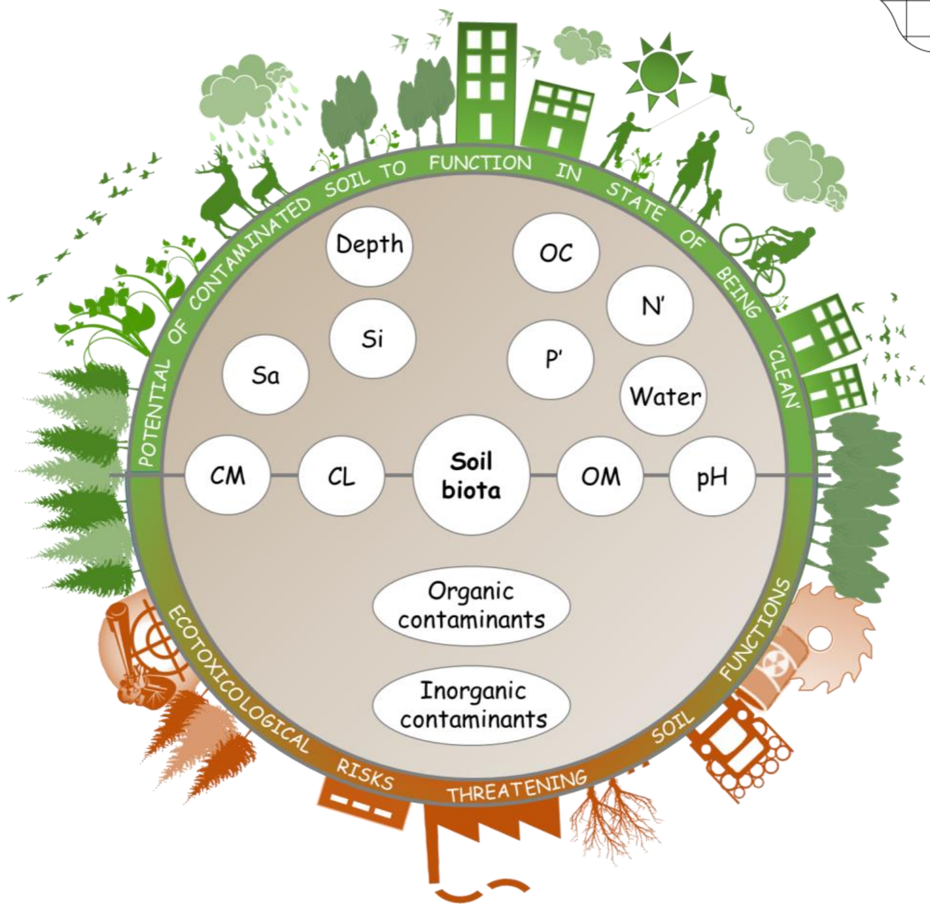

The Updated Version of SF Box

A method for soil quality classification as a basis for applicable site-specific environmental risk assessment of contaminated soils

YEVHENIYA VOLCHKO[1], LARS ROSÉN[1], CHRISTOPHER M. JONES[2], MARIA VIKETOFT[2], ANKE M. HERRMANN[2], A. SIGRUN DAHLIN[2], DAN BERGGREN KLEJA[2,3]

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Research Group Engineering Geology

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019
Technical Note

TECHNICAL NOTE

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”Change the way you look at things, and the things you look at change.”

~Wayne W. Dyer~

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Cover:
Conceptualisation of a holistic view on soil performance (‘capability + condition’) at brownfields for more careful risk assessment and sustainable remediation of contaminated soils. Drawing and idea for illustration by Yevheniya Volchko, ©CHALMERS UNIVERSITY 2018. CM: coarse material. Sa: sand. Si: silt. CL: clay. OM: organic matter. OC: organic carbon. N´ and P´: optimal levels of nitrogen and phosphorus, respectively, available for soil biota.

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ABSTRACT

This technical note summarises major changes in the updated version of SF Box, which is part of the SCORE – the Multi-Criteria Decision Analysis method for decision support in soil remediation projects. SCORE stands for the **S**ustainable **C**hoice **O**f **RE**mediation and SF Box stands for **S**oil **F**unction tool**Box**. The SF Box tool has been developed for soil function assessment to complement environmental risk assessments, in order to increase awareness of decision-makers for inherent *soil qualities* other than concentration of contaminants and their availability/mobility, which are *critical for proper soil functioning*, e.g. availability of water and nutrients for soil organisms, but often ignored in remediation projects (driven by protection of the soil environment with ambition to recover ecosystem functions) in Sweden. The tool is based on a scoring method using soil quality indicators (SQIs) for assessing (I) the soil's capacity to perform its functions in its own reference state of being 'clean', i.e. "what can this soil do and can it perform its functions well, assuming that it is free of contaminants?", and (II) the effects of the remedial actions themselves on soil functions, i.e. "can the remediated soil continue to perform these functions well?". The earlier version of SF Box addresses the soil functions associated with *Primary Production*. By (*i*) taking into consideration the perspectives of soil microbiology, soil fauna and vegetation, (*ii*) slightly modifying the set of SQIs (consisting of *soil texture, content of coarse material, organic carbon/matter, available water, C/N ratio, pH and available phosphorus*), and (*iii*) revisiting the curves for scoring of soil performances on each SQI, the SF Box tool has been updated to assess the soils' capacity to function as a basis for *Life and Habitat* of flora and fauna. This updated version is therefore aimed to provide an improved basis for site-specific environmental risk assessment by means of (1) differentiating between *the effects of contamination* on soil biota and *the effects of soil capability* to function as a host to these species in its own reference state free from contaminants, and (2) classification of the soils (usually characterized by heterogeneity at contaminated sites) in accordance with their overall performance on the selected SQIs for further analysis of ecotoxicological risks in each soil class.

Key words: soil functions, soil quality, soil classification, contaminated sites, sustainable remediation, environmental risk assessment

Contents

Preface

The work presented in this technical note has been carried out within the scope of the research project APPLICERA (Applicable Site-specific Environmental Risk Assessment of Contaminated Soils). APPLICERA is initiated by researchers and consultants with decades of experience in risk assessment and management of contaminated soils in Sweden, with the aim of developing an applicable site-specific methodology for environmental risk assessment (ERA) to protect the soil environment.

The working research group has been established within the APPLICERA project to adapt the earlier developed SF Box (**S**oil **F**unction tool**Box**) method, which is part of the SCORE (**S**ustainable **C**hoice **O**f **RE**mediation) framework for decision support in remediation projects, for its application as a basis for site-specific ERA.

This technical note first provides the reader with a background, the overall aim as well as limitations of previous and the updated SF Box (Chapter 1). Thereafter, the methods used in this study are briefly described (Chapter 2) and the major changes in SF Box are presented (Chapter 3). Finally, the outcomes of this work are discussed (Chapter 4), and summarised in several concluding remarks (Chapter 5).

The APPLICERA project is part of the TUFFO program financed by the Research Council FORMAS, the Road Administration Authority and the Swedish Geotechnical Institute. The funders are gratefully acknowledged for the financial support.

Project acronym:
APPLICERA

Full project title:
Applicable Site-specific Environmental Risk Assessment of Contaminated Soils

Research consortium:
Swedish University of Agricultural Sciences
Swedish Geotechnical Institute
Örebro University
Chalmers University of Technology

Project coordinator:
Prof. Karin Wiberg

Project coordinator organisation:
Swedish University of Agricultural Sciences

Gothenburg, 2019
Yevheniya Volchko

1 Introduction

The first chapter provides the background to the technical note. The aim and objectives of the work are specified. Important limitations of the work are also presented.

1.1 Background

Soils are multifunctional and non-renewable resources within a human life span. It takes thousands of years to transform bedrocks into mature soils characterised by well-developed soil profiles (Jenny, 1941). Formation of the fertile uppermost soil layer rich in nitrogen and organic matter requires decades, and sometimes centuries, of complex and dynamic interactions between biotic and abiotic soil components (Ibid). The upper soil layers host the majority of soil organisms (Lavelle, 2012). These organisms, which are sometimes grouped into four assemblages of (*i*) decomposers, (*ii*) nutrient transformers, (*iii*) ecosystem engineers, and (*iv*) biocontrollers, mediate four aggregate ecosystem functions of (I) carbon transformation, (II) nutrient cycling, (III) soil structure maintenance, and (IV) biological population regulation (see Kibblewhite et al., 2008; Barrios et al., 2012; Brussaard, 2012 for details).

More than four decades ago, soil scientists introduced the concept of multi-functionality of soils and placed a high degree of importance on soil functions (SF) for ecosystem functioning as a whole (e.g. Schlichting, 1972; cited in Lehmann and Stahr, 2010). Ecosystem functions, in turn, result in ecosystem services (ESS) when they are delivered to and utilised by society to promote human well-being (Costanza et al., 1987; de Groot et. al, 1992). Essential soil functions that underpin a vast majority of ESS have been specified in scientific publications (e.g. de Groot, 2002, 2006; Daily, 1997; Lavelle et al., 2006; Barrios et al. 2007; Kibblewhite et al., 2008; Dominati et al., 2010; Barrios et al., 2012; Brussaard, 2012), the high impact UN report *Millennium Ecosystem Assessment* (MEA, 2005), and frameworks developed for classification of ESS (TEEB, 2010; CICES, 2013). This body of work underscores the soil ecosystem's role as a stock of natural capital fulfilling human needs (Dominati et al., 2010).

In 2006, in a published draft proposal of the *Soil Framework Directive* (COM, 2006), policy-makers recognised that soils provide SFs that are critical and fundamental for survival of ecosystems and humans. Their aim was to develop a unified soil protection strategy across EU countries and to combat threats to SFs, such as soil contamination. These emerging regulatory requirements necessitate a more holistic view on soil quality in soil management projects, taking into consideration the interplay of physical, chemical and biological soil properties that are usually assessed with help of soil quality indicators (SQIs) (e.g. Rodrigues et al, 2009; Bone et al, 2010). However, due to differences in national soil protection legislation and well-established traditions of contaminated soil management, several member states have perceived this new legislation rather as a bottleneck than a "one-size-fits-all" solution for soil protection. As a result, after pending for seven years in the European Parliament, the draft has unfortunately been withdrawn (COM, 2014).

However, the underpinning role, i.e. function in biophysical and socio-economic perspectives, of the worlds' soils in tackling global societal challenges of "food, water and energy security, climate change abatement, biodiversity protection [to supply ESS] and human health" must be recognised in policy and legislation (McBratney et al., 2017a). Efforts to bring together scientific communities across different disciplines, policy-makers, investors and citizens in all parts of the globe have resulted in the concept of *Soil Security (*McBratney et al., 2014), which aims to (1) improve the understanding of the fundamental role that soils have to play in tackling current societal challenges, and (2) "guide the development of policies addressing… [the above mentioned] challenges" (McBratney et al., 2017a). This concept integrates the earlier developed concepts of *soil quality*, *soil health*, *soil functions*, *ecosystem services*, *soil resilience*, *soil protection*, and *soil conservation* (see McBratney et al, 2017b for overview), and provides a framework for action on the global scale by means of addressing the 5C's of **C**apability, **C**ondition, **C**apital, **C**onnectivity, and **C**odification.

The *Capability* domain refers to the soil's intrinsic capability to perform its functions "in the context of its own reference state" (McBratney et al., 2014). The *Condition* domain addresses "the current state of the soil and refers to the shift in capability compared to the reference state" (Ibid.). The domain of *Capital* recognises the soil as a stock of natural capital, i.e. an asset with monetary value, contributing to human wellbeing. The domain of *Connectivity* brings in societal aspects with respects to stakeholders' knowledge and resources "to manage the soil according to its capability" (Ibid.). Finally, the domain of *Codification* deals with public policy and regulation to serve as a 'safety net' by (*i*) management of the soil in accordance with its *capability* to its best *condition*, (*ii*) placing monetary value on natural *capital*, and (*iii*) involving stakeholders into the management process for *connectivity*. The domain of *Codification* is aimed to translate the codified knowledge of soil science into language understandable to a wide audience (not necessarily soil experts), to "provide practical solutions" for proper soil management (McBratney et al., 2014).

Soil functions have been overlooked in soil remediation projects (Volchko et al., 2013). However, by conceptualising the linkages between soil functions, soil ecosystem services and the three domains of sustainability, and by involving stakeholders into assessment process, the SCORE method (Rosén et al., 2015) revolutionises approaches to decision support in soil remediation projects (Carré et al., 2017). SCORE addresses soils' *capability* and *condition* by means of the SF Box method (Volchko et al., 2014b,c), which is part of SCORE and a complement to environmental risk assessment. The socio-cultural domain of SCORE addresses *connectivity.* While the economic domain addresses *connectivity* and *capital* in the broader sense than natural capital. SCORE provides a basis for integrating national ambitions of soil protection to "sustain/restore ecosystem functions to a level that corresponds to the intended land use" (SEPA, 2009) and, in this sense, addresses *codification*.

Based on scoring of the selected SQIs, the SF Box method seeks to, in understandable and somewhat simplified language, (I) answer "what can this soil do and can it perform its functions well in its reference state, assuming that it is free of contaminants?" and (II) evaluate the effects of remedial actions themselves on these functions as part of sustainability assessment, i.e. "can the remediated soil continue to perform these functions well?". The earlier version of SF Box addresses soil functions associated with *Primary Production*. By taking into consideration the perspectives of soil microbiology, soil fauna and vegetation, the updated version of SF Box, presented in this technical note, is aimed to assess the soils' capacity to function as a basis for *Life and Habitat* of flora and fauna.

The updated version of SF Box is aimed to facilitate *codification* and provide a better basis for site-specific environmental risk assessment (ERA) within the scope of the APPLICERA project. Aiming to develop an applicable site-specific methodology for ERA and protect the soil environment based on known benefits for the ecosystem, APPLICERA brings together researchers across different disciplines (i.e. soil biology, ecotoxicology, soil chemistry, geology, and land management) and consultants with decades of experience from risk assessment and management of contaminated soils in Sweden.

1.2 Aim and objectives

The overall aim of this technical note is

> *to summarise major changes in the updated version of the SF Box method for application of soil quality classification as a basis for applicable site-specific environmental risk assessments within the APPLICERA framework.*

The specific objectives to reach the aim are:

(i) to provide a brief description of the scoring method for classification of contaminated soils, where each class reflects the overall soil performance on the selected SQIs, in order to form an opinion on the capacity of contaminated soils to function in the reference state of being 'clean';

(ii) to describe the working process behind the adaptation of this method providing a basis for applicable site-specific ERA;

(iii) to revisit and update the scoring curves for each SQI to reflect the capacity of soils to function as a basis for *Life and Habitat* of flora and fauna;

(iv) to describe the major changes in the updated version of SF Box used for operationalisation of the scoring method for soil quality classification.

1.3 Limitations

Similar to the previous version of the SF Box, the updated version explicitly handles *uncertainties in the predicted soil class* which reflects the capacity of the soil to perform its functions *at a remediation site as a whole*. These uncertainties result from spatial heterogeneity of SQIs, limited sampling size, and analytical errors. Classification of each soil sample by the scoring curves is, however, based on a deterministic model, i.e. soil classes of separate soil samples are based on point values of the computed soil quality indices. Therefore, the uncertainties in the determined soil class of *each soil sample* are not taken into account. This is a significant limitation which must be addressed in future studies, in order to provide an improved basis for site-specific ERA within the APPLICERA framework, where ecotoxicological risks are suggested to be analysed in each soil class.

Also, excess nitrogen (N) and phosphorus (P) in the soil is not considered to be detrimental to above- and below-ground soil biota (i.e. vegetation, soil fauna and microorganisms). This rationale is used for scoring the performance of the soil on these SQIs. The levels of N and P that are considered toxic will likely be much higher than commonly observed values in soils, even frequently fertilized agricultural soils. The authors, however, recognise that excess N and P may indeed have negative environmental impacts due to leaching and run-off of nutrients into surface- and groundwater.

2 Methods

This chapter briefly summarises the methods used for soil quality classification in the updated version of the SF Box providing the basis for applicable site-specific environmental risk assessment of contaminated soils.

2.1 Minimum data set

Soil functions are difficult to measure directly, and are usually assessed by measuring soil quality indicators (SQIs) and evaluating soil performance on these SQIs to form an opinion of the soil's capacity to function. It is a common practice to identify a minimum set of SQIs, i.e. a minimum data set (MDS), usually using expert judgement (e.g. Lehmann and Stahr, 2010), statistical studies (e.g. Moebius-Clune et al., 2016), and methods which combine expert judgement and sieving approaches (e.g. Ritz et al., 2009). There is no universal MDS, because different functions require different sets of indicators to be measured and evaluated. Thus, different studies have often used different MDSs to assess the same soil function (see compilation in Volchko, 2014). The MDS for soil function assessment in remediation projects by Volchko et al. (2014a) has been used in this study with further minor modifications (see Chapter 3).

2.2 Scoring method

A scoring method is used in this study for soil function assessment and classification of the soils in accordance to their overall performance on the selected SQIs. The schematic description of the method is presented in *Figure 1*. The scoring method was (*i*) initially described by Karlen et al. (2001, 2003) and Andrews et al. (2004) and it is forming the basis for Soil Management Assessment Framework, SMAF; (*ii*) followed by Moebius-Clune et al. (2016), Gugino et al. (2008), Idowu et al. (2008), Schindelbeck et al. (2008) and it is realised in the Cornell Framework for Soil Health Assessment; and (*iii*) further adapted for contaminated soil management in the studies by Volchko et al. (2014 a,b,c). Scoring is performed in three steps: (1) selection of an MDS, (2) interpretation of SQIs, and (3) calculation of the soil quality index (Andrews et al., 2004).

The works by Moebius-Clune et al. (2016), Gugino et al. (2008), Idowu et al. (2008), Schindelbeck et al. (2008) extended the method by classification of soils in accordance with their overall performance on the selected SQIs. The studies by Volchko et al. (2014 a,b,c) added a step of uncertainty analysis to the scoring procedure, in order to handle uncertainties in the assessment results while applying this method to assess the effects of remedial actions on soil functions within the SCORE framework for decision support in remediation projects (see Volchko et al., 2014c for details). Furthermore, although the arithmetic mean has been suggested for aggregation of the sub-scores (Andrews et al., 2004), there is a possibility in the scoring procedure by Volchko et al. (2014a,b,c) to choose between two methods for aggregation of transformed SQIs into a soil quality index, using arithmetic mean or geometric mean. In contrast to the arithmetic mean, the geometric mean does not allow for compensation of a weak performance on one SQI by a stronger performance on another SQI. The geometric mean is therefore recommended to be used for aggregation.

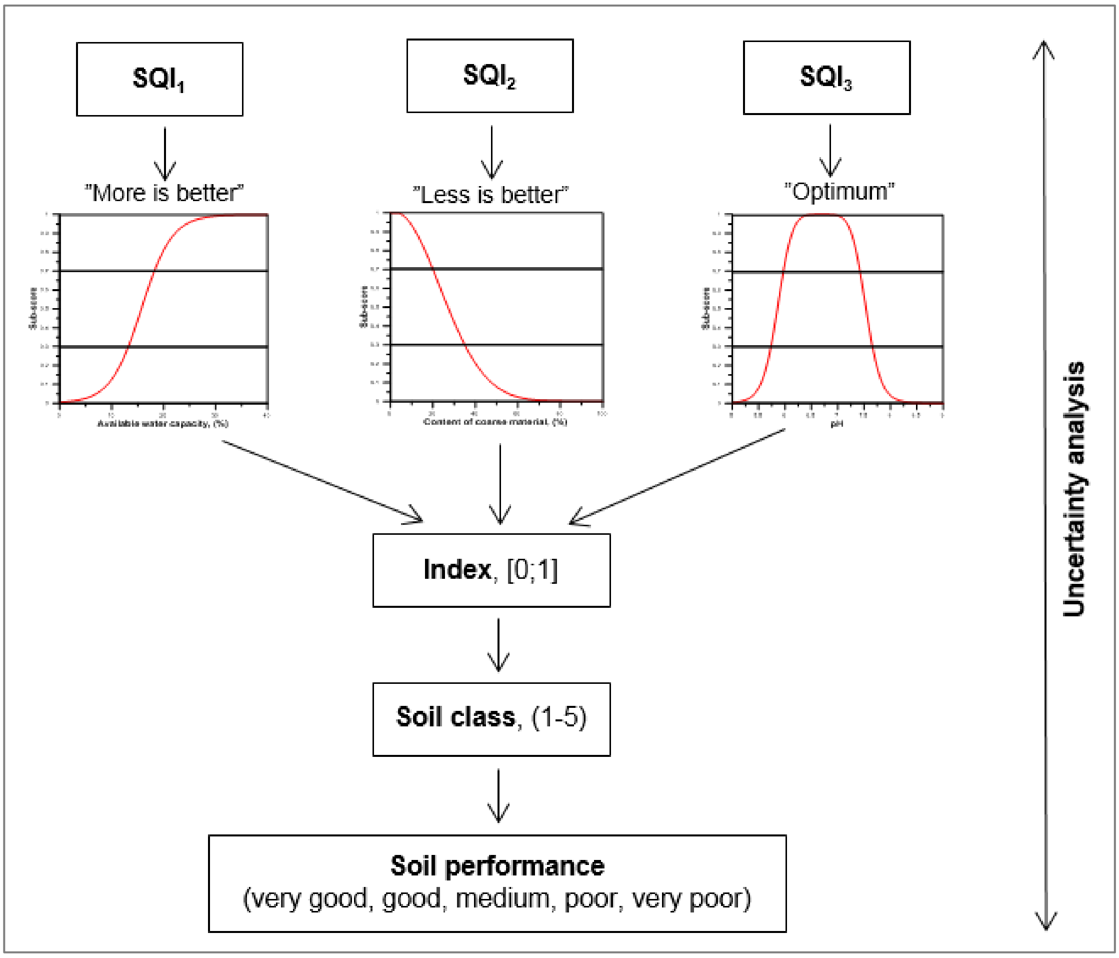


Figure 1. The scoring method for soil function assessment with examples of scoring curves (in red colour) used for interpretation of the measured values of soil quality indicators (SQIs).

To interpret the measured values of SQIs, three types of scoring curves are used, i.e. "more is better", "optimum", and "less is better" (*Figure 1*). For the "more is better" example, the higher the value of the SQI, the higher the sub-score of this indicator. For the "less is better" example, the lower the value of the SQI, the higher the sub-score. For the "optimum" example, there is a limited range of values corresponding to high sub-scores, whereas "less" and "more" than these optimum values are scored lower. The sub-scores of [1; 0.71], [0.7; 0.31], [0.3; 0] represent soils of "good", "medium" and "poor" qualities, respectively (reflected with help of green, yellow and red colour codes, respectively; see *Table 3* below for details).

The soil quality index forms a basis for soil classification into five soil classes corresponding to “very good”, “good”, “medium”, “poor”, and “very poor” soil performances (*Table 1*).

Table 1: Correspondence between soil classes, soil performances and a soil quality index (Volchko et al., 2014a).

Soil class	Soil performance	Soil quality index
1	Very good	> 0.85
2	Good	0.70 – 0.85
3	Medium	0.55 – 0.69
4	Poor	0.40 – 0.54
5	Very poor	< 0.40

2.3 The working process

A working group consisting of soil scientists, a geologist and a land management expert (the authors of this technical note) was established within the scope of the APPLICERA project. Their aim was to adapt the earlier version of SF Box for its application in ERA of contaminated soils. The scoring curves in the updated version of SF Box have been revisited and updated by the working group in a workshop setting. Taking into consideration the perspectives of soil microbiology, soil fauna and vegetation, the baseline scoring of intrinsic capabilities of the soil to function as a basis for *Life and Habitat* was obtained through a systematic review of the scientific evidence and expert judgement in the case of limited empirical evidence.

The procedure of expert knowledge elicitation was carried out in four steps:

(I) problem definition – given soil heterogeneity at the contaminated sites, there is a difficulty in assessing environmental risks using biological indicators, available ecotoxicity tests and principal component analysis, *if a distinction* between the effects of contaminants on soil biota and other conditions crucial for operation of biota in the soil *is not made*;

(II) preparation for elicitation – a systematic review of scientific evidence in the literature on “what conditions are good?” and “what conditions are poor?” for realisation of intrinsic capabilities of the soil to function as a basis for *Life and Habitat* of flora and fauna in urban parks and pristine grassland has been made by the members of the working group;

(III) the elicitation itself in a workshop setting – conjoint update of the scoring curves by the members of the working group, based on step (II) and expert judgement; and

(IV) documentation of the expert knowledge elicitation results.

3 Assessment of the soils' capacity to function as basis for Life and Habitat of Flora and Fauna

This chapter briefly describes the major changes in the updated version of SF Box.

3.1 The minimum data set

A minimum dataset for assessment of soil function *Life and Habitat* of flora and fauna is presented in *Table 2*. The set of SQIs for assessment of this function slightly differs from those in the study by Volchko et al. (2014a), as potentially mineralizable N is replaced with the C/N ratio and an SQI of soil depth is added. Soil depth becomes an important measurement for evaluating soil functions, because active life and habitat take place in the upper layers of the soil, i.e., down to 0.6–1 m below the surface. Furthermore, organic carbon (OC) has also been added to the MDS to make the method more practical and flexible, as this parameter correlates strongly to the earlier suggested SQI of organic matter (OM) while allowing for quantification of C/N ratios.

Table 2: A minimum dataset for assessment of soil functions in remediation projects (modified after Volchko et al. 2014a).

Soil quality indicators (SQIs)
Soil depth
Soil texture
Content of coarse material (CM)
Organic carbon (OC), or organic matter (OM)
Available water (AW)
C/N ratio (C/N)
pH
Phosphorus (P)

3.2 The flowchart for soil function assessment

The overall flowchart for assessment of soil function *Life and Habitat* of flora and fauna is presented in *Figure 2*. There are four important features in the flowchart for assessment of *Life and Habitat* function of the soil:

(I) Available water is determined as a function of clay, silt, sand and organic matter using Eq.1 (Behrman, 2016):

$$AW = \frac{0.05Sa + 0.26Si + 0.08Cl + 0.9OM}{Sa + Si + Cl + OM}, \qquad (1)$$

where *AW* is available water (%), and *Sa, Si, Cl* and *OM* are contents of sand (%), silt (%), clay (%) and organic matter (%) respectively.
Note, *Sa, Si, Cl* and *OM* constitute 100%.

In practice, AW is first evaluated for each soil horizon, multiplied by a thickness of horizons and thereafter these values are added to derive AW in the whole soil profile. If the depth to bedrock is shallower than one meter, then AW is multiplied by the depth of 1 m (Soil Survey, 1976). The latter is used in SF Box, because the thickness of soil layers at which soil samples are usually taken for analysis in remediation projects are less or equal to 1 m, e.g. 0-0.5 m or 0.5-1 m.

The contents of clay, silt, and sand are also used to determine soil texture by means of the Food and Agriculture Organisation of United Nations (FAO) triangle (FAO 2006). Soil texture is not scored but it provides valuable information on the inherent soil quality. Here, *Sa*, *Si* and *Cl* constitute 100%.

(II) Organic carbon is computed as a function of organic matter and vice versa using the "van Bemmelen factor" of 1.724 which is based on the assumption that organic matter contains 58% organic carbon (Eq. 2):

$$OM = 1.724 \cdot OC\,, \tag{2}$$

where *OM* is organic matter (%) determined as loss on ignition at temperature *T* and *OC* is the carbon content of OM (%).

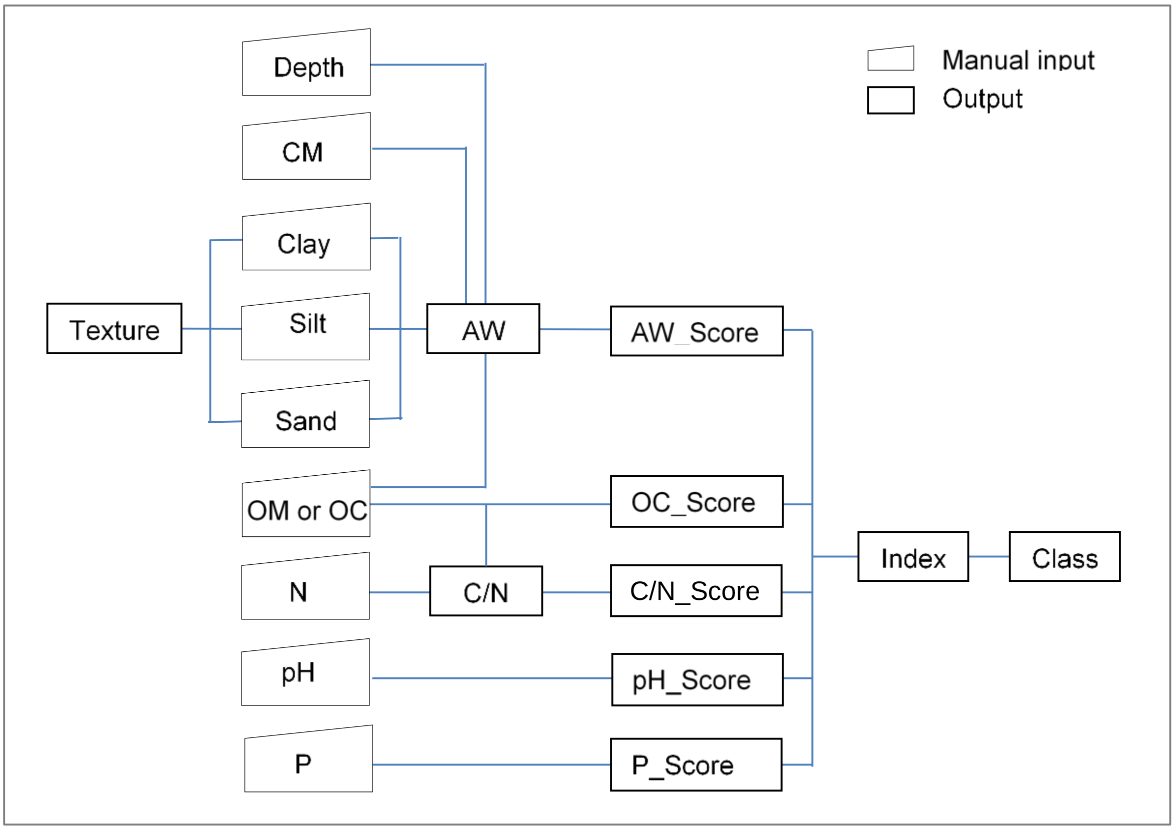


Figure 2. Schematic drawing of the overall input/output flow for assessment of soil function Basis for Life and Habitat of Flora and Fauna (modified after Volchko et al., 2014b). CM – content of coarse material, OM – organic matter, OC – organic carbon, N – total nitrogen, P – available phosphorus, AW – available water, C/N – C/N ratio. AW_Score, OC_Score, C/N_Score, pH_Score, P_Score – the scores for available water, organic carbon, the C/N ratio, pH and available phosphorus, respectively.

(III) CM is not scored but accounted for, in order to correct the pools of AW and P in soils (Eq. 3) before scoring of these SQIs, using a correction factor (Soil Survey, 1976) (Eq. 4):

$$\begin{aligned} AW_{corr} &= AW \cdot F \\ P_{corr} &= P \cdot F \end{aligned}, \tag{3}$$

where F is a correction factor, AW_{corr} and P_{corr} are corrected pools of AW (%) and P (mg/kg) in soils respectively.

$$F = \frac{100 - CM}{100}, \tag{4}$$

where F is a correction factor and CM is a content of coarse material (%), i.e. particles of ø > 2 mm.

Pools of OM (or OC) and N are not corrected for contents of coarse material in the soil, because these SQIs are only used as inputs to computation of the C/N ratio and AW. The rationale is that multiplying the numerator and denominator of a fraction by the same factor results in a fraction that is equivalent to the original fraction.

(IV) The Olsen-P values (ISO 11263) are used as inputs for scoring of available P. However, AL-P values (Egner et al. 1960) can also be used as input for the scoring. The Olsen-P values are then computed as a function of AL-P values, pH and a clay content in the soil (Otabbong et al., 2009), using Eq. 5:

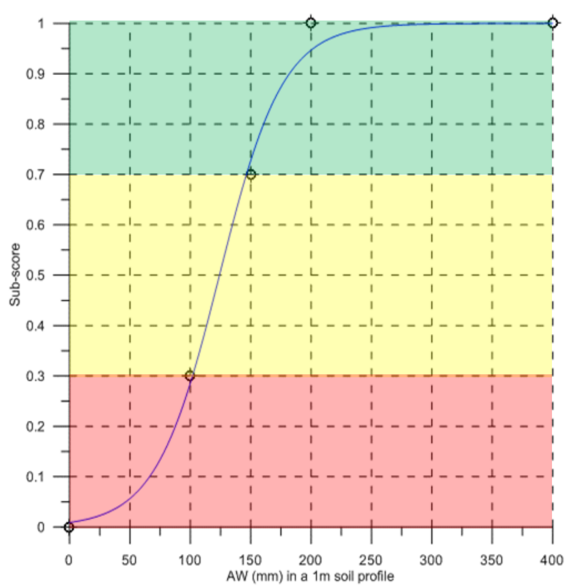
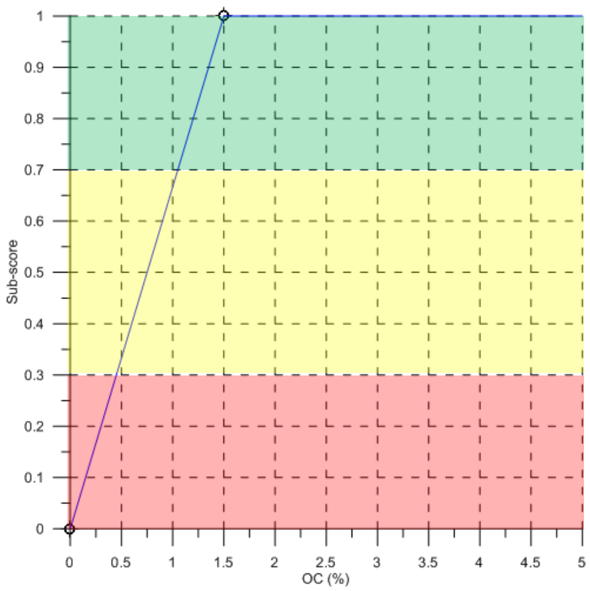
$$P_{Olsen} = \left(12.786 + 0.599 \cdot P_{AL}^{0.5} + 0.232 \cdot Cl^{0.5} - 1.985 \cdot pH\right)^2, \tag{5}$$

where P_{Olsen} is a Olsen-P value (mg/kg), P_{AL} is a AL-P value (mg/kg), and Cl is a clay content (%).

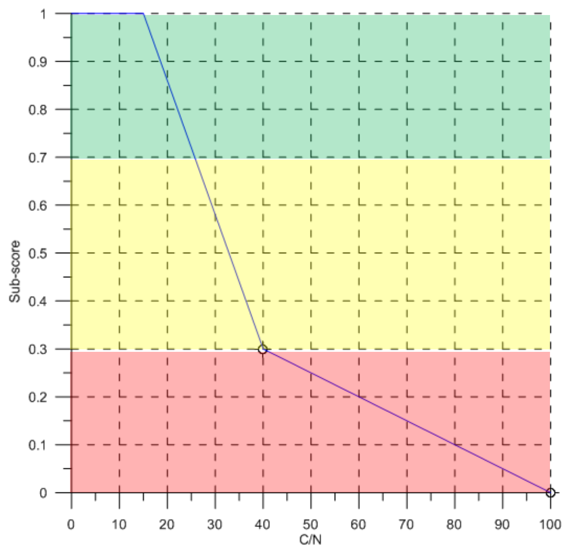
3.3 The updated scoring curves

The scoring curves (*Table 3*) for assessment of the soil function *Life and Habitat* of flora and fauna in the reference state, i.e. no adverse impact of contamination, are derived using the procedure described in *Section 2.3*. These scoring curves support evaluation of the overall soil performance based? on the selected SQIs, sorting out soils into classes in accordance with their potential to perform *Life and Habitat* function in their own reference state (free of contaminants). The limit which separates “good” and “medium” quality soils (green and yellow colour codes, respectively, in *Table 3*) from “poor” quality soils (a red colour code in *Table 3*) cuts off extreme values of SQIs. These extreme values imply limited opportunities for the soil to function as a host to a wide range of species (from soil microorganisms to vegetation).

Table 3: Scoring curves for soil function assessment at contaminated sites. The colour codes of red, yellow and green in the graphs correspond to 'poor', 'medium' and 'good' soil quality of the respective indicator.

Graph of a scoring curve	**Mathematic description and comment**
3.1 Scoring curve for available water (AW) – shape of "more is better" *meaning that the higher the value of AW, the higher the sub-score of and the soil performance on this SQI.*	
	The scoring curve for available water in a soil profile of 1 m depth is based on Soil Survey (1976). It is described by the Sigmoid function: $$f(x)=\frac{1}{1+e^{-0.03799(10x-124.11629)}}.$$
3.2 Scoring curve for organic carbon (OC) – shape of "more is better" *meaning that the higher the value of OC, the higher the sub-score of and the soil performance on this SQI.*	
	The scoring curve for organic carbon is based on the works by (1) Herrmann and Witter (2002) representing a plant perspective, (2) Lerch et al. (2013) representing a soil microbiology perspective, and (3) Hendrix et al. (1992) representing a soil fauna perspective. It is described by the system of linear equations: $$f(x)=\begin{cases}0.66667x, & 0\le x<1.5;\\ 1, & x\ge 1.5.\end{cases}$$

***3.3 Scoring curve for the C/N ratio (C/N) – shape of "less is better"** meaning that the lower the value of the C/N ratio, the higher the sub-score of and the soil performance on this SQI.*

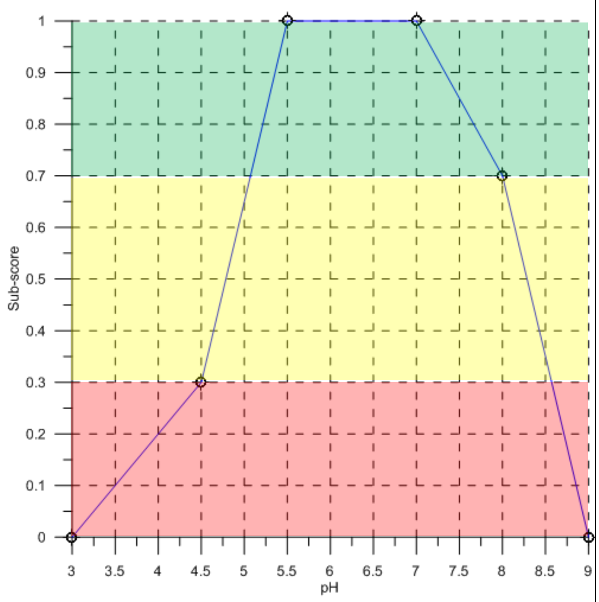


The scoring curve for the C/N ratio is based on the studies by Herrmann and Witter (2008) and Zechmeister-Boltenstern et al. (2015) representing plant and microbiology perspectives respectively. It is described by the system of linear equations:

$$f(x)=\begin{cases} 1, & x \le 15; \\ -0.028x+1.42, & 15 < x < 40; \\ -0.005x+0.5, & 40 \le x < 100; \\ 0, & x \ge 100. \end{cases}$$

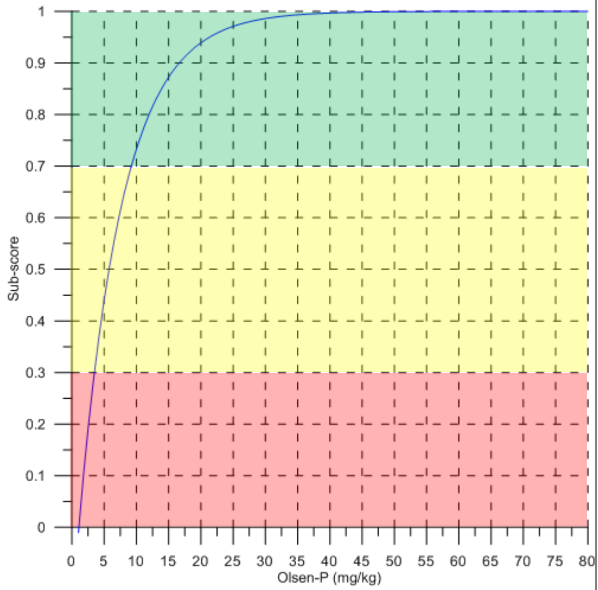
The rationale behind the shape of scoring curve is that the excess of N does not affect soil biota (see *Section 1.3* for details).

***3.4 Scoring curve for pH – shape of "optimum"** meaning that a limited range of pH values corresponds to high sub-scores of and performances on this SQI, whereas "less" and "more" than these optimum values are scored lower.*



The scoring curve for pH is based on (*i*) Wiertz et al. (1992) and Rosen et al. (1998) representing a plant perspective, (*ii*) Enwall et al. (2007) and Lauber et al. (2009) representing a microbiology perspective, and (*iii*) Burns (1971) representing a soil fauna perspective. It is described by the system of linear equations:

$$f(x)=\begin{cases} 0.2x-0.6, & 3 \le x < 4.5; \\ 0.7x-2.85, & 4.5 \le x < 5.5; \\ 1, & 5.5 \le x \le 7; \\ -0.3x+3.1, & 7 < x < 8; \\ -0.7x+6.3, & 8 \le x < 9; \\ 0, & 9 \le x < 3. \end{cases}$$

<table>
<tr><td></td><td>A pH value of 8 is chosen to separate “good quality” soils from “poor quality” soils, in order to also acknowledge specific soil conditions in some regions of Sweden which are characterized by a high lime content in the soil.</td></tr>
<tr><td colspan="2">3.4 Scoring curve for phosphorus (P) – shape of “more is better” meaning that the higher the value of P, the higher the sub-score of and the soil performance on this SQI.</td></tr>
<tr><td>
</td><td>The scoring curve for available phosphorus (Olsen P) is based on the studies by Tang et al. (2009) and Jordan-Meille et al. (2012) representing a plant perspective. The curve reflects relative yield responses to soil Olsen P which are simulated using the Mitscherlich model. The scoring curve is described by the exponential function (Tang et al., 2009):

$f\left(x\right)=1-e^{-0.148\left(x-1.07\right)}$.

The rationale behind the shape of scoring curve is that the excess of P does not affect soil biota (see Section 1.3 for details).</td></tr>
</table>

3.4 Operationalisation of the scoring method

Using Visual Basic for Applications, the updated scoring method (*Section 2.2*) is realised in the updated version of SF Box programme in accordance with changes summarised in this chapter (*Figure 2* and *Table 3*), in order to provide a basis for assessment of environmental risks within the APPLICERA framework. The updated version of SF Box is part of the SCORE tool which is planned to be available for download in 2019. Please contact lars.rosen@chalmers.se for further information.

4 Discussion

The SF Box tool takes into consideration the perspectives of soil microbiology, soil fauna and vegetation, in order to assess the soil's capacity to function as a basis for *Life and Habitat* in its reference state, i.e. assuming *no adverse impact of contamination*. This, in turn, assists in differentiating between *the effects of contamination* on soil biota and *the effects of soils' capacity* to serve as a host to species in its reference state. The ability to distinguish between these effects provides an improved basis for the APPLICERA framework for applicable site-specific ERA. The distinction is made by means of the updated version of SF Box in accordance with the overall performance of the soil on the selected SQIs.

In relation to the *Soil Security* concept, the capacity of the soil to perform its functions "in the context of its own reference state" refers to *capability* (McBratney et al., 2014). However, the MDS used in this study also consists of SQIs (e.g. organic matter, available water, pH) attributed to the *condition* by the work of Field and Sanderson (2017), i.e. "the current state of the soil and refers to the shift in capability compared to the reference state" as defined by McBratney et al. (2014). In this respect, the SF Box method addresses the *capability* of the contaminated soils to function *in their reference state of being 'clean'*, assuming that the soils are free of contaminants and other important soil attributes, e.g. water and nutrients critical for survival of soil organisms, are in place. In contrast, the site-specific ERA deals with assessment of the current state of this soil, i.e. *condition*.

Therefore, the APPLICERA framework for ERA may facilitate management of the soil in accordance with its *capability* and to its best *condition* for life and habitat of the diversity of species. Protection of biodiversity in the soil may be motivated not only to supply ESS as suggested in McBratney et al. (2017a) but also by ethical values as described in Back et al. (2019). Furthermore, the value can then be placed on the sustained or restored ecosystem functions, using the criterion of social profitability in the economic domain of SCORE (Söderqvist et al., 2015), addressing the dimension of *capital* in a broader sense of land use and soil protection. This domain of SCORE also implies involvement of stakeholders for qualitative valuation as the first step of economic assessment, addressing *connectivity*.

The updated version of SF Box transmits complex information on soil quality and functions in a simple way that makes this information approachable for non-experts in soil science, contributing to *codification*. In order to turn sustainable ambitions of soil protection to recover ecosystem functions, there is an urgent need to increase awareness of policy- and decision-makers for *soil qualities* other than concentration of contaminants and their availability/mobility, which are *critical for proper soil functioning*, e.g. availability of water and nutrients for soil organisms. These qualities are, however, often ignored in remediation projects at the expense of future generations.

Given scarcity of land for development and the EU zero net land take target of 2050 (COM, 2015), the contaminated sites which are often found in attractive locations of a city map form a valuable resource. More careful risk management may help to effectively sustain and restore ecosystem functions to the level of the intended land use and prevent redundant remedial actions associated with waste of money, time and effort. There is therefore an urgent need for the improved *codification* of scientific soil knowledge in policy and regulation. The *Soil Security* concept will, hopefully, facilitate this *codification* process for enabling the conjoint well-coordinated action on soil security in all parts of the globe *in time, for humanity.*

5 Concluding remarks

The following conclusions can be drawn from this study:

- Given scarcity of land for development and the EU zero net land take target, contaminated sites which are often found in attractive locations of a city map should be managed in accordance with the soils' *capability* and their best *condition* in order to prevent redundant remedial actions and losing of valuable resources such as money, time and effort.

- In order *to turn sustainable ambitions* to recover ecosystem functions through soil protection *into action*, there is an urgent need to increase awareness amongst policy- and decision-makers for *soil qualities* other than concentration of contaminants and their availability/mobility. These qualities are *critical for proper soil functioning*, e.g. availability of water and nutrients for soil organisms. However, these aspects are often ignored in remediation projects at the expense of future generations.

- The updated version of SF Box is aimed to improve the basis for ERA by seeking to answer the questions "what can this soil actually do and can it perform its *Life and Habitat* function well, assuming that it is free of contaminants?" and thus to assist in making a distinction between *the effects of contamination* on soil biota and *the effects of soil capability* to function as a host to these species in its own reference state free of contaminants.

- In this study, the application of the earlier developed and operationalised soil classification method with SF Box as part of SCORE for sustainable remediation has been extended to serve as an improved basis for site-specific ERA within the APPLICERA framework.

- There is a potential for using SF Box for soil function assessment not only in remediation projects but also for other types of land management projects focused on soil functions.

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