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Rapid Soil Tests for Assessing Soil Health

Jan Adriaan Reijneveld [1,*] and Oene Oenema [2]

[1] Eurofins International, Competence Center, Binnenhaven 5, 6709 PD Wageningen, The Netherlands
[2] Wageningen Environmental Research, Wageningen University & Research, P.O. Box 47, 6700 AA Wageningen, The Netherlands; oene.oenema@wur.nl
* Correspondence: arjan.reijneveld@ftbnl.eurofins.com; Tel.: +31-(0)652002111

Abstract

Soil testing has long been used to optimize fertilization and crop production. More recently, soil health testing has emerged to reflect the growing interest in soil multifunctionality and ecosystem services. Soil health encompasses physical, chemical, and biological properties that support ecosystem functions and sustainable agriculture. Despite its relevance to several United Nations Sustainable Development Goals (SDGs 1, 2, 3, 6, 12, 13, and 15), comprehensive soil health testing is not widely practiced due to complexity and cost. The aim of the study presented here was to contribute to the further development, implementation, and testing of an integrated procedure for soil health assessment in practice. We developed and tested a rapid, standardized soil health assessment tool that combines near-infrared spectroscopy (NIRS) and multi-nutrient 0.01 M $CaCl_2$ extraction with Inductive Coupled Plasma Mass Spectroscopy analysis. The tool evaluates a wide range of soil characteristics with high accuracy ($R^2 \geq 0.88$ for most parameters) and has been evaluated across more than 15 countries, including those in Europe, China, New Zealand, and Vietnam. The results are compiled into a soil health indicator report with tailored management advice and a five-level ABCDE score. In a Dutch test set, 6% of soils scored A (optimal), while 2% scored E (degraded). This scalable tool supports land users, agrifood industries, and policymakers in advancing sustainable soil management and evidence-based environmental policy.

Keywords: near infrared spectroscopy; 0.01 M Calcium chloride; Sustainable Development Goals; soil health indicators; translation functions; outcome-based policy

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1. Introduction

Soil testing is a tool for crop growers and land managers to help optimize fertilization of soil–crop systems, and thereby to optimize the soil fertility level and crop production [1]. The focus in soil testing is often on the main essential nutrient elements phosphorus (P), potassium (K), and nitrogen (N), soil pH, and soil organic matter, although it is well-known that there are up to 17 essential nutrients and possibly more elements potentially limiting plant growth and development, and that soil water holding capacity, soil infiltration and drainage, soil depth, soil structure, soil bulk density, heavy metal contents and soil faunal and microbial diversity may affect crop growth and development [2,3]. Next to the crop production function, soils have a range of other functions, which are generally defined as 'soil ecosystem services' [4,5], and which receive increasing attention from governments, land management, agrifood industries, and nature conservation agencies because of their role in sustainable land management. That is why the attention in soil management has shifted over time from soil fertility to soil quality to soil health, e.g., [6,7], and why there is increasing interest in soil health assessments. Soil health is commonly defined as the continued capacity of soils to contribute to ecosystem services [8]. Soil health reflects the multifunctionality of soils. As a consequence, a range of soil characteristics has to be quantified for an adequate soil health assessment.

In addition to land users and governments, soil health also gained a lot of interest from the agrifood-industry, including the fertilizer industry (for example Yara [9] (Olso, Norway), ICL [10] (Tel Aviv, Israel), Anglo America [11] (London, UK)), the potato industry [12], dairy industry [13,14], the seed industry [15,16], and crop protection industry [17,18]. These companies all accentuate their commitment to maintain or increase soil health. Agrifood companies like Nestlé [19] (Vevey, Switzerland), Cargill [20] (Wayzata, MN, USA), Kraft Heinz [21] (Chicago, IL, USA), Carlsberg [22] (Copenhagen, Denmark), PepsiCo [23] (Purchase, NY, USA), and supermarkets including Aholddelhaize [24] (Zaandam, The Netherlands), Lidl [25] (Neckarsulm, Germany), and Waltmart [26] (Bentonville, AR, USA) do the same. Some of these companies have their own advisors to jointly work with land users on soil health, sometimes in collaboration with extension services. Consultancy firms like Arvesta [27] (Leuven, Belgium) Agrifirm [28] (Apeldoorn, The Netherlands), ProAgria [29] (Helsinki, Finland), Procam [30] (Lavenham, UK), and Seges [31] (Aarhus, Denmark) all significantly increased their signature on soil health. Wang et al. [32] called these agricultural extension services the 'foundation of sustainable agricultural development'

The importance of soil health assessment is also recognized by governments. Governmental agencies in some countries recently launched soil health monitoring projects (e.g., Canada [33], and the Netherlands [34]). Further, some 193 counties recently agreed on the seventeen Sustainable Development Goals (UN-SDGs), and soil health is integral to achieving many of these UN-SDGs, including zero hunger (SDG2), good health wellbeing (SDG3), clean water and sanitation (SDG6), sustainable consumption and production (SDG12), climate action (SDG13) and life on land (SDG15) [35,36]. The increased attention on soil health raises the need for uniform definitions [37], and clear ambitions and goals [38].

Though there is now broad agreement about the importance of soil health and its assessment, and the need for proper sampling protocols to tackle spatial soil heterogeneity, there are still discussions about (i) the selection of relevant soil properties and processes (soil indicators), (ii) the methods used to quantify these indicators, (iii) the linkages between the indicators and soil ecosystem services (i.e., soil health outcomes), and (iv) about the integration, i.e., how to determine the relative contribution of the various indicators to an overall soil health score [7,39,40]. As soil is multifunctional, a relatively wide range of different indicators is needed [7,39,40], but more indicators often mean more costs for soil analyses, which suggests that a balance is needed here. There is especially discussion about the selection of appropriate soil biological indicators [40]. Next to proper soil sampling, relatively large costs are related to quantitative soil analyses, depending on methods. Recent advances in analytical techniques and methods have greatly broadened the range of soil properties that can be measured easily and the speed of analyses, but new methods and procedures do not necessarily match with the existing knowledge base related to conventional soil analyses methods and users [41,42]. A main challenge is linking the soil health indicators to soil health outcomes, i.e., soil ecosystem services, especially following soil management interventions, as there is a paucity of studies that have tried to do so in practice in different landscapes and environments. The need for integration of soil indicators into an overall soil indicator score likely depends on the user of the score and the spatial scale [7,39]; policy makers of (supra-)national organization may embrace a 'simple' score for ease of communication, but growers and land managers may be more interested in an overview of single soil indicators to base management decisions. Also, a recent comparison of different integrated soil health assessment tools revealed that different tools may give different soil health indices [43], which is not helpful for generalizations.

Evidently, there is need for further elaboration and testing of soil health indicators, and for monitoring projects to measure the soil health baseline status and changes in soil health over time. Routine soil testing in agricultural, urban and natural areas is as yet scarce. Even when soil testing of cropland is routine in some countries, often only a limited number of soil characteristics are measured, often reflecting soil fertility testing and not soil health testing [44,45]. Comprehensive routine soil health testing is not common, because commonly agreed soil health assessment tools are not yet well established, as discussed above, and because several different tests and methods are needed, which are often laborious and expensive to conduct. Furthermore, some laboratory tests require chemicals, dangerous to human health and the environment [46,47]. Innovative soil tests may overcome the limitations of some of the current routine soil tests and may be used to create soil health test reports that increase the guidance value of soil testing. A universal soil health test report would help stakeholders, including governmental agencies of different countries and multinational agrifood industries, to explain the soil test results. It is well accepted that the many different soil testing methods across countries make it very difficult to compare the results of soil health testing and the impacts of for example improved agroecological approaches [48,49].

The aim of this study was to contribute to the further development, implementation, and testing of an integrated procedure for soil health assessment in practice. We selected more than 50 soil properties pertinent to soil health. These properties were assessed through an innovative three-step analytical approach, which was tested across 15 countries. We analyzed more than 100,000 samples from cropland, grassland, urban and natural areas, following standard sampling protocols, and present results for >50 soil health indicators, with reference and target values, as well as for a soil health score, which follows the recently proposed EU soil monitoring law. Further, we describe the soil health indicator report, which includes all results of the assessments, and which is meant for land users (agriculture, nature/forest, urban areas), agrifood industry, governmental agencies and research institutions. This study builds on existing knowledge and prior publications, but includes substantial original research through the development and testing of a scalable soil health assessment tool designed for multiple stakeholders, including the introduction of a novel ABCDE scoring system

2. Materials and Methods

A brief overview of the three-step approach is given below. In step 1, key soil properties and promising soil testing techniques were selected (and the techniques were analytically calibrated and validated) for measuring meaningful characteristics so as to obtain a rapid and integrated soil health assessment. Near-Infrared spectroscopy (NIRS) (Q-interline, Tølløse, Denmark) was chosen for measuring key physical, chemical, and biological soil characteristics under controlled laboratory conditions, using dried and sieved soil samples, while multi-element extractions were performed with 0.01 M $CaCl_2$ followed by Inductive Coupled Plasma Mass Spectroscopy (ICP-MS) (Agilent Technologies, Santa Clara, CA, USA) and Discrete Analysis (DA) (KPM (AMS Alliance, Westborough, MA, USA) for assessing a wide range of plant available elements.

Step 2 is an intermediate phase (Figure 1) used to 'translate' the results of step 1 into values of conventional soil analysis methods, whenever needed. Since we do not have a direct NIRS calibration for every soil characteristic, this step allows us to use existing calibration results and, when appropriate, apply conversion functions to estimate conventional method outcomes. Step 3 then reports the outcomes of the broad spectrum soil tests to a full soil health report, including a soil health score, soil and crop management guidelines and thresholds.

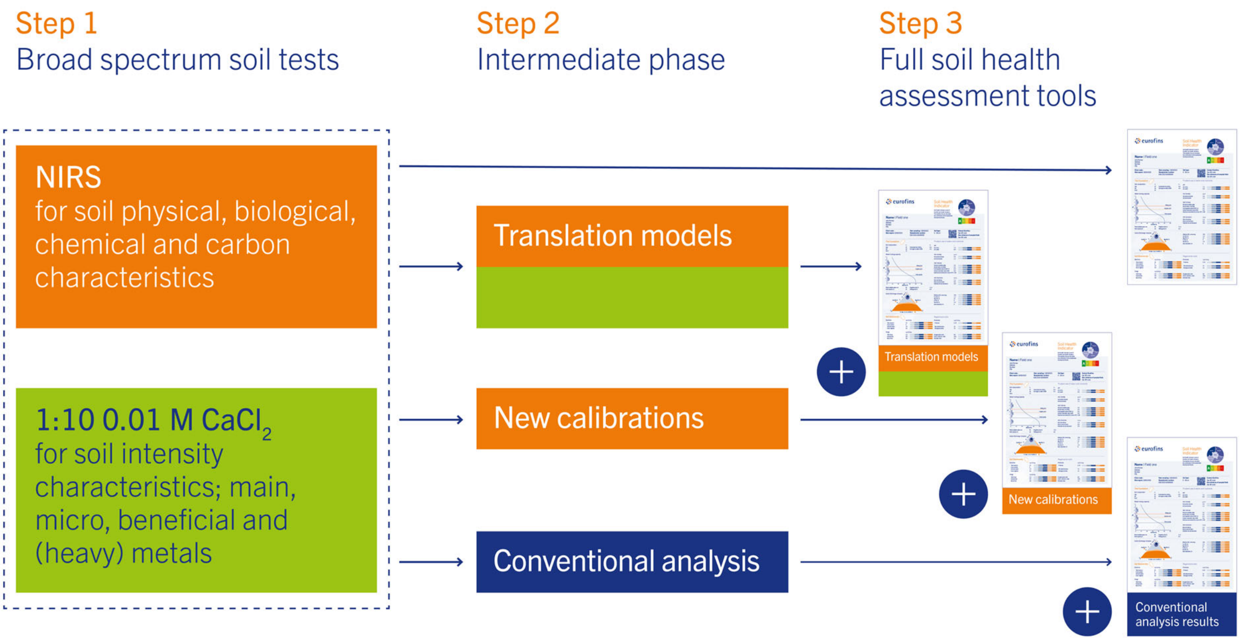

Figure 1. The conceptual framework of the three-step approach to assess and monitor soil health.

2.1. Step 1a: Near Infrared Spectroscopy

Near-Infrared Spectroscopy (NIRS) allows for fast, quantitative, non-destructive and cost-effective estimation of multiple physical, chemical, and biological soil characteristics.

Since the introduction of NIRS for soil testing into practice in 2004, many soil characteristics have gradually been introduced in routine soil tests. The current calibration models are based on a minimum of 1000 to more than 100,000 reference samples depending on the year of introduction, the specific soil characteristic, the efforts made to create high-quality calibration models, and the number of 'outliers' (which are re-analyzed by the reference methods and after that included in the calibration system). To evaluate the calibration system, validation tests were conducted in several European countries, China, New Zealand, and Vietnam, with initial efforts initiated in California (USA) [43, 51) (Table 1). Since the 2022 publication, the calibration results have been updated, and the results from California, which were not previously published, are now included.

Table 1. Results of the calibration and validation of the determination of SOC percentages by NIRS. Samples have been taken in different countries but were analyzed following the same standard procedures [50]. Results are presented for number of samples, the 5th (P5), and 95th (P95) percentiles, mean, standard deviation (SD), determination coefficient (R^2), relative percentage difference (RPD for $n \geq 100$), and root mean squared error of prediction (RMSEP). SOC, soil organic carbon; NIRS, near-infrared spectroscopy.

Type	Region	n	P5	Mean	SD	P95	R^2	RPD	RMSEP
Calibration	-	23,322	0.7	1.8	1.7	5.2	0.99	13.2	0.48
Validation	California, USA	40	0.4	1.3	0.9	3.0	0.93	-	0.13
Validation	China	223	0.4	1.0	1.8	3.1	0.96	4.7	0.29
Validation	Europe	4037	1.0	3.3	2.7	9.3	0.98	8.7	0.32
Validation	New Zealand	234	2.0	6.1	5.5	14	0.99	14.1	0.33
Validation	Vietnam	213	0.3	1.4	0.6	4.2	0.96	4.7	0.12

2.2. Step 1b: Soil Intensity Characteristics Measured with Multi-Nutrient Extractions with 0.01 M $CaCl_2$

Multi-nutrient extractions with 0.01 M $CaCl_2$ were first proposed for assessing the readily available nutrients in soil more than half a century ago. Currently, this extraction method is used worldwide and is embedded in many scientific soil testing programs (Reijneveld et al., 2022) [42]. The method has been promoted since the unbuffered solution of a 0.01 M $CaCl_2$ extract has a comparable ionic strength to soil solutions of most soils; thus, the measured nutrients in the extract reflect the availability of the nutrients at the pH and ionic strength of the soil solution. Moreover, various nutrients as well as metals can be measured in a single extract simultaneously, which allows us to consider the relationships between available nutrients. Prior to extraction, soil samples were dried at 40 °C, gently milled, and sieved (2 mm) to remove gravel, stubble, and roots. After extraction at a 1:10 extraction ratio (w/v) for two hours at 20 °C, nitrogen and phosphorus concentrations in the filtered extract were determined by DA and all other elements by ICP-MS under controlled conditions. Results were verified analytically through reference samples, duplicate samples, and ring tests. Below, we present a summary of the results for bio-available heavy metals, including nickel—an element also recognized as an essential micronutrient. These data, which were not included in our previous 2022 publication [42], are based on 1886 routine soil tests conducted across the Netherlands between 2024 and 2025. The samples represent a variety of land uses, including natural/forest areas, arable land, and grassland, and are part of a larger dataset comprising over 100,000 routine samples collected annually in the Netherlands. This randomly selected subset, stratified by location, was also used to evaluate the ABCDE score (see below).

2.3. Step 2: Intermediate Phase

Going directly from step 1 (creating the soil test results) to step 3 (creating full soil health assessment reports; see Figure 1) is feasible in countries without a history of soil testing or in countries where, for example, the extension services are willing to accept and promote a new concept of soil health assessment using new soil tests reports. In other situations, users of soil tests often want references to their 'conventional' methods and/or legislative methods. References to conventional/legislative methods can be obtained through (i) recalculations with NIRS and $CaCl_2$ data, using existing translation models, (ii) new calibrations and/or the creation of new translation models, or (iii) new soil tests using both the conventional/legislative reference methods and the two broad-spectrum methods, followed by calibration and the establishment of new translation models. Below we sum up the routine soil test packages and methods for several countries as examples for these approaches.

2.4. Step 3: Soil Health Indicator Report

The Soil Health Indicator (SHI) report has seven 7 sections (Figure 2). The first section (A) is the soil physical part. The second section (B) reports on soil biological characteristics, the third section (C) on soil carbon fractions, the fourth section (D) on essential nutrient elements, the fifth section (E) on potential contaminants (heavy metals), the sixth section (F) on recommendations of crop and soil management practices, and the seventh section (G) on the ABCDE-score. The ABCDE-score reflects the soil health assessment proposed by the European Commission (proposal for Soil Monitoring Law) [51]. The ABCDE-score is based on soil tests for salinization (EC), loss of organic carbon (SOC/Clay ratio), excess nutrient accumulation in soil (P), soil contamination (concentrations of heavy metals in soils), acidification (pH), and loss of biodiversity (microbial biomass), and uses indicative thresholds.

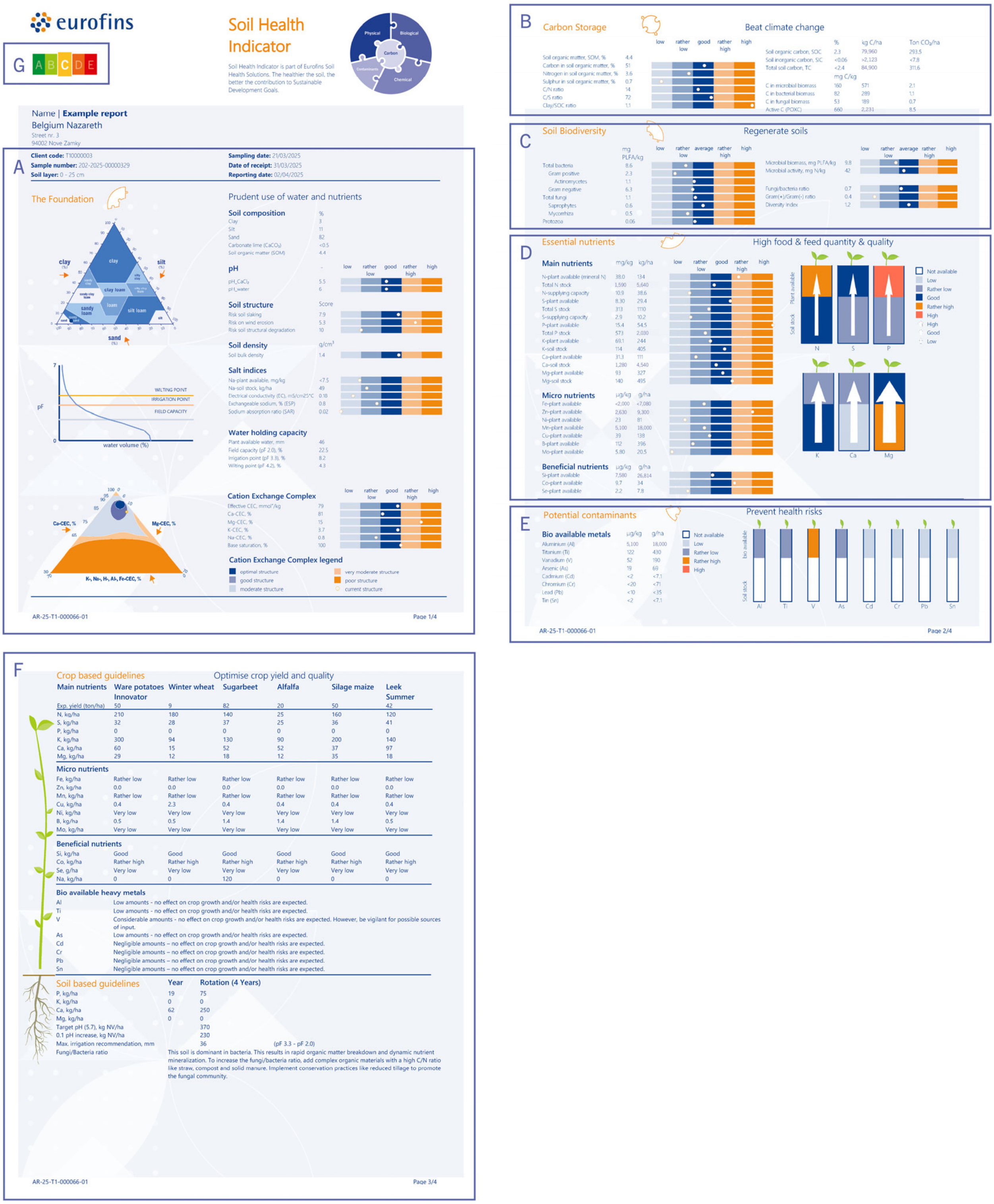

Figure 2. The soil health indicator report has 7 sections, (**A**) soil physical part (**B**) biological characteristics, (**C**) carbon fractions, (**D**) essential (chemical) elements, (**E**) potential contaminants, (**F**) crop and soil based guidelines and (**G**) ABCDE-score.

3. Results

3.1. Step 1a: Soil Characteristics Determined with NIRS

The calibration and validation of NIRS spectra to the results of reference methods are presented in [42,50]. Table 1 illustrates the outcomes of the updated validation and calibration for soil organic carbon (SOC). The outcome of the validation indicates high accuracy for soil organic matter (SOM) and carbon (SOC), soil inorganic carbon (SIC), total nitrogen (TN), total sulfur (TS), total phosphorus (TP), effective CEC (ECEC), Ca-CEC, clay, sand, pH-$CaCl_2$, and soil bulk density, with $R^2 \geq 0.95$; for soil bulk density, we use a pedotransfer function, based on [50,52]. The PFLA-based soil biological characteristics, active carbon (permanganate-oxidizable carbon (POXC)), potential mineralizable nitrogen (PMN), Ca-water, Mg-CEC, and medium sand (M50) all showed reasonably high accuracy ($R^2 \geq 0.84$). Salinization characteristics (Na-CEC, and EC) and oxalate-extractable P have been determined with R^2 of 0.75; 0.81 and 0.83, respectively, while oxalate-extractable Fe and Al have an $R^2 > 0.90$.

3.2. Step 1b: Extractability of Nutrients and Heavy Metals with 0.01 M $CaCl_2$

All essential macro- and micronutrients for plants (N, S, P, K, Mg, Na, Mn, Fe, Cu, Zn, Ni, B, and Mo) are being assessed through multi-nutrient extractions with 0.01 M $CaCl_2$ (apart from Ca and Cl). In addition, two elements that are essential for animals and humans have been included (Se, Co), together with pH and silicon (Si) (Reijneveld et al., 2022) [42]. Bio-available (heavy) metals are also routinely analyzed since 2024; extracted quantities commonly decrease in the following order: aluminum (Al) > titanium (Ti)~chromium (Cr)~vanadium (V) > arsenic (As) > cadmium (Cd) > chromium (Cr)~lead (Pb) > tin (Sn), although the order depends, in part, on soil pH (Figure 3, Table 2).

Table 2. Descriptive statistics of the 0.01 M $CaCl_2$ extractions (1:10 soil to solution ratio: *w*/*v*) of pH, essential element Ni and 8 (heavy) metals. The element concentrations have been expressed in $\mu\ kg^{-1}$. Soil samples (0–25/30 cm) originate from agricultural and natural fields in the Netherlands. N = 1886; based on ISO 10390 [53] for pH and 17294-2:2016 for the elements [54,55].

Soil Characteristic	Reporting Limit	First Quartile	Median	Third Quartile	Average	St. Dev.	Kurtosis	Skewness
pH	-	4.9	5.5	6.8	5.6	1.2	−0.8	−0.1
Aluminium (Al)	600	1460	2820	5838	8971	17,719	14	3.5
Titanium (Ti)	100	100	100	100	122	74	59	6.5
Vanadium (V)	3.0	8.1	15	33	27	35	33	4.5
Arsenic (As)	2.0	9.2	14	22	21	22	31	4.4
Cadmium (Cd)	2.0	2.0	11	25	20	32	163	9.0
Chromium (Cr)	2.0	20	20	20	21	4.2	76	8.1
Lead (Pb)	10	10	10	15	46	116	65	6.5
Tin (Sn)	2.0	2.0	2.0	2.0	2.0	0.7	731	26
Nickel (Ni)	20	22	42	95	85	124	61	5.9

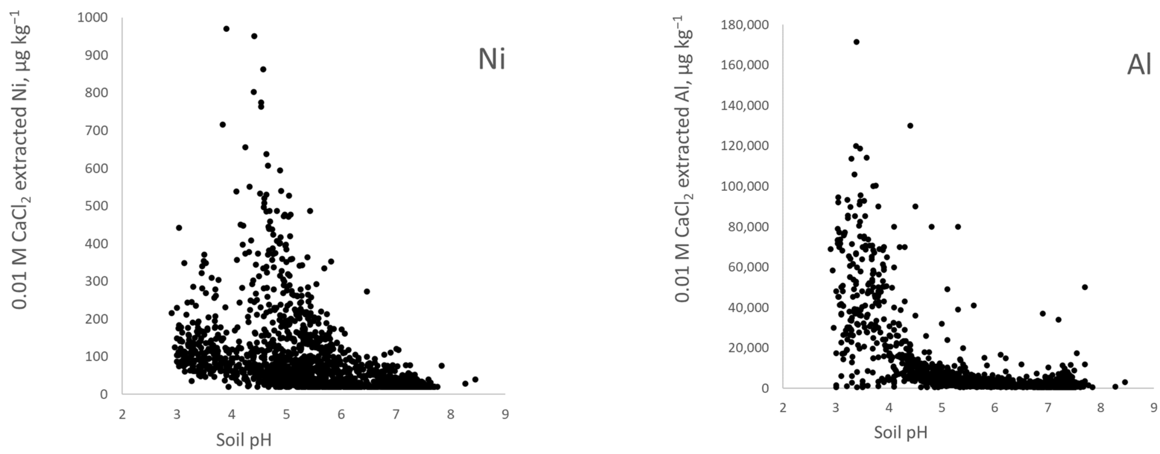

Figure 3. *Cont.*

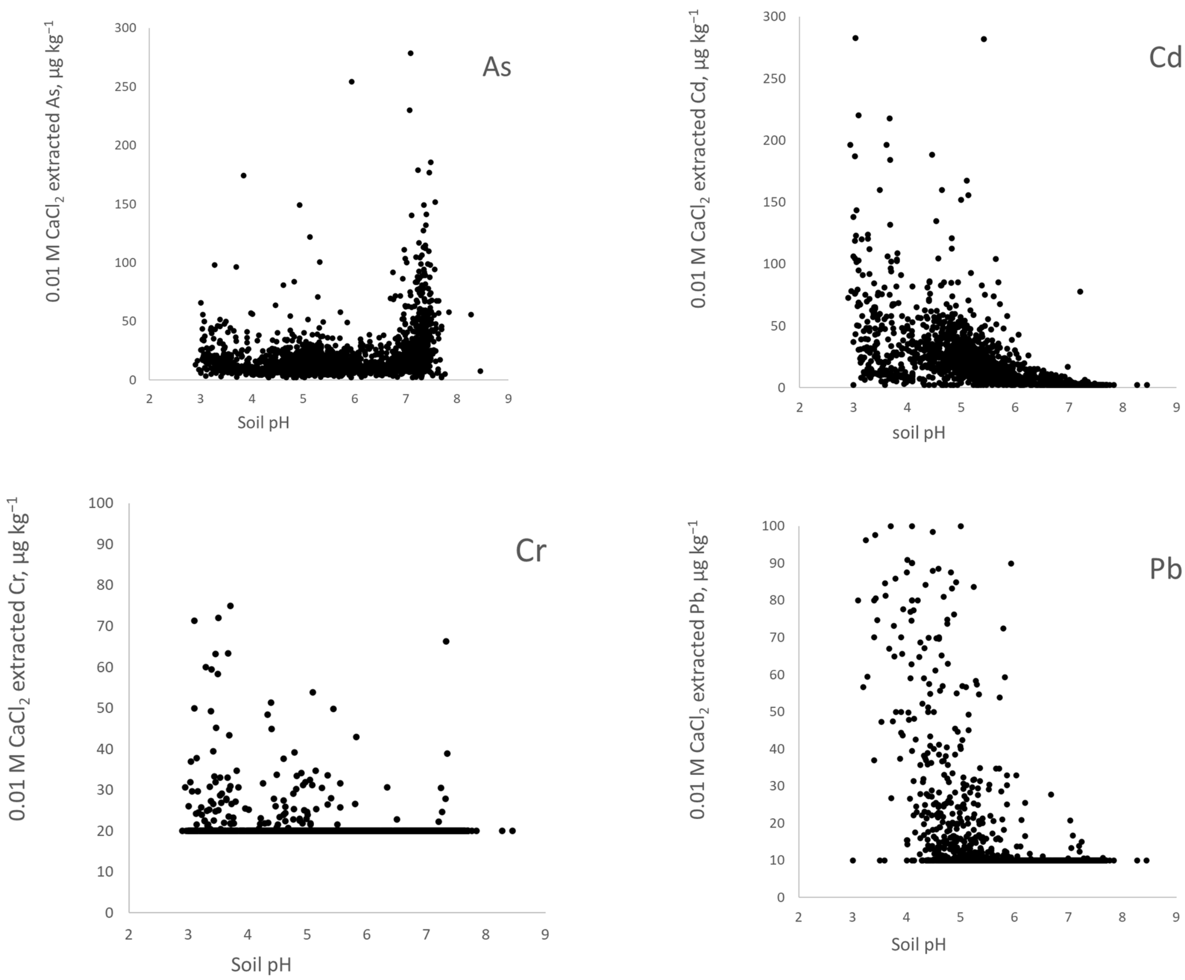

Figure 3. Relationship between soil pH—0.01 M $CaCl_2$ (*x*-axis) and 0.01 M $CaCl_2$-extracted nickel (Ni), aluminum (Al), arsenic (As), cadmium (Cd), chromium (Cr), and lead (Pb) (*y*-axis, µg kg^{-1}). Soil samples (0–25/30 cm) originate from agricultural, natural, and urban fields in Europe (n = 1886).

Generally, the intensity of metal elements Al, Cd, Cr, Pb, and Ni was low in high-pH soils, and highly variable in low-pH soils (Figure 3). Conversely, the concentration of As was often low at low pH and showed a wide range as the pH increased. The other metal elements (Ti, V, and Sn) did not vary much with the soil pH status.

3.3. Step 2: Translation or New Calibrations

An overview of the main current routine soil tests for selected countries is given in Table 3. The number of soil characteristics in a routine soil test package ranges between 4 and 6 for China, Germany, Lithuania, Sweden, and the UK, and exceeds 15 for Finland, France, and the Netherlands. All routine soil tests include P, K, and pH. The essential (main) nutrient sulfur (S) is only included in routine soil tests in the Netherlands. Micronutrients are not routinely analyzed, while some countries (e.g., Vietnam) have no history of routine soil testing and, hence, no formal routine soil tests.

The soil indicators used by countries listed in Table 3 often have a different method than used in the soil health indicator discussed in this paper. For these countries, translation functions (see Figure 1, step 2) can be used, to translate the results of the soil health indicator in the pertinent routine soil tests. Since only few soil characteristics are routinely determined in most countries, the translation functions are most important for P, K, and pH.

Table 3. Most common soil characteristics in routine soil tests for selected countries. Also included are the main soil characteristics proposed by the EU Soil Law.

Countries	N [1]	S	P	K	Ca	Mg	Clay	Silt	Sand	pH	Na	EC	CEC	SOM	TC	SOC	Soil Biology	References
Flanders			✓				✓	✓	✓	✓						✓		[56]
Wallonia	✓		✓	✓	✓	✓	✓			✓			✓	✓				[57]
Finland	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓	[58]
France	✓		✓	✓	✓	✓	✓	✓	✓	✓			✓	✓		✓	✓	[59]
Germany			✓	✓		✓				✓								[60]
Lithuania			✓	✓						✓				✓				[61]
Norway			✓	✓	✓	✓	✓			✓				✓				[62]
Sweden			✓	✓	✓	✓				✓								[63]
The Neth.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓	[64]
UK			✓	✓	✓					✓					✓			[65]
Brazil			✓	✓	✓					✓								[66]
USA			✓	✓	✓	✓				✓		✓		✓				[67]
China	✓		✓	✓						✓		✓		✓				[68]
N. Zealand			✓	✓	✓	✓				✓								[69]
Vietnam																		[70]
EU	✓		✓				✓			✓		✓	✓			✓	✓	[51]

[1] Mineral nitrogen in soil is often analyzed either at the start of the growing season, during the growing season (for adjustment of topdressing) and/or at the end of the season (often for N-legislation, like in Flanders and Germany). In those situations, it is part of a separate soil test, not as a routine soil fertility test, and therefore not presented in this overview. ✓ = valid result.

Olsen phosphorus (P-Olsen), which is used in several countries and included in the EU proposal, can be translated using total phosphorus (P-total) and oxalate-extractable phosphorus (P), iron (Fe), and aluminum (Al), with reported correlations of $R^2 > 0.70$ [71–73]. Future translation functions—potentially incorporating P-total, oxalate-extractable P, P-binding capacity (all of which can be assessed using near-infrared spectroscopy (NIRS) [42,74,75]), and $CaCl_2$-extractable P (P-$CaCl_2$)—may further improve the accuracy of the translation functions for P-Olsen.

For the soil health indicator, both pH measured in $CaCl_2$ and in water are included. The relationships between these two and pH measured in KCl are well established [76,77]. Other soil characteristics—though often not part of routine soil testing—can also be translated relatively easily. For example, the relationship between total nitrogen measured via the Dumas method (used in the soil health indicator) and the Kjeldahl method is strong, with $R^2 \geq 0.96$ e.g., [78].

Several translation functions are available to relate EC 1:5 (used in the Soil Health Indicator) to ECe, as proposed in the EU framework. For example, Kargas et al. (2022) [79] reported a model requiring only EC 1:5 and soil texture to estimate ECe, achieving an R^2 of 0.99 and an RMSE of 1.39 dS/m. Similarly, cation exchange capacity (CEC) values show strong agreement across several analytical methods, with correlations $R^2 > 0.92$ e.g., [80].

Because soil tests for (heavy) metals, bulk density, and biological soil characteristics are relatively new to many national routine soil testing programs, translation functions for these parameters are currently not needed.

3.4. Step 3: Soil Health Indicator Report

The soil health indicator report is based on the results of the aforementioned two broad-spectrum soil tests (NIRS, and multi-nutrient 0.01 M $CaCl_2$ extraction with ICP-MS analysis) and consists of seven sections (Figure 2). Section A reports on soil physical characteristics including soil texture (contents of clay, silt, sand), carbonates, SOM, pH-$CaCl_2$ and pH-water, soil structure, soil bulk density, salt indices, water holding capacity and CEC. The CEC with exchangeable cations is used to indicate the potential risk of dispersion (the separation of soil into single particles) and flocculation [81,82] The water-holding capacity is based on a pedotransfer function [83,84]. The salt indices comprise so-called plant-available Na (Na-0.01 M $CaCl_2$), sodium at the CEC in kg per area unit, exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR) [85,86], and the EC [87–89]. Risks on soil slaking, wind erosion, and soil structural degradation have been derived from calculations using soil texture and SOM [90]. Soil bulk density is derived from a pedotransfer function [50,52].

Section B reports on soil carbon characteristics, including SOC, SIC, SOM, and several ratios like C/N, S/C, and SOC/clay. The SOC/SOM ratio has been presented as carbon percentage (SOC/SOM-ratio $\times$ 100). The indicators are meant for monitoring purposes, but they also have been incorporated in the soil organic carbon balance to provide insight into how much carbon is needed to maintain or improve the soil carbon content. For carbon sequestration monitoring purposes, SOC, SIC, and TC are also given in tons of CO_2 per land unit (e.g., hectare or acre) using the soil bulk density and the soil layer as input for the calculations.

Section C presents the soil biological characteristics based on PLFA-reference methods [91–94] including total mass of bacteria, fungi, protozoa, total microbial biomass, and some ratios (like fungi/bacteria ratio).

Section D presents the essential main nutrients, following the soil intensity, soil buffering, and soil quantity approach [42,95,96]. Most essential micronutrients and three beneficial nutrients (Si, Co, Se) have been included.

Section E presents the potential contamination of the soil by heavy metals. The report presents target and threshold values, indicating the risk of toxicity, based on the literature data [97–101].

Section F presents recommendations for soil and crop management, based on the results of the soil tests. For establishing the recommendations, the following input data need to be known: land use (agriculture, forest/nature, urban/industrial), crop type and variety, desired units (e.g., hectare, acre, feddan), expected yields, and the length of the growing season or climate zone. Recommendations for all essential nutrients, soil organic carbon and soil structure management, and for (minimizing the risk of) heavy metal pollution have been included.

The final section G reports on the ABCDE score, an integrated assessment, following a recent proposal of the European Union [51]. Part A of the proposed soil monitoring law includes the following four indicators: (A1) salinization (EC), (A2) soil erosion, (A3) loss of soil organic carbon (SOC:clay ratio for mineral soils) and A4) subsoil compaction. Part B includes 3 indicators as follows: (B1) Excess nutrient content in soil (P-Olsen), (B2) soil contamination (heavy metals), and (B3) reduction of soil capacity to retain water. Part C includes the following 5 indicators: (C1) excess nutrient content in soil (N-total). (C2) soil acidity (pH), (C3) bulk density, (C4) loss of soil biodiversity, and (C5) soil basal respiration. The ABCDE score is derived from a combination of parameters A1, A3, B1, B2, C2, and C4 (Table 4, Figure 5), with the final score calculated as the arithmetic mean of these individual values.

Table 4. Thresholds used for an integrated assessment of soil health, an ABCDE score, based on a recent proposal of the European Union [51].

EU	ABCDE	A	B	C	D	E	Unit
A1	ECe	<2	2–4	4–6	6–8	>8	dS m^{-1}
A3	SOC:clay	>1/8	1/8–1/10	1/10–1/13	1/13–1/16	<1/16	-
B1	P-Olsen	30–50	20–30 or 50–60	15–20 or 60–70	10–15 or 70–80	<10 or >80	mg P kg^{-1}
B2	Heavy metals (Cd)			pH dependent system, see Figure 4			µg Cd kg^{-1}
C2	Soil pH	5.5–6.5	5.2–5.5 or 6.5–7.0	5.0–5.2 or 7.0–7.5	4.5–5.0 or >7.5	<4.5	-
C4	Biodiversity			SOC dependent system, see text			mg PLFA kg^{-1}

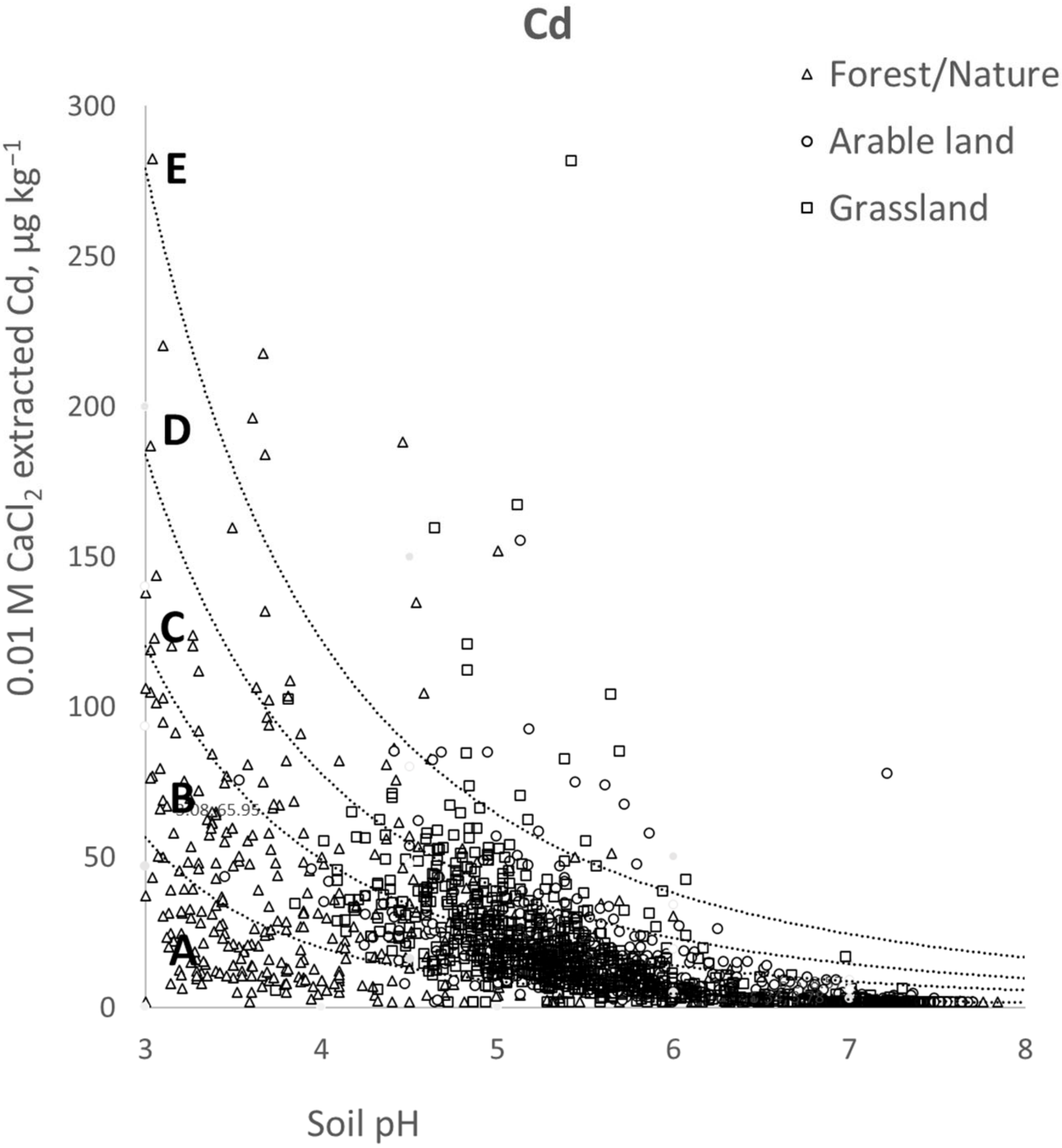

Figure 4. The ABCDE score (Table 4) for cadmium depends on the pH-$CaCl_2$ status.

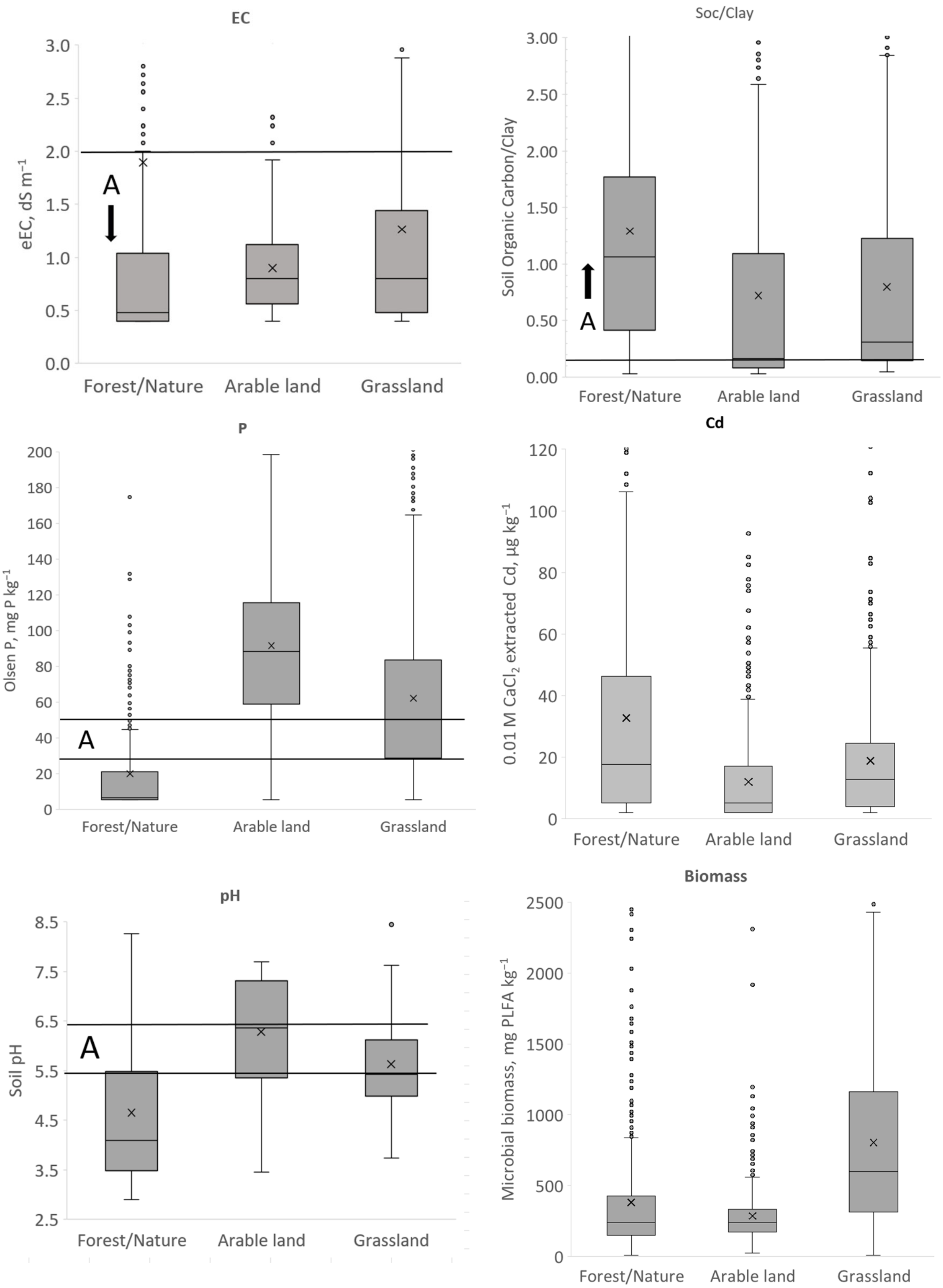

Figure 5. Box plot of soil EC, SOC:clay ratio, soil Olsen P, soil cadmium (Cd), soil pH, and soil biomass values in forest/nature, arable land, and grassland soils. For methods and units, see Table 4. For the ABCDE score, we considered A = very good; letters printed in the figure refer to these ABCDE categories. The horizontal line within each box represents the median; the "x" denotes the mean.

We established some additional translation and classification functions to be able to determine the ABCDE score. Thus, the ECe (saturated soil paste extract) with a threshold of

<4 dS m^{-1} [51] has been converted to EC. Further, although there is some debate about the optimal ranges for the SOC:clay ratio [102–105] for mineral soils, we used target values of 1/8, 1/10, 1/13 and 1/16 for 'very good', 'good', 'moderate' and 'degraded' levels [100]. For the ABCDE score we considered A = very good, B = good, C = moderate, D = degraded and E = very degraded (i.e., SOC/clay ratio > 1/16). Table 4 presents the ABCDE score system used in the soil health indicator report, with ranges for each class. For soil contamination by cadmium, the ABCDE scores depend on the soil pH (see Figure 4). The average scores for the randomized test set, stratified by postal code, were 6%, 41%, 37%, 14%, and 2% for groups A, B, C, D, and E, respectively. If a 'one out, all out' scoring approach had been applied, then—based solely on soil P status—85% would have been classified as group E.

4. Discussion

We aimed to create a soil health test framework that is cost-effective, has a low environmental impact, is fast, and can routinely analyze a wide variety of soil characteristics relevant to soil health and the aforementioned SDGs. Moreover, the soil health assessments need to be acceptable and easily implementable by land users to optimize their land management, and by the agrifood industry to verify and comply with their sustainability claims. For that, two broad-spectrum soil tests have been successfully calibrated and validated [42,50] (Table 1), which culminated in the 'soil health indicator report' (Figure 2). Thereby, we aim to contribute to the further development, implementation, and testing of an integrated procedure for soil health assessment in practice. We selected a wide range of soil physical, chemical, and biological soil properties and present the results for each soil health indicator, as well as for an integrated soil health score. The soil health indicator system was tested in 15 different countries, but we have not yet compared the outcome with other soil health assessment procedures.

There is general agreement on the need for a more sustainable development. In 2015, the UN Assembly approved 17 sustainable development goals [106,107]. Regarding sustainable soil management and climate-smart agriculture, several national and regional initiatives followed, including the Soil Monitoring Law in Europe [108], Platform of Latin America and the Caribbean for Climate Action on Agriculture [109], Adapting African Agriculture [110], and Living Soils of the Americas [111]. Soil health plays an important role in realizing several SDGs by 2030, in terms of contributing to food production (SDG2), good health and wellbeing (SDG3), water quality (SDG6), sustainable production (SDG12), carbon capture and mitigation of greenhouse gas emissions (SDG13), and biodiversity preservation (SDG15). To monitor soil health status and check progress, several programs have been initiated or re-energized, like LUCAS [112] for the European Union, Carbon Content and Soil Health monitoring in the Netherlands [34], and the ambition to map soil health status in Vietnam [113]. These initiatives are largely initiated by (supra)national governmental organizations, and although a bottom-up approach has been strongly recommended and emphasized, this has not yet materialized in practice, partly because soil health testing and assessment by land users is often not feasible because the current routine soil tests are often too limited (Table 3).

4.1. Choice of Soil Health Indicators

For the soil health indicator (SHI) report, we used both Tier 1 and Tier 2 indicators, following the suggestions of the Soil Health Institute [37,114]. Tier 1 indicators are compatible with the following criteria (i) widely considered effective to indicate soil health, (ii) defined regionally and by soil groupings, (iii) known thresholds to index outcome-based soil health status, and (iv) responsive to land use and management practices for soil function improvement. Tier 2 indicators are (i) proven relevant to soil health, (ii) impacting trends on soil health are clear, (iii) ranges and outcome-based thresholds are known for at least some regions, (iv) improvement strategies can be suggested, and (v) additional research may be needed for further validation. In Section A (physical soil health, Figure 2) of the SHI report, Tier 1 indicators are soil texture, soil pH, soil bulk density, soil electrical conductivity, cation exchange complex, base saturation, and available water-holding capacity, while Tier 2 indicators include soil sodium adsorption ratio. Section B of the SHI report (soil biology, Figure 2) includes mainly Tier 2 indicators, such as soil phospholipid fatty acid (PLFA) profiles. Section C (carbon characteristics, Figure 2) includes mainly Tier 1 indicators, i.e., soil organic carbon content. Section D (chemical soil health) mainly reports Tier 1 indicators, i.e., soil total nitrogen, extractable main nutrients (P, K, Ca, Mg), and micronutrients (Fe, Zn, Ni, Mn, Cu, B), and the beneficial nutrients Si and Co. Section E also presents Tier 1 indicators, i.e., potential contaminants, including aluminum (Al), arsenic (As), cadmium (Cd), chromium (Cr), and lead (Pb). For Section F(soil and crop husbandry management recommendations), the expected crop yield (Tier 1) has to be provided by the users of the soil tests, but the short-time mineralization rate (Tier 1) is being derived from soil test data and additional calculations.

Two Tier 1 indicators, i.e., soil aggregate stability and saturated hydraulic conductivity, have not yet been included in the SHI, but efforts are made to include these indicators also in the SHI report; this requires additional calibration and validation work. The Tier 2 indicators nitrogen mineralization rate and strontium (Sr), as well as barium (Ba) contents, cannot be determined with our current soil tests, but titanium (Ti), vanadium (V), tin (Sn), and the beneficial element Se can be determined and are presented in the SHI report, although these elements are not part of Tier 1 or 2 according to the Soil Health Institute [37,114].

Out of the long list of formal Tier 1 indicators, heavy metals will be relatively new for most soil test users. It appears that 0.01 M $CaCl_2$ is a very good extractant for evaluating the bioavailability of heavy metals in soil, especially the bioavailability for plants [115,116]. Recently, Zhang et al. (2022) [117] found that Cd and Pb concentrations in soil invertebrates are best explained by 0.01 M $CaCl_2$ extractions. In general, elevated heavy metal concentrations in soil may affect biota adversely, including aquatic organisms, microorganisms, plants, animals and humans [118]. Also, the increased attention for food safety worldwide makes it necessary to monitor this aspect of soil health [119].

Soil salinity (and sodicity) indicators are also becoming more important because of their impact on crop growth and quality, and soil structure. The area of irrigated agriculture has increased greatly during recent decades, and, with the looming climate change, it is likely that the areas of land affected by salinization and/or sodification will increase further [120]. Thus, the soil salinity indicators, soil electrical conductivity and soil sodium adsorption ratio, i.e., Tier 1 and 2 indicators, respectively, are both in the SHI report (Figure 2).

Results of soil tests require a balanced consideration; the results must be useful to practitioners and at the same time must contribute to environmental protection and to achieving environmental goals. Thus, an optimal fertilization recommendation balances between high crop yield, high crop quality, and safeguarding air and water quality, minimizing the input of finite nutrient resources and economic costs. This balance is also emphasized for potassium by Jalali M. and Jalali M. (2022) [121], and for phosphorus by Van Doorn et al. (2024) [122]. The latter authors indicate that the oxalate extraction method can be considered as a high potential agri-environmental soil test since it measures total reversibly soil bound P, which acts as a reserve for total plant-available soil P, but at the same time acts as an indicator for the risk of P losses via leaching. In the SHI report, both P-binding capacity and P-saturation are being presented.

Several studies also collectively support the use of $CaCl_2$-extracted phosphorus as a valuable indicator for assessing and managing both (agronomical) land management as well as the environmental risks associated with phosphorus leaching and/or runoff [123,124]. The combination of $CaCl_2$-extractable phosphorus and P-Olsen is useful, since the former appears to be more sensitive than the latter in some cases. For example, we found that the P-$CaCl_2$ ranged from 0.4 (very low) to 2.8 (rather high) mg P kg^{-1} within the P-Olsen category 3–4 mg P $(100\ g)^{-1}$ (which is considered 'good') [125]. However, in our current ABCDE calculation we still use the P-Olsen solely (Section G, Table 4).

4.2. Boosting Soil Health

The SHI report includes almost all proposed Tier 1 and Tier 2 soil health indicators, which makes it a comprehensive soil health test report, offering a holistic understanding of soil health, functionality, and fertility. By simultaneously assessing nutrient availability and potential toxicities, it enables precise, site-specific nutrient management while identifying risks to crop health and food safety. Inclusion of biological indicators, such as soil microbial activity and soil biodiversity, provides insight into nutrient cycling, disease suppression, and overall soil resilience. Physical properties like soil structure and soil water retention further inform decision makers regarding the need for tillage, irrigation, and crop selection. Together, this integrative approach supports more accurate, sustainable, and tailored strategies aimed at improving soil health and crop productivity, while minimizing environmental impact.

The SHI framework discussed here has been successfully introduced in several countries, for example in Finland [126], Vietnam [127], and Belgium [27]. The introduction has been accompanied by promotional campaigns and field schools where land users and their advisors discussed the newly added information (e.g., plant-available micronutrients, CEC, biological characteristics, and the organic carbon balance). Bi-annual meetings were also organized with advisors, extension service representatives, governmental officials, and researchers to facilitate ongoing discussions and discuss remaining questions. However, the gap between the current routine soil test packages and the soil tests of the SHI report discussed in this paper is sometimes very large (Table 3). To overcome that gap, a joined-up approach on soil health is required. Such approach includes awareness raising and education, policy support and incentives, research and innovation, capacity building and training, farmer-to-farmer knowledge exchange, and public-private partnerships. Recently, the European Commission presented a mission statement on joint learning between land users, advisors, scientists, and citizens via living labs. Evidently, soil health tests, joint learning and capacity building are important building blocks for sustainable soil management [128].

4.3. Towards a Uniform ABCDE Soil Health Scoring

Internalizing the importance of 'soil health' for human and environmental health requires the full involvement of the agrifood industry. In recent years, the global agrifood industry has promoted sustainable practices in food production, with emphasis on monitoring and verifying environmentally friendly and socially responsible practices, e.g., [23–25,129]. Depending on world regions, Nakelse and Dennis [130] listed the following approximate order in the focus of the agrifood industry: animal welfare > soil health > water footprint > deforestation > biodiversity > waste management > GHG emissions and climate change > food waste > plastic use. Despite the strong focus on soil health (second after animal welfare), the authors found that soil health assessments were qualitative, relying on self-reporting and limited data collection efforts [130]. Objective and quantifiable measures and targets for improved soil health were absent. We argue that soil health claims should be supported by solid soil health tests and monitoring, for the benefit of farmers, society, and the environment. A single soil test reflects a missed opportunity because the two broad-spectrum soil tests discussed here allow for the assessment of a broad range of agronomically, environmentally, and economically useful indicators

The thresholds for EC, SOC:clay ratio, and Olsen P—for the ABCDE score (Table 4) have been proposed by the European Commission [51], but no clear thresholds have been proposed yet for the other indicators. For heavy metals, we have selected 0.01 M $CaCl_2$-extractable cadmium (Cd), and for biodiversity the results of the PLFA method for inclusion in the ABCDE score. Thresholds for biodiversity are based on the methodology outlined in 'Four approaches to setting soil health targets and thresholds in agricultural soils' by Matson et al. (2024) [131], using the so-called 'distribution' approach, combined with literature references. For Cd, we used a combination of a 'fixed' threshold, based on literature data, and a 'distribution' approach using five pro mille for the E-score, but corrected for the pH value (Figure 4).

We have not included total nitrogen (N-total) as a descriptor for excess nutrients in soil (as proposed in the EU Soil Law, Part C), because most of the total nitrogen is part of soil organic matter (Van Groenigen et al., 2017) [132]. The accumulation of organic matter is encouraged by various initiatives, including the 4/1000 Paris Agreement [133], and a high organic matter content in soil is seen as beneficial for SDG13 and soil health in general.

Target soil pH values were included in the ABCDE score (Table 4; Figure 5), with a broad range (pH-$CaCl_2$ 5.5–6.5). A minimum target pH greater than 5.5 would enhance effective cation exchange capacity (CEC) [134], whilst a pH value > 6.5 will decrease the plant-available cadmium and some micronutrients (Figures 4 and 5). However, the optimum or target pH is a compromise, balancing the bioavailability of elements such as copper (Cu) and manganese (Mn), which are more bioavailable at low pH, and molybdenum (Mo), which becomes less available at low pH.

New scientific insights regarding thresholds will require adjustments to the calculation method and ultimately to the ABCDE score. For instance, target SOC:clay ratios are currently under debate, and it is conceivable that factors such as iron (Fe) and aluminum (Al) (hydr)oxides—key drivers of the soil's capacity to sequester carbon and phosphorus—could be integrated into the system, linking actual SOC to achievable or potential SOC levels (e.g., Van Doorn) [135]. Further, the base saturation: aluminum ratio could serve as an additional indicator of soil acidification. It is also conceivable that the soil characteristics of the SHI report will be used by other soil health initiatives, like the OSI [136], Soil Health Card (India) [137], The Cornell Soil Health Test [138], Soil Management Assessment Framework [139], Soil Quality Test Kit of USDA NRCS [140], The Land Degradation Surveillance Framework [141], and The Soil Biodiversity Indicator [142].

4.4. Outlook

The recent strategic policy dialogue on the future of agriculture emphasizes sustainable development, framing sustainability within the context of the UN Sustainable Development Goals (SDGs). This dialogue has also led to several national initiatives to promote sustainable intensification of agricultural production. For instance, Vietnam aims to become a major exporter of agricultural products while reducing fertilizer use and enhancing soil health [143]. Egypt plans to reclaim several hundred thousand hectares of desert land and increase crop yields, in part by improving soil health [144]. Such ambitious projects require the integration of both agronomic and environmental objectives.

The soil health indicator report could serve as an outcome-based tool, allowing land users to report on sustainability in a transparent and goal-oriented way. We therefore advocate that policies should focus on achieving the thresholds of the reported set of indicators rather than prescribing specific top-down management measures. This approach would create opportunities for innovation and entrepreneurship among land users [145,146].

Our study contributed to the debates about the selection of relevant soil properties and processes (soil indicators), and about the methods used to quantify these indicators. However, further studies are needed to link the indicators to soil ecosystem services (i.e., soil health outcomes) in an explicit and convincing manner. Such studies should include both soil monitoring projects as well as focused experimental field studies. Further, the ABCDE health score needs to be further validated, and possibly updated.

5. Conclusions

- This paper presents an internationally applicable rapid tool for comprehensive soil health testing for land users (agriculture, nature & forest, and urban & industry), the agrifood industry, research, and governmental agencies involved in land use planning and management.
- Soil health is defined as the continued capacity of soils to contribute to ecosystem services and encompasses soil physical, chemical, and biological characteristics. Soil health testing thus involves analyses of the key soil physical, chemical, and biological characteristics, combined with an integrated assessment of the soil health status and its capacity to contribute to soil ecosystem services.
- For a cost-efficient, fast, comprehensive soil health test, we used two broad-spectrum soil tests, i.e., NIRS and 0.01 M $CaCl_2$ extraction of soil samples followed by advanced analytical techniques, i.e., discrete analysis (DA) and ICP-MS.
- Based on successful calibration and validation studies, the results of the broad-spectrum test were used to develop the soil health indicator report, which reports on the fitness of the soil for providing a range of ecosystem services.
- The SHI encompasses both Tier 1 and Tier 2 indicators proposed by the Soil Health Institute, i.e., soil physical, biological, and chemical characteristics needed to optimize soil management.
- The comprehensive soil health report has been successfully introduced in several countries, often through promotional campaigns by extension services. While incentives from governmental agencies and the agrifood sector can promote soil health testing, long-term success in maintaining soil health will depend on land users embracing innovative, sustainable crop husbandry practices.
- The soil health test discussed here is scalable and standardized. To further boost its potential, soil health literacy and monitoring should be energized further, perhaps best by consumers asking the agrifood industry to actually measure soil health as part of their sustainability claims.

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