- Loveland PJ and Whalley WR 2000. Particle size analysis. In: Simith KA and CE Williams (editors), *Soil and environmental analysis - Second edition (Revised and Expanded)*. Marcel Dekker Inc., New York & Basel, pp 281-314.
- Magnusson B and Örnemark U 2014. *The Fitness for Purpose of Analytical Methods – A Laboratory Guide to Method Validation and Related Topics (2nd ed.)*, Eurachem. [https://www.eurachem.org/images/stories/Guides/pdf/MV\\_guide\\_2nd\\_ed\\_EN.pdf](https://www.eurachem.org/images/stories/Guides/pdf/MV_guide_2nd_ed_EN.pdf)
- Maire V, Wright IJ, Prentice IC, Batjes NH, Bhaskar R, van Bodegom PM, Cornwell WK, Ellsworth D, Niinemets U, Ordóñez A, Reich PB and Santiago LS 2015. Global effects of soil and climate on leaf photosynthetic traits and rates. *Global Ecology and Biogeography* 24, 706-717. <https://doi.org/10.1111/geb.12296>
- Makó A, Hernádi H, Barna G, Balázs R, Molnár S, Labancz V, Tóth B and Bakacsi Z 2017. Particle size distribution analysis using the pipette method: Comparison and conversion of Hungarian and international standards. *Agrokemia és Talajtan* 66, 295-315. <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85037697327&doi=10.1556%2f0088.2017.66.2.1&partnerID=40&md5=2b445650ffae8c65c47fb545b851b7>
- Mallarino P 1995. Comparison of Mehlich-3, Olsen, and Bray-P1 procedures for phosphorus in calcareous soils. In: Rehm G, (editor), *Proceedings of the twenty-fifth North Central extension-industry soil fertility conference*. Potash & Phosphate Institute, Manhattan (KS) pp 96-101. <http://www.agronext.iastate.edu/soilfertility/info/ComparisonofMehlich-3OlsenandBray-P1Procedures.pdf>

- Marschner P and Rengel Z 2023. Nutrient availability in soils. In: Rengel Z, I Cakmak and PJ White (editors), *Marschner's Mineral Nutrition of Plants (Fourth Edition)*. Academic Press, San Diego, pp 499-522. <https://www.sciencedirect.com/science/article/pii/B9780128197738000034>
- Minasny B and McBratney AB 2002. The efficiency of various approaches to obtaining estimates of soil hydraulic properties. *Geoderma* 107, 55-70. <http://www.sciencedirect.com/science/article/B6V67-442NWN-1/2/9b77dfc0ab8db94c0f7e6647a4a1694d>
- Minasny B, McBratney AB, Wadoux AMJC, Alobe EN and Sabrina T 2020. Precocious 19th century soil carbon science. *Geoderma Regional* 22, e00306. <http://www.sciencedirect.com/science/article/pii/S2352009420300559>
- Minasny B, McBratney AB, Field DJ, Tranter G, McKenzie NJ and Brough DM 2007. Relationships between field texture and particle-size distribution in Australia and their implications. *Australian Journal of Soil Research* 45, 428-437. <http://www.publish.csiro.au/paper/SR07051>
- Moeys J 2018. *The soil texture wizard: R functions for plotting, classifying, transforming and exploring soil texture data*, 104 p. [https://cran.r-project.org/web/packages/soiltexture/vignettes/soiltexture\\_vignette.pdf](https://cran.r-project.org/web/packages/soiltexture/vignettes/soiltexture_vignette.pdf)
- NATP 2015. *North American Proficiency Testing (NAPT) Program*. <http://www.naptprogram.org/>
- Nelson DL and Sommers LE 1982. Total carbon, organic carbon, and organic matter. In: Page AL (editor), *Methods of Soil Analysis*. American Society of Agronomy, Madison, WI, pp 539-579.
- Nemes A, Wösten JHM, Lilly A and Oude Voshaar JH 1999. Evaluation of different procedures to interpolate particle-size distributions to achieve compatibility within soil databases. *Geoderma* 90, 187-202. <http://www.sciencedirect.com/science/article/pii/S0016706199000142>
- Nemes A, Schaap MG, Leij FJ and Wösten JHM 2001. Description of the unsaturated soil hydraulic database UNSODA version 2.0. *Journal of Hydrology* 251, 151-162. <https://www.sciencedirect.com/science/article/pii/S0022169401004656>
- Olsen SR, Cole CV, Watanabe FS and Dean LA 1954. *Estimation of available phosphorus in soils by extraction with sodium bicarbonate*, U.S. Govt. Print. Office, Washington, DC.
- Palma R, Janiak B, Sousa LMD, Schleidt K, Tomáš Rezník, Egmond Fv, Leenaars J, Moshou D, Mouazen A, Peter Wilson, Medveckyj-Scott D, Ritchie A, Yigini Y and Vargas R 2024. GloSIS: The Global Soil Information System Web Ontology. *arXiv:2403.16778* <https://doi.org/10.48550/arXiv.2403.16778>
- Pansu M and Gautheyrou J 2006. *Handbook of Soil Analysis: Mineralogical, Organic and Inorganic Methods*. Springer, 993 p. <https://link.springer.com/content/pdf/10.1007/978-3-540-31211-6.pdf>
- Partida C, Safanelli JL, Mitu SM, Murad MOF, Ge Y, Ferguson R, Shepherd K and Sanderman J 2025. Building a near-infrared (NIR) soil spectral dataset and predictive machine learning models using a handheld NIR spectrophotometer. *Data in Brief* 58, 111229. <https://www.sciencedirect.com/science/article/pii/S2352340924011910>
- Pieri L, Bittelli M and Pisa PR 2006. Laser diffraction, transmission electron microscopy and image analysis to evaluate a bimodal Gaussian model for particle size distribution in soils. *Geoderma* 135, 118-132. <https://www.sciencedirect.com/science/article/pii/S001670610500306X>
- Poggio L, de Sousa L, Batjes NH, Heuvelink GBM, Kempen B, Riberio E and Rossiter D 2021. SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty. *SOIL* 7, 217-240. <https://doi.org/10.5194/soil-7-217-2021>
- Pourret O, Bollinger J-C and Hursthouse A 2021. Heavy metal: a misused term? *Acta Geochim* 40, 466-471. <https://doi.org/10.1007/s11631-021-00468-0>
- Pribyl DW 2010. A critical review of the conventional SOC to SOM conversion factor. *Geoderma* 156, 75-83. <http://www.sciencedirect.com/science/article/pii/S0016706110000388>
- Rayment ER and Lyons DJ 2011. *Soil chemical methods - Australasia*. CSIRO Publishing, 495 p. <https://www.publish.csiro.au/book/6418>
- Rayment GE and Peverill KI 2002. Proficiency testing for soil and plant analysis in Australasia. *Communications in Soil Science and Plant Analysis* 33, 2441-2455. <https://doi.org/10.1081/CSS-120014459>
- Rhoades JD, Chanduvi F and Lesch S 1999. *Soil salinity assessment: Methods and interpretation of electrical conductivity measurements*, FAO, Rome, 150 p. <http://www.fao.org/docrep/019/x2002e/x2002e.pdf>
- Ribeiro E, Batjes NH and Van Oostrum AJM 2020. *World Soil Information Service (WoSIS) - Towards the standardization and harmonization of world soil data. Procedures Manual 2020*. ISRIC Report 2020/01, ISRIC - World Soil Information, Wageningen, 153 p. <http://dx.doi.org/10.17027/isric-wdc-2020-01>
- Richer-de-Forges AC, Arrouays D, Poggio L, Chen SC, Lacoste M, Minasny B, Libohova Z, Roudier P, Mulder VL, Nédélec H, Martelet G, Lemerrier B, Lagacherie P and Bourennane H 2023. Hand-feel soil texture observations to evaluate the accuracy of digital soil maps for local prediction of soil particle size

- distribution: A case study in Central France. *Pedosphere* 33(5), 731--743.  
[http://pedosphere.issas.ac.cn/trqen/ch/reader/view\\_abstract.aspx?file\\_no=20230506&flag=1](http://pedosphere.issas.ac.cn/trqen/ch/reader/view_abstract.aspx?file_no=20230506&flag=1)
- Ross DS, Bailey SW, Briggs RD, Curry J, Fernandez IJ, Fredriksen G, Goodale CL, Hazlett PW, Heine PR, Johnson CE, Larson JT, Lawrence GB, Kolka RK, Ouimet R, Paré D, Richter Dd, Schirmer CD and Warby RA 2015. Inter-laboratory variation in the chemical analysis of acidic forest soil reference samples from eastern North America. *Ecosphere* 6, art73. <http://dx.doi.org/10.1890/ES14-00209.1>
- Rousseva SS 1997. Data transformations between soil texture schemes. *European Journal of Soil Science* 48, 749-758. <http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2389.1997.tb00574.x/abstract>
- Sadovski A and Ivanova M 2020. Transformation of soil texture schemes and determination of water-physical properties of soils. *Eurasian Journal of Soil Science* 9, 306-313. <https://doi.org/10.18393/ejss.760201>
- Safanelli JL, Hengl T, Parente LL, Minarik R, Bloom DE, Todd-Brown K, Gholizadeh A, Mendes WdS and Sanderman J 2025. Open Soil Spectral Library (OSSL): Building reproducible soil calibration models through open development and community engagement. *PLOS ONE* 20, e0296545.  
<https://doi.org/10.1371/journal.pone.0296545>
- Shamrikova EV, Kondratenok BM, Tumanova EA, Vanchikova EV, Lapteva EM, Zonova TV, Lu-Lyan-Min EI, Davydova AP, Libohova Z and Suvannang N 2022. Transferability between soil organic matter measurement methods for database harmonization. *Geoderma* 412  
<https://doi.org/10.1016/j.geoderma.2021.115547>
- Shepherd KD, Ferguson R, Hoover D, van Egmond F, Sanderman J and Ge Y 2022. A global soil spectral calibration library and estimation service. *Soil Security* 7, 100061.  
<https://doi.org/10.1016/j.soisec.2022.100061>
- Sims JT 1989. Comparison of mehlich 1 and mehlich 3 extractants for P, K, Ca, Mg, Mn, Cu and Zn in atlantic coastal plain soils. *Communications in Soil Science and Plant Analysis* 20, 1707-1726.  
<https://doi.org/10.1080/00103628909368178>
- Soil Survey Staff 1951. *Soil Survey Manual*. United States Agriculture Handbook 18, USDA, Washington, 203 p.  
[https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/ref/?cid=nrcs142p2\\_054262](https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/ref/?cid=nrcs142p2_054262)
- Soil Survey Staff 1975. *Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys*. Soil Conservation Service, USDA Agriculture Handbook 436, USDA, Washington
- Soil Survey Staff 2014. *Keys to Soil Taxonomy*, 12th ed. USDA-Natural Resources Conservation Service, Washington, DC.  
[https://www.nrcs.usda.gov/wps/PA\\_NRCSCConsumption/download?cid=stelprdb1252094&ext=pdf](https://www.nrcs.usda.gov/wps/PA_NRCSCConsumption/download?cid=stelprdb1252094&ext=pdf)
- Soil Survey Staff 2017. *Soil Survey Manual (rev. ed.)*. United States Agriculture Handbook 18, USDA, Washington  
<https://www.nrcs.usda.gov/sites/default/files/2022-09/The-Soil-Survey-Manual.pdf>
- Soil Survey Staff 2022a. *Soil Survey Laboratory Methods Manual (Version 6.0., Part1: Curren methods)*, Soil Survey Investigations Report No. 42, v6. U.S. Department of Agriculture, Natural Resources Conservation Service, Lincoln (Nebraska), 1001 p. <https://www.nrcs.usda.gov/sites/default/files/2023-01/SSIR42.pdf>
- Soil Survey Staff 2022b. *Keys to Soil Taxonomy*, 13th ed. USDA-Natural Resources Conservation Service, Washington, DC.  
<https://www.nrcs.usda.gov/sites/default/files/2022-09/Keys-to-Soil-Taxonomy.pdf>
- SOPHIE 2022. Soil Program on Hydro-Physics via International Engagement, 6th Meeting of the Global Soil Laboratory Network (GLOSOLAN). FAO, Rome, pp 15.  
[https://www.fao.org/fileadmin/user\\_upload/GSP/GLOSOLAN/6\\_glosolan\\_meeting/6th\\_GLOSOLAN\\_meetin\\_g\\_item\\_7\\_-\\_Sophie\\_AuroreDegre.pdf](https://www.fao.org/fileadmin/user_upload/GSP/GLOSOLAN/6_glosolan_meeting/6th_GLOSOLAN_meetin_g_item_7_-_Sophie_AuroreDegre.pdf)
- Takahashi T, Nakano K, Nira R, Kumagai E, Nishida M and Namikawa M 2020. Conversion of soil particle size distribution and texture classification from ISSS system to FAO/USDA system in Japanese paddy soils. *Soil Science and Plant Nutrition* 66, 407-414. <https://doi.org/10.1080/00380768.2020.1763143>
- Turek ME, Poggio L, Batjes NH, Armindo RA, de Jong van Lier Q, de Sousa L and Heuvelink GBM 2023. Global mapping of volumetric water retention at 100, 330 and 15000 cm suction using the WoSIS database. *International Soil and Water Conservation Research* 11, 225-239.  
<https://www.sciencedirect.com/science/article/pii/S2095633922000636>
- US-EPA 2015. Quality Management Tools - Best Practices for Laboratory Quality Systems, U.S. Environmental Protection Agency (US-EPA). <http://www.epa.gov/quality/bestlabs.html>
- US Salinity Laboratory Staff 1954. *Diagnosis and improvement of saline and alkali soils*. Agric. Handb. 60. United States Department of Agriculture, Washington, DC, 166 p.  
[https://www.ars.usda.gov/ARSUserFiles/20360500/hb60\\_pdf/hb60complete.pdf](https://www.ars.usda.gov/ARSUserFiles/20360500/hb60_pdf/hb60complete.pdf)
- USDA-NCSS 2021. *National Cooperative Soil Survey (NCSS) Soil Characterization Database*, United States Department of Agriculture, Natural Resources Conservation Service, Lincoln.  
[https://ncsslabsdatamart.sc.egov.usda.gov/database\\_download.aspx](https://ncsslabsdatamart.sc.egov.usda.gov/database_download.aspx)

- van Alphen BJ, Bootink HWG and Bouma J 2001. Combining pedotransfer functions with physical measurements to improve the estimation of soil hydraulic properties. *Geoderma* 103, 133-147. <http://www.sciencedirect.com/science/article/pii/S0016706101000738>
- van Bemmelen DJM 1890. Über die Bestimmung des Wassers, des Humus, des Schwefels, der in den colloidalen Silikaten gebundenen Kieselsäure, des Mangans u. s. w. im Ackerboden. *Die Landwirthschaftlichen Versuchs-Stationen*, 37, 279-290. <http://edepot.wur.nl/211282>
- van Genuchten MT 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* 44, 892-898.
- van Genuchten P 2022. Overview code lists. <https://eipsoil.github.io/soildata-assimilation-guidance/codelists.html>
- van Leeuwen CCE 2024. Statistical modelling of analytical and spectral soil measurement errors, Wageningen University, Wageningen <https://research.wur.nl/en/publications/statistical-modelling-of-analytical-and-spectral-soil-measurement>
- van Leeuwen CCE, Mulder VL, Batjes NH and Heuvelink GBM 2024. Effect of measurement error in wet chemistry soil data on the calibration and model performance of pedotransfer functions. *Geoderma* 442, 116762. <https://www.sciencedirect.com/science/article/pii/S0016706123004391>
- van Reeuwijk LP 2002. *Procedures for soil analysis (6th ed.)*. Technical Paper 9, ISRIC, Wageningen, 81 p. [https://www.isric.org/sites/default/files/ISRIC\\_TechPap09.pdf](https://www.isric.org/sites/default/files/ISRIC_TechPap09.pdf)
- van Reeuwijk LP and Houba VJG 1998. External quality control of data. In: Van Reeuwijk LP (editor), *Guidelines for quality management in soil and plant laboratories*. ISRIC and FAO, Rome, pp 121-127. <http://www.fao.org/docrep/W7295E/W7295E00.htm>
- Vereecken H, Diels J, Van Oorshoven J, Feyen J and Bouma J 1992. Functional evaluation of pedotransfer functions for the estimation of soil hydraulic properties. *Soil Science Society of America Journal* 56, 1371-1379. <https://doi.org/10.2136/sssaj1992.03615995005600050007x>
- Viscarra Rossel RA, Shen Z, Ramirez Lopez L, Behrens T, Shi Z, Wetterlind J, Sudduth KA, Stenberg B, Guerrero C, Gholizadeh A, Ben-Dor E, St Luce M and Orellano C 2024. An imperative for soil spectroscopic modelling is to think global but fit local with transfer learning. *Earth-Science Reviews* 254, 104797. <https://www.sciencedirect.com/science/article/pii/S0012825224001247>
- Viscarra Rossel RA, Behrens T, Ben-Dor E, Brown DJ, Demattê JAM, Shepherd KD, Shi Z, Stenberg B, Stevens A, Adamchuk V, Aichi H, Barthès BG, Bartholomeus HM, Bayer AD, Bernoux M, Böttcher K, Brodský L, Du CW, Chappell A, Fouad Y, Genot V, Gomez C, Grunwald S, Gubler A, Guerrero C, Hedley CB, Knadel M, Morrás HJM, Nocita M, Ramirez-Lopez L, Roudier P, Campos EMR, Sanborn P, Sellitto VM, Sudduth KA, Rawlins BG, Walter C, Winowiecki LA, Hong SY and Ji W 2016. A global spectral library to characterize the world's soil. *Earth-Science Reviews* 155, 198-230. <http://dx.doi.org/10.1016/j.earscirev.2016.01.012>
- Wadoux AMJ-C and Heuvelink GBM 2023. Uncertainty of spatial averages and totals of natural resource maps. *Methods in Ecology and Evolution* 14, 1320-1332. <https://besjournals.onlinelibrary.wiley.com/doi/abs/10.1111/2041-210X.14106>
- Walkley A and Black IA 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science* 37, 29-38. [https://journals.lww.com/soilsci/Fulltext/1934/01000/AN\\_EXAMINATION\\_OF\\_THE\\_DEGTJAREFF\\_METHOD\\_FOR.3.aspx](https://journals.lww.com/soilsci/Fulltext/1934/01000/AN_EXAMINATION_OF_THE_DEGTJAREFF_METHOD_FOR.3.aspx)
- WEPAL 2022. WEPAL. Wageningen Evaluating Programmes for Analytical Laboratories. <https://www.wepal.nl/en/wepal.htm>
- WHO 2011. *Laboratory quality management system: handbook*. World Health Organization Lyon (FR), 247 p. [http://whqlibdoc.who.int/publications/2011/9789241548274\\_eng.pdf?ua=1](http://whqlibdoc.who.int/publications/2011/9789241548274_eng.pdf?ua=1)
- Wösten JHM, Finke PA and Jansen MJW 1995. Comparison of class and continuous pedotransfer functions to generate soil hydraulic characteristics. *Geoderma* 66, 227-237. [https://doi.org/10.1016/0016-7061\(94\)00079-P](https://doi.org/10.1016/0016-7061(94)00079-P)
- Wösten JHM, Lilly A, Nemes A and Le Bas C 1999. Development and use of a database of hydraulic properties of European soils. *Geoderma* 90, 169-185. <https://www.sciencedirect.com/science/article/pii/S0016706198001323>
- Wuana RA and Okieimen FE 2011. Heavy Metals in Contaminated Soils: A Review of Sources, Chemistry, Risks and Best Available Strategies for Remediation. *International Scholarly Research Notices* 2011, 402647. <https://onlinelibrary.wiley.com/doi/abs/10.5402/2011/402647>
- Yaghmaeian Mahabadi N and Givi J 2008. Comparison of Different Methods of Gypsum Determination in Selected Soils from Isfahan. *Journal of Water and Soil Science* 11, 565-576. <http://jstnar.iut.ac.ir/article-1-810-en.html>





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