



DATA PAPER

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Aggregated database of forest soil chemical properties in the Czech Republic based on surveys from 2000 to 2020

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Abstract

Key message The dataset includes data from forest soil surveys conducted in the period 2000–2020. It provides soil and site variables from 8269 locations. Data are aggregated in three basic soil layers: upper organic soil horizon (FH, 6875 locations), upper mineral layer 0–30 cm (M03, 8051 locations) and deeper mineral soil layer 30–80 cm (M38, 2260 locations).

The dataset is available at <https://doi.org/10.5281/zenodo.10608814>, and access to the metadata is at <https://metadata.afs.nancy.inra.fr/geonetwork/srv/fre/catalog.search#/metadata/38f24573-3c0d-469a-a66a-7060ce082155>.

Keywords Soil database, Forest soil, Soil chemistry, Forest stand parameters, Quality control, Spatial modelling

1 Background

The quality of forest soils, an important factor affecting the productivity and stability of forest ecosystems, may be a limiting factor for the long-term sustainability of forest management (Jonard et al. 2015; Garrett et al. 2021). Forest soil condition is also one of the fundamental properties influencing an ecosystem's potential adaptation to climate change (Babst et al. 2013; Charru et al. 2014).

Current data show serious nutrient deficiencies in a large part of the Czech Republic (Novotný et al. 2018; Borůvka et al. 2020b; Pecháček et al. 2023) and a discrepancy between measured and expected soil properties according to the national forest typological system (Viewegh et al. 2003; Šrámek et al. 2013). Several soil surveys with slightly different sampling and analytical methods were organized in the last 20 years (e.g., within the

ICP-Forest Programme, National Forest Inventory, and soil monitoring in polluted areas) in the country, which made the overall evaluation complicated. For this reason, data from different soil surveys were validated (Šrámek et al. 2020) harmonized and aggregated to create a single comprehensive database. Subsequently, environmental and geographic parameters were added for the sampling sites. The dataset is a collection of information about fundamental soil properties relevant to forest nutrition.

2 Methods

2.1 Soil data origin

Data entered into the database were provided by three institutions and consisted of four sub-databases with varying degrees of homogeneity related to individual soil surveys (Table 1). (1) The Central Institute for Supervising and Testing in Agriculture database (CISTA db) contains soil sampling data focused on forest nutrition surveys in formerly air-polluted areas and genetically valuable forest stands (genetic conservation units) (Fiala et al. 2013; Reininger et al. 2011). During the survey, three soil layers were sampled: the upper organic layer (OFH), organo-mineral soil horizon (A),

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Table 1 The original database's main information

Database	FMI_typological db	FMI_NIL2 db	FGMRI db	CISTA db
Data provider				
Sampling period	2000–2019	2011–2015	2000–2020	2001–2017
Number of samples	FH 900	729	756	4491
	M03 1295	1509	757	4490
	M38 695	1187	344	34
	Total 2890	3425	1857	9015
Sampling layers	Genetic horizons	Genetic horizons	Upper organic layer (OFH) Mineral soil 0–10 cm Mineral soil 10–20 cm Mineral soil 20–40 cm Mineral soil 40–80 cm	Upper organic layer (OFH) Organo-mineral soil horizon (A) 1–5 cm Mineral soil 5–30 cm Mineral soil >30 cm
Analytical methods used	See Table 5 in Appendix			

usually 1–5 cm thick, and the deeper mineral soil down to the depth of ca. 30 cm. Samples were analyzed in the CISTA laboratory, which was accredited according to the EN ISO/IEC 17043:2010 standard.

(2) The National Forest Inventory database (FMI_NIL 2 db) was administrated by the Forest Management Institute (FMI) (Kučera and Adolt 2019). The sampling was carried out according to a standardized methodology by genetic horizons (not fixed depths) and by multiple sampling teams. A constant spectrum of chemical parameters was analyzed in the samples, and analyses were carried out in the FMI laboratories, in some cases with lower accuracy of determination (total element contents with an accuracy of 100 mg kg⁻¹).

(3) The FMI typological database (FMI_typological db) has been sampled over the years by many teams according to a standardized methodology by genetic horizons and analyzed by different methods. It contains a variable number of parameters determined in individual samples.

(4) The database of the Forestry and Game Management Research Institute (FGMRI db), contains a very homogeneous spectrum of sampling carried out within the ICP Forests programme and BioSoil project (de Vos and Cools 2011, Lorenz and Becher 2012; Šrámek et al. 2013), as well as systematic sampling for the preparation and control of liming and fertilization projects in forest stands and other types of soil surveys carried out within research projects. The sampling was carried out by a very close research team, typically for fixed depths, following the methodology of the ICP Forests programme (Cools and De Vos 2016). The full range of soil chemistry parameters was analyzed by the FGMRI testing laboratory, which has developed a high standard of quality assurance and quality control, including regular participation in national and international ring tests.

2.2 Data proceeding

The collected data were verified in the first step by numerical and graphical analyses. In all the surveys, the upper organic layer (humus layer OFH) was sampled separately; the depth of sampled mineral soil, however, differs. Thus, the verified data had been converted to three harmonized layers using a weighted average: (i) upper organic layer (FH), (ii) upper mineral soil in depth from 0 to 30 cm (M30), and (iii) deeper mineral layer in depths from 30 to 80 cm (M38).

2.3 Comparison of analytical methods

Combining the results of different surveys was complicated because different methods of chemical analysis (leachate) were used. To make the database more homogeneous the original data were recalculated in cases where the sound correlation between the two used methods was disposable (e.g. Záhornadská 2002, Čechmánková et al. 2021). For exchangeable elements, the leachate in BaCl₂, for extractable elements Aqua regia leachate is used as a standard in the database. Used transfer functions with corresponding coefficient of determination are introduced in Table 2. Nevertheless, the original analytical method is stated in the database to make users able to re-convert data to their original values, if needed. For elements where no suitable transfer function was known to authors, the data were not recalculated and were presented according to the individual analytic method. Such a layout is not the ideal one but it allows the users to work with recalculated data, and original data—e.g., only with a part with identical analytical methods—or use their own procedure for data homogenization.

Table 2 Conversion of elemental concentrations in forest soils

Methods	Element	Recalculation	Comment
BaCl ₂ : NH ₄ Cl		Data not recalculated	
BaCl ₂ (y): Mehlich III (x)	Calcium	$y = 0.944x + 45.6$; ($r^2 = 0.943$)	Čechmánková et al. 2021
	Magnesium	$y = 1.2712x - 20.9$; ($r^2 = 0.990$)	Čechmánková et al. 2021
	Potassium	$y = 1.1310x - 16$; ($r^2 = 0.966$)	Čechmánková et al. 2021
HCl + H ₂ SO ₄ (y): Mehlich III (x)	Phosphorus	$y = 1.3504 + 14.56$; ($r^2 = 0.837$)	Záhornadská 2002
Aqua regia(y): HNO ₃ (x) (mineral soil)	Calcium	$y = 0.9249x + 158.3$; ($r^2 = 0.992$)	Čechmánková et al. 2021
	Magnesium	$y = 4.7461x + 54.2$; ($r^2 = 0.512$)	Šrámek et al. (not published)
	Potassium	$y = 11.962x + 19.06$; ($r^2 = 0.593$)	Šrámek et al. (not published)
	Phosphorus	Data not recalculated	
Aqua regia(y): HNO ₃ (x) (organic soil)	Calcium	$y = 0.9874x$; ($r^2 = 0.976$)	Záhornadská 2002
	Magnesium	$y = 0.9026x - 245.09$; ($r^2 = 0.920$)	Záhornadská 2002
	Potassium	$y = 1.1658x - 119.6$; ($r^2 = 0.661$)	Záhornadská 2002
	Phosphorus	Data not recalculated	
Aqua regia: HCl		Data not recalculated	

2.4 Environmental and geographical parameters

Environmental and geographical data were obtained from different digital maps and databases which are described in the metadata paragraph below (Borůvka et al. 2022).

3 Access to the data and metadata description

The dataset is available at <https://doi.org/10.5281/zenodo.10608814>. The associated metadata is available at <https://metadata-afs.nancy.inra.fr/geonetwork/srv/fr/catalog/search#/metadata/38f24573-3c0d-469a-a66a-7060ce082155>.

The data are contained in the *Agregated_Soil_Data-base.xlsx* file (Neudertová Hellebrandová et al. 2023). The first column (*Sampling_Site_ID*) contains the sampling site identifier, obtained from the source databases, the second column (*Data_Source*) informs about the original data provider (FGMRI db: data from the Forestry and Game Management Research Institute database; CISTA db: data from the Central Institute for Supervising and Testing in Agriculture database; FMI_typological db: data from the Forest Management Institute typological database; FMI_NIL 2 db: data from the Forest Management Institute National Forest Inventory database) and the third column (*Layer*) identifies the soil layer (FH: upper organic soil horizon; M03: upper mineral soil layer 0–30 cm; M38: deeper mineral soil layer 30–80 cm). Columns *Date* and *Year* contain information about the sampling date (if it is available) and year.

Sampling site characteristics include information about terrain, climate, forest site and soil class.

Geographical coordinates (Lat, Long) were measured during sampling. The altitude (Altitude) was extracted from the raster DTM 4G (Digital Terrain Model of the Czech Republic 4th Generation) with a resolution of 5 m (Brázdil 2010) and the steepness (Slope) and the orientation to cardinal directions (Aspect) were calculated using Surface Toolbox in ArcMap 10.5.

Climate data (Aver_Temp: mean annual temperature and Annual_Prec: average annual precipitation for 2000–2020) were obtained from the database WorldClim.org at a resolution of 1 km (Fick & Hijmans 2017).

The forest sites were characterized by land cover categories (Deciduous, Mixed and Coniferous forest) obtained from the database CORINE Land Cover 2018 (EEA 2018) at a resolution of 100 m.

Other forest site characteristics (FVZ: forest vegetation zone; ES: ecological series; EC: edaphic category) were obtained from the map of forest typology at a scale of 1:10,000 (ÚHÚL 2020a, b a). This map is derived from the “Typological System of Forest Management Institute”, based on ecological environmental factors (Viewegh et al. 2003).

Structured stand type (SST), which provides information about groups of tree species and the characteristics of their mixing in the stand, was obtained from the map of structured stand types at a scale of 1:10,000 (ÚHÚL 2020a, b b). For example, the code D1P3P7 provides information that the stand consists of Norway spruce (*Picea abies*) (Group 1), Scots pine (*Pinus silvestris*) (Group 3) and European ash (*Fraxinus excelsior*) and/or Narrow-leaved ash (*Fraxinus angustifolia*) (Group 7).

Norway spruce has a 70–89.9% representation (D), Scots pine and ash have a 10–29.9% representation (P). The creation of codes for SST is described in Tables 3 and 4.

The last forest site characteristic is grouped soil class (GSC), extracted from the Czech soil information system PUGIS at the scale 1:250,000 (Kozák et al. 1996).

The results of the chemical analyses were recorded using the following variables: the pH (pH_{H₂O}, pH_{exch}), exchangeable calcium (Ca_{exch}), magnesium (Mg_{exch}) and potassium (K_{exch}), the available phosphorus (P_{pa}), total calcium (Ca_{tot}), magnesium (Mg_{tot}), potassium (K_{tot}) and phosphorus (P_{tot}), the total content of carbon (C_{tot}) and nitrogen (N_{tot}), the cation exchange capacity (CEC) and the base saturation (BS). Each of these variables also has an associated variable "method" (_met) that provides information about the method of determination. The list of methods

used in different source databases is mentioned See Table 5 in [Appendix](#).

4 Technical validation

Basic data analysis identified the following sources of error:

- 1) Errors in the sampling:

Incorrect determination of the boundary between the overlying organic horizon and the organomineral/mineral soil layer.

Missing or overlapping of some sampling depths in the case of sampling by genetic horizons.

Confusion of samples during collection or transport.

Table 3 Structured stand type (SST)—tree groups

Code	Species
1	<i>Picea abies</i>
1e	other spruces
2	<i>Abies alba</i>
2e	other firs
3	<i>Pinus sylvestris</i>
3e	other pines
4	larches
4 k	<i>Pinus mugo</i>
4x	other conifers
5	<i>Quercus robur</i> , <i>Quercus petraea</i> , <i>Quercus pubescens</i> , <i>Quercus palustris</i> , <i>Quercus cerris</i> , <i>Ulmus minor</i> , <i>Ulmus glabra</i> , <i>Ulmus laevis</i> , <i>Tilia cordata</i> , <i>Tilia platyphyllos</i> , <i>Tilia tomentosa</i>
5e	other oaks, <i>Juglans regia</i> , <i>Juglans nigra</i>
6	<i>Fagus sylvatica</i> , <i>Acer platanooides</i> , <i>Acer pseudoplatanus</i> , <i>Prunus avium</i>
7	<i>Fraxinus excelsior</i> , <i>Fraxinus angustifolia</i>
7e	<i>Robinia pseudoacacia</i>
8	<i>Alnus glutinosa</i> , <i>Alnus incana</i> , <i>Alnus alnobetula</i>
9	willows, poplars
9x	<i>Castanea sativa</i> , <i>Aesculus hippocastanum</i> , <i>Platanus acerifolia</i> , other maples, <i>Fraxinus americana</i> , <i>Ailanthus altissima</i>
9e	other broadleaves, bushes

(ÚHÚL 2020a, b)

Table 4 Structured stand type (SST)—nature of mixing

Nature of mixing	Description
Homogenous (C)	One tree species with 90–100% representation
Mixed (S)	Dominant (D)—one tree species with 70–89.9% representation Majority (M)—one tree species with 50–69.9% representation
Incoherent (N)	Basic (Z) —one tree species with 30–49.9% representation Intermixed (P) —one tree species with 10–29.9% representation
Embedded (V)	Groups of trees up to 10% are generally not considered

(ÚHÚL 2020a, b)

2) Errors in laboratory processing:

Insufficient homogenization of the sample before analysis.

Errors in the compilation of data into output reports (e.g., confusion of columns).

Errors in the manual transcription of measurement results for older samples.

3) Errors in the compilation of databases:

Various combinations of formal errors, in particular, copying data into the wrong fields, incorrectly entered units in the case of databases containing different data sources, etc.

To verify the accuracy of the data, minimum and maximum thresholds for individual parameters, as well as limits based on the relationships between selected parameters, were tested, e.g. $\text{pH}(\text{KCl}):\text{pH}(\text{H}_2\text{O})$ (Fig. 1), $\text{C}_{\text{tot}}:\text{N}_{\text{tot}}$, $\text{pH}(\text{H}_2\text{O}):\text{Ca}_{\text{exch}}$; $\text{Ca}_{\text{exch}}:\text{Ca}_{\text{tot}}$, $\text{P}_{\text{pa}}:\text{pH}(\text{H}_2\text{O})$ (Fig. 2) etc. (Šrámek et al. 2020). As a base for such a relationship, the results of the BioSoil project were used, as particular attention was paid to quality assurance and quality control of sampling and analysis within this project.

Most of the limit values were set at two levels. The first was a 'warning' (suspicious values which the provider of data was prompted to check). Depending on the result of the check, the value was left in the database, corrected or removed. The second value was 'error' (strongly

suspicious values). Such values were removed from the database unless the provider of data did correct them.

The limit (control) values for the upper organic soil horizon (FH), the upper mineral soil layer (M03) and the deeper mineral soil layer (M38) are given See Tables 6, 7 and 8 in [Appendix](#).

5 Reuse potential and limits

This is a unique dataset providing valuable information on the state of forest soils in the Czech Republic.

The data have already been successfully used in previous studies focused on the assessment of forest soil quality in terms of nutrition and adaptation of forest stands (Vašát et al. 2021a, b, Komprdová et al. 2021, Borůvka et al. 2020a, Borůvka et al. 2020b, Novotný et al. 2020). Recently data were used by different partners in four scientific projects focusing on soil carbon sequestration, quality of NATURA 2000 sites, landscape quality and biodiversity. There is also a vision to use this dataset as a base for the next forest soil survey in the Czech Republic, especially as a tool for evaluating change and trends in soil chemistry. Releasing the data in open source publication will increase the potential to use them also in broader international studies.

The limits of the database are clearly associated with a limited number of parameters which are restricted to basic chemical properties only. The next challenge for authors will be to complete the dataset with reliable data for risk elements (e.g. cadmium, lead) and physical soil properties if they will be available in sufficient quality.

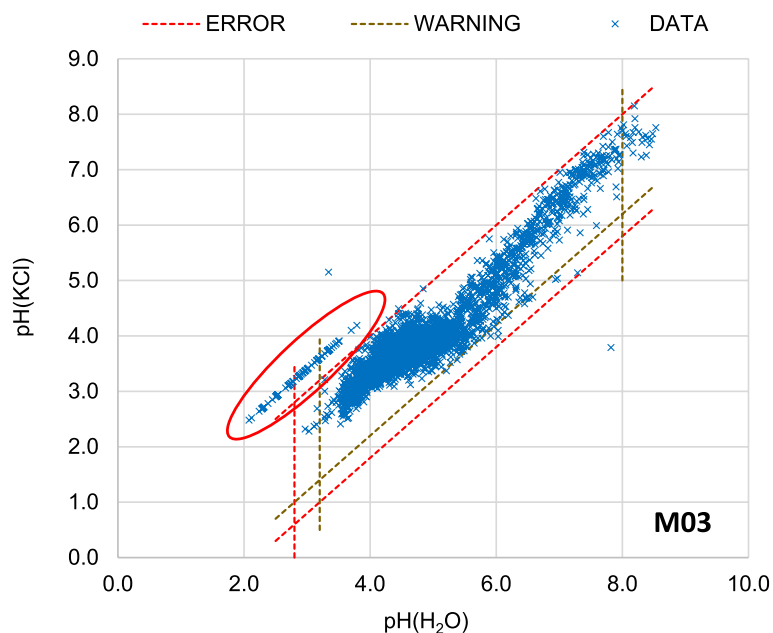


Fig. 1 Check of data quality: relation of active $\text{pH}(\text{H}_2\text{O})$ and exchangeable $\text{pH}(\text{KCl})$ soil reaction in the upper mineral soil 0–30 cm. Wrong values (errors) originating most probably from incorrect pH calculation ($\text{pH}(\text{H}_2\text{O}) \neq \text{pH}(\text{KCl}) + 0.5$) are marked by a red ellipse (Šrámek et al. 2020)

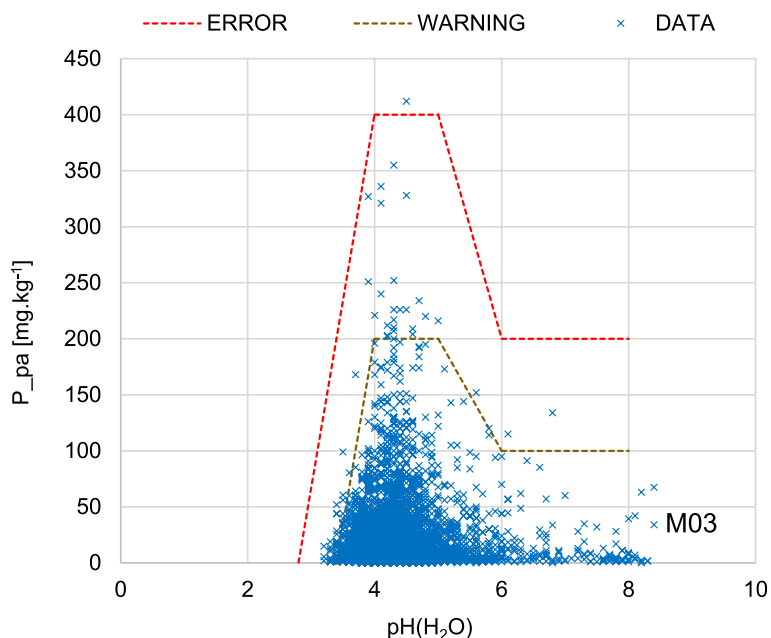


Fig. 2 Check of data quality: Relation between pH(H₂O) and available phosphorus in the upper mineral soil layer 0–30 cm. (Šrámek et al. 2020)

Appendix

Table 5 List of analytical methods used

Variable	Method	Use of the method in source database				Units	Comments
		FMI_typological db	FMI_NIL2 db	FGMRI db	CISTA db		
pH _{H₂O}	Soil reaction in water suspension	x	x	x	x	-log(cH ⁺)	determined potentiometrically using a glass electrode
pH _{exch}	Soil reaction in KCl suspension	x	x	x		-log(cH ⁺)	determined potentiometrically using a glass electrode
pH _{exch}	Soil reaction in CaCl ₂ suspension			x	x	-log(cH ⁺)	determined potentiometrically using a glass electrode
Ca _{exch} ^a	0.1M BaCl ₂ extract	x	x		x	mg.kg ⁻¹	determination by the AAS method (atomic absorption spectrometry)
Ca _{exch}	Mehlich III extract				x	mg.kg ⁻¹	determination by the AAS method (atomic absorption spectrometry)
Ca _{exch}	1M NH ₄ Cl extract			x		mg.kg ⁻¹	determination by the AAS method (atomic absorption spectrometry)
Mg _{exch}	0.1M BaCl ₂ extract	x	x		x	mg.kg ⁻¹	determination by the AAS method (atomic absorption spectrometry)
Mg _{exch}	1M NH ₄ Cl extract			x		mg.kg ⁻¹	determination by the AAS method (atomic absorption spectrometry)

Variable	Method	Use of the method in source database				Units	Comments
		FMI_typological db	FMI_NIL2 db	FGMRI db	CISTA db		
Mg_exch	Mehlich III extract				x	mg.kg ⁻¹	determination by the AAS method (atomic absorption spectrometry)
K_exch	0.1M BaCl ₂ extract	x	x		x	mg.kg ⁻¹	determination by the AAS method (atomic absorption spectrometry)
K_exch	1M NH ₄ Cl extract			x		mg.kg ⁻¹	determination by the AAS method (atomic absorption spectrometry)
K_exch	Mehlich III extract				x	mg.kg ⁻¹	determination by the AAS method (atomic absorption spectrometry)
P_pa ^b	HCl+H ₂ SO ₄ extract			x		mg.kg ⁻¹	determination using automatised spectrometry
P_pa	P_aa recalculation	x	x			mg.kg ⁻¹	correction calculated according to available content in the Mehlich III extract
P_pa	Mehlich III extract				x	mg.kg ⁻¹	determination by the AAS method (atomic absorption spectrometry)
Ca_tot ^c	2M HNO ₃ extract				x	mg.kg ⁻¹	determination by ICP-OES (optical emission spectrometry with inductively coupled plasma)
Ca_tot	Aqua regia extract			x	x	mg.kg ⁻¹	determination by the AAS method (atomic absorption spectrometry)
Ca_tot	20% HCl extract	x	x			mg.kg ⁻¹	determination by the AAS method (atomic absorption spectrometry)
Mg_tot	2M HNO ₃ extract				x	mg.kg ⁻¹	determination by ICP-OES (optical emission spectrometry with inductively coupled plasma)
Mg_tot	Aqua regia extract			x	x	mg.kg ⁻¹	determination by the AAS method (atomic absorption spectrometry)
Mg_tot	20% HCl extract	x	x			mg.kg ⁻¹	determination by the AAS method (atomic absorption spectrometry)
K_tot	2M HNO ₃ extract				x	mg.kg ⁻¹	determination by ICP-OES (optical emission spectrometry with inductively coupled plasma)
K_tot	Aqua regia extract			x	x	mg.kg ⁻¹	determination by the AAS method (atomic absorption spectrometry)
K_tot	20% HCl extract	x	x			mg.kg ⁻¹	determination by the AAS method (atomic absorption spectrometry)
P_tot	2M HNO ₃ extract				x	mg.kg ⁻¹	determination by ICP-OES (optical emission spectrometry with inductively coupled plasma)
P_tot	Aqua regia extract			x	x	mg.kg ⁻¹	determination by the AAS method (atomic absorption spectrometry)
P_tot	20% HCl extract	x	x			mg.kg ⁻¹	determination by the AAS method (atomic absorption spectrometry)
C_tot	Elemental analysis (CNS analyser)			x		%	
C_tot	Combustion method	x	x			%	
C_tot	NIRS (near infra-red spectroscopy)				x	%	
N_tot	Elemental analysis (CNS analyser)			x		%	
N_tot	Combustion method	x	x			%	

Variable	Method	Use of the method in source database				Units	Comments
		FMI_typological db	FMI_NIL2 db	FGMRI db	CISTA db		
N _{tot}	NIRS (near infra-red spectroscopy)				x	%	
N _{tot}	Kjeldahl method (mineralisation)			x	x	%	determination by automatised spectrophotometry
CEC	Calculation	x	x			cmol ⁺ /kg	calculated as the sum of exchangeable elements (H ⁺ , Al, Ca, Fe, K, Mg, Mn and Na)
CEC	0.1M BaCl ₂ extract				x	mmol/kg	
BS	Calculation	x	x	x	x	%	calculated as the ratio of base elements content and CEC

^a *exch* exchangeable content

^b *pa* plant-available phosphorus

^c *tot* total content

Table 6 Summary of limits for the overlying organic horizon (FH)

Parameter	Condition (range)	Lower limit		Upper limit	
		Error	Warning	Warning	Error
pH (H ₂ O)		≤ 2.5	≤ 3.0	≥ 7.5	≥ 8.5
pH (<i>exch</i> ^a)		≤ (pH (H ₂ O) – 2.2)	≤ (pH (H ₂ O) – 1.8)	–	> pH (H ₂ O)
C (C _{tot} ^b and C _{org} ^c)		≤ 5%	≤ 15%	≥ 50%	≥ 55%
N (N _{tot} and N _{kjehl} ^d)		≤ 0.25%	< 0.025 × C _{tot} – 0.16	> 0.082 × C _{tot} + 0.32	≥ 3%
C/N			≤ 10	≥ 40	
Ca _{exch}	Except for freshly limed areas		≤ 1000 × pH (H ₂ O) – 6000	≥ 3750 × pH (H ₂ O) – 11,250	≥ 6700 × pH (H ₂ O) – 16,740
Ca _{exch}		< 0.14 × Ca _{tot} – 700		> Ca _{tot}	> 1.15 × Ca _{tot}
Ca _{tot}				> 10,000 mg.kg ⁻¹	> 31,000 mg.kg ⁻¹
K _{exch}				≥ 445 × pH (H ₂ O) – 1111	≥ 445 × pH (H ₂ O) – 611
K _{exch}				> K _{tot}	> 1.15 × K _{tot}
K _{tot}				> 15,000 mg.kg ⁻¹	> 25,000 mg.kg ⁻¹
Mg _{exch}				> 3000 mg.kg ⁻¹	≥ 1667 × pH (H ₂ O) – 4160
Mg _{exch}					> 4500 mg.kg ⁻¹
Mg _{exch}				> Mg _{tot}	> 1.15 × Mg _{tot}
Mg _{tot}				> 15,000 mg.kg ⁻¹	> 30,000 mg.kg ⁻¹
P _{pa} ^e				> 250 mg.kg ⁻¹	> 500 mg.kg ⁻¹
P _{pa}				> 0.3 × P _{tot}	> P _{tot}
P _{tot}				> 2000 mg.kg ⁻¹	> 4000 mg.kg ⁻¹

^a *exch* exchangeable content

^b *tot* total content

^c *org* organic

^d *kjehl* nitrogen determined by the Kjeldahl method

^e *pa* plant-available phosphorus

(Šrámek et al. 2020)

Table 7 Summary of limits for the upper mineral horizon (M03)

Parameter	Condition (range)	Error	Warning	Warning	Error
pH (H ₂ O)		≤ 2.8	≤ 3.2	≥ 8.0	≥ 8.5
pH (exch ^a)		≤ (pH (H ₂ O) – 2.2)	≤ (pH (H ₂ O)–1.8)		> pH (H ₂ O)
C (C _{tot} ^b and C _{org} ^c)	Except for organosols; surface horizons A, possibly to a depth of 10 cm (0–5 cm, 0–10 cm)			> 20%	> 40%
C (C _{tot} and C _{org})	Except for organosols; surface horizons comprising mineral layers below 10 cm, e.g. 0–20 cm, 20–30 cm, 10–30 cm, etc			> 20%	> 25%
N (N _{tot} and N _{kjehl})	Except for organosols; surface horizons A, possibly to a depth of 10 cm (0–5 cm, 0–10 cm)		< 0.05 × C _{tot} – 0.44	> 0.063 × C _{tot} + 0.3	≥ 2.5
N (N _{tot} and N _{kjehl} ^d)	Except for organosols; surface horizons comprising mineral layers below 10 cm, e.g. 0–20 cm, 20–30 cm, 10–30 cm, etc		< 0.05 × C _{tot} – 0.44	> 0.063 × C _{tot} + 0.3	≥ 1.5
Ca _{exch}	Except for freshly limed areas	≤ 1000*pH (H ₂ O) – 6000		≥ 1925 × pH (H ₂ O) – 5380	≥ 2885 × pH (H ₂ O) – 8070
Ca _{exch}			< 0.13 × Ca _{tot} – 333	> Ca _{tot}	> 1.15 × Ca _{tot}
Ca _{tot}				> 10,000 mg.kg ⁻¹	> 31,000 mg.kg ⁻¹
K _{exch}				> 350 mg.kg ⁻¹	≥ 280 × pH (H ₂ O) – 700
K _{exch}					> 500 mg.kg ⁻¹
K _{exch}				> K _{tot}	> 1.15 × K _{tot}
K _{tot}				> 15,000 mg.kg ⁻¹	> 25,000 mg.kg ⁻¹
Mg _{exch}	Except for freshly limed areas			> 1500 mg.kg ⁻¹	> 2000 mg.kg ⁻¹
Mg _{exch}	Except for freshly limed areas			> 1500 mg.kg ⁻¹	≥ 570 × pH (H ₂ O) – 1425
Mg _{exch}				> Mg _{tot}	> 1.15 × Mg _{tot}
Mg _{tot}				> 15,000 mg.kg ⁻¹	> 40,000 mg.kg ⁻¹
BS	pH (H ₂ O) < 3.5			≥ 10%	≥ 30%
BS	pH (H ₂ O) in 5–6 range		≤ 72 × pH (H ₂ O) – 350		
BS	pH (H ₂ O) > 6	≤ 70%	≤ 90%		
P _{pa} ^e	pH (H ₂ O) < 4			≥ 334 × pH (H ₂ O) – 1135	≥ 334 × pH (H ₂ O) – 935
P _{pa}	pH (H ₂ O) in 4–5 range			> 200 mg.kg ⁻¹	> 400 mg.kg ⁻¹
P _{pa}	pH (H ₂ O) in 5–6 range			≥ – 100 × pH (H ₂ O) + 700	≥ – 200 × pH (H ₂ O) + 1400
P _{pa}	pH (H ₂ O) > 6			> 100 mg.kg ⁻¹	> 200 mg.kg ⁻¹
P _{pa}				> 0.75 × P _{tot}	> P _{tot}
P _{tot}				> 2000 mg.kg ⁻¹	> 6500 mg.kg ⁻¹

^a *exch* exchangeable content^b *tot* total content^c *org* organic^d *kjehl* nitrogen determined by the Kjeldahl method^e *pa* Plant-available phosphorus

(Šrámek et al. 2020)

Table 8 Summary of limits for the deeper mineral horizon (M38)

Parameter	Condition (range)	Lower limit		Upper limit	
		Error	Warning	Warning	Error
pH (H ₂ O)		≤ 3.0	≤ 3.5	≥ 8.0	≥ 9.0
pH (exch ^a)		≤ (pH (H ₂ O) – 2.2)	≤ (pH (H ₂ O) – 1.8)		> pH (H ₂ O)
C (C _{tot} ^b and C _{org} ^c)	Except for organosols			> 6%	> 20%
N (N _{tot} and N _{kjehl} ^d)	Except for organosols		< 0.043 × C _{tot} – 0.15	> 0.065 × C _{tot} + 0.2	≥ 0.8%
Ca _{exch}	Except for freshly limed areas	≤ 1000 × pH (H ₂ O) – 6000		≥ 1555 × pH (H ₂ O) – 5444	≥ 3000 × pH (H ₂ O) – 9000
Ca _{exch}			< 0.13 × Ca _{tot} – 333	> Ca _{tot}	> 1.15 × Ca _{tot}
Ca _{tot}	pH (H ₂ O) ≤ 6.5			> 10,000 mg.kg ⁻¹	> 31,000 mg.kg ⁻¹
Ca _{tot}	pH (H ₂ O) > 6.5			> 31,000 mg.kg ⁻¹	> 200,000 mg.kg ⁻¹
K _{exch}				> 250 mg.kg ⁻¹	≥ 280 × pH (H ₂ O) – 840
K _{exch}					> 300 mg.kg ⁻¹
K _{exch}				> K _{tot}	> 1.15 × K _{tot}
K _{tot}				> 15,000 mg.kg ⁻¹	> 25,000 mg.kg ⁻¹
Mg _{exch}	Except for freshly limed areas			> 1500 mg.kg ⁻¹	> 2000 mg.kg ⁻¹
Mg _{exch}	Except for freshly limed areas				≥ 666 × pH (H ₂ O) – 1990
Mg _{exch}				> Mg _{tot}	> 1.15 × Mg _{tot}
Mg _{tot}				> 25,000 mg.kg ⁻¹	> 40,000 mg.kg ⁻¹
BS	pH (H ₂ O) < 4			≥ 10%	≥ 30%
BS	pH (H ₂ O) in 4–5 range			≥ 83 × pH (H ₂ O) – 320	
BS	pH (H ₂ O) in 5–6 range		≤ 83 × pH (H ₂ O) – 410		
BS	pH (H ₂ O) > 6	≤ 70%	≤ 90%		
P _{pa} ^e	pH (H ₂ O) < 4			≥ 533 × pH (H ₂ O) – 1532	≥ 533 × pH (H ₂ O) – 1332
P _{pa}	pH (H ₂ O) in 4–6 range			> 600 mg.kg ⁻¹	> 800 mg.kg ⁻¹
P _{pa}	pH (H ₂ O) in 6–7 range			≥ –500 × pH (H ₂ O) + 3600	≥ –500 × pH (H ₂ O) + 3800
P _{pa}	pH (H ₂ O) > 6			> 100 mg.kg ⁻¹	> 300 mg.kg ⁻¹
P _{pa}				> 0.75 × P _{tot}	> P _{tot}
P _{tot}				> 2000 mg.kg ⁻¹	> 6500 mg.kg ⁻¹

^a *exch* exchangeable content^b *tot* total content^c *org* organic^d *kjehl* nitrogen determined by the Kjeldahl method^e *pa* plant-available phosphorus

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Authors' contributions

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Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

All authors gave their informed consent to this publication and its content.

Competing interests

The authors declare that they have no conflict of interest.

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