NBSOIL
Nature-Based Solutions for Soil Management

Soil Health Index - online tool and user's guide middle version

Deliverable 2.2

30.11.2024

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Deliverable 2.2	**Soil Health Index - online tool and user´s guide middle version**
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1 Introduction

The quantitative assessment of the status of soil health is a key goal of current monitoring efforts at the European level in the context of the European Directive on Soil Monitoring and Resilience (European Commission, 2023). This requires adequate methodologies as well as user-oriented visualization tools to disseminate results of soil health improvement towards practical implementation in the context of soil advisory and management innovation.

NBSOIL therefore develops an advisor- and land owner-oriented soil health assessment framework ("*NBSOIL health index tool*") that provides (i) integration of quantitative measurement data (indicators) of soil samples into relevant soil ecosystem functions and (ii) data processing and visualization that facilitates interpretability of the state of soil to comply with advisory tasks as well as monitoring, verification and reporting goals in view of the implementation of the Soil Monitoring and Resilience Directive.

The NBSOIL Health Index Tool is a web-based platform designed to assist next-generation soil advisors and farmers. It aggregates quantitative data from multiple sources—including laboratory analyses, potentially on-farm digital tools and satellite-derived information—into actionable insights about soil functions. By assessing the current state of soil health, the tool aids in evaluating progress in mitigating soil threats at the field scale under specific management regimes.

The tool is accessible online through the NBSOIL website, accompanied by a comprehensive guidebook to ensure effective usage. Both the tool and guidebook are integrated into the educational offerings of the NBSOIL Academy, which provides structured courses to promote the tool's adoption and dissemination.

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2 Background and methodology for the NBS Soil Health Index Tool

2.1 Scientific background

Soil health is a concept that captures soils as living ecosystems with multiple ecosystem functions and services (Lehmann et al., 2020). The term soil health in particular captures the biological side of soil ecosystem functions that has been increasingly recognized in recent years.

Basic soil properties (e.g. texture, profile depth, pH), emerging from primary pedogenetic drivers (climate, parent material, topography, age), constitute the boundary conditions for the strengths and weaknesses of specific soil types in the different soil ecosystem functions. In spite of the importance of basic soil properties, these factors cannot be changed by soil managers. On the contrary, soil properties emerging from soil biological processes are strongly influenced by land use and management and are therefore under the control of human decisions. A modern perception of soil health thus builds on the recognition of the specific genetic backbone of different soil types (natural boundary conditions), while aiming to optimize soils within these boundaries based on management decisions that foster biological processes underlying soil ecosystem function.

Furthermore, remote sensing and monitoring technologies, such as satellite-based teledetection, potentially provide a powerful means to observe changes in soil properties and ecosystem functions over time. These tools enable large-scale assessments of soil health, complementing ground-based measurements and offering critical insights into spatial and temporal variations.

Therefore, in order to comprehensively evaluate a management system in practice there are two basic requirements:

(1) The natural location influence, which represents the unchangeable framework of potential improvements in response to management, must be taken into consideration and weighted to define achievable management targets (e.g., Bøe et al., 2023).
(2) Various soil target functions or ecosystem services (e.g., food production, climate protection, groundwater protection, etc.) must be taken into account (e.g., Greiner et al., 2017).

Current concepts of soil health intend to capture the multifunctional nature of soils and their different ecosystem functions. Frequently soil functions have been classified into chemical, physical and biological aspects (e.g., Karlen and Stoff, 1994). Beyond this coarse classification, modern soil health assessment classifies single indicators in relation to soil processes, soil functions and related soil threats (Bünemann et al., 2018). Thereby the multifunctional nature of soil is taken into account, which facilitates the development of monitoring frameworks that comply with the societal targets of protecting the different ecosystem services provided by soils.

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2.1.1 Soil ecosystem functions

The NBS soil health index tool follows the classification of soil ecosystem functions proposed by Schulte et al. (2014) and applied within the EU Landmarks project. According to this concept, the five key soil functions include (1) production of biomass, (ii) cycling of nutrients, (iii) storage and purification of water, (iv) habitat for biodiversity and (v) regulation of the climate. Specifically these soil functions refer to:

- **Productivity function:** Nature based solutions for sustainable soil use have to ensure provision of biomass production for food, feed, fibre and energy.
- **Water resource function:** Nature based solutions for sustainable soil use should contribute to ensure the quality of water resources and enhance soils' capability for infiltration, storage and purification of water, thereby significantly contributing to climate change adaptation.
- **Nutrient use function:** Nature based solutions for sustainable soil use are intended to close nutrient cycles, thereby reducing losses that negatively affect other ecosystems and improving the efficiency of nutrient use in human land use systems.
- **Climate function:** Nature based solutions for sustainable soil use strengthen soils as greenhouse gas sinks via sequestration of CO2 as stable organic matter and reduction of N2O losses via improved nitrogen use efficiency.
- **Biodiversity function:** Nature based solutions for sustainable soil use ensure and improve the function of soils as terrestrial habitat with the highest diversity of organisms that in turn are key components of all other soil functions.

The different soil functions are related among each other and their interrelation defines the challenges and potentials to achieve a simultaneous co-optimization within an improved management approach (Figure 1). Plant autotrophic growth provides carbon input for the soil food web as the essential driver of soil health. Soil (micro)biology mediates both, soil structure formation as a key manageable aspect of the soil water function as well as soil nutrient cycles. These two soil functions feedback to the soil production function by providing water and nutrients for plant growth. Soil structure formation is also related to soil biological habitats (pore geometry), i.e. there is a close relation between soil biological activity and soil habitats which is captures by the concept of soil biology – together with plant roots - as soil structure engineers (e.g. Lavallee et al., 2016). Within the dynamic processes of plant-microbe-soil interactions, the climate function of soils is affected, e.g. via stable storage of carbon by mineral association and aggregate occlusion or via interactions between nutrient release (nitrogen mineralization) and structure (air vs. water filled pore space) in greenhouse gas emissions (N_2O), underlining their dual capacity to act as a source or sink of greenhouse gases depending on how soil health and ecosystem functions are managed.

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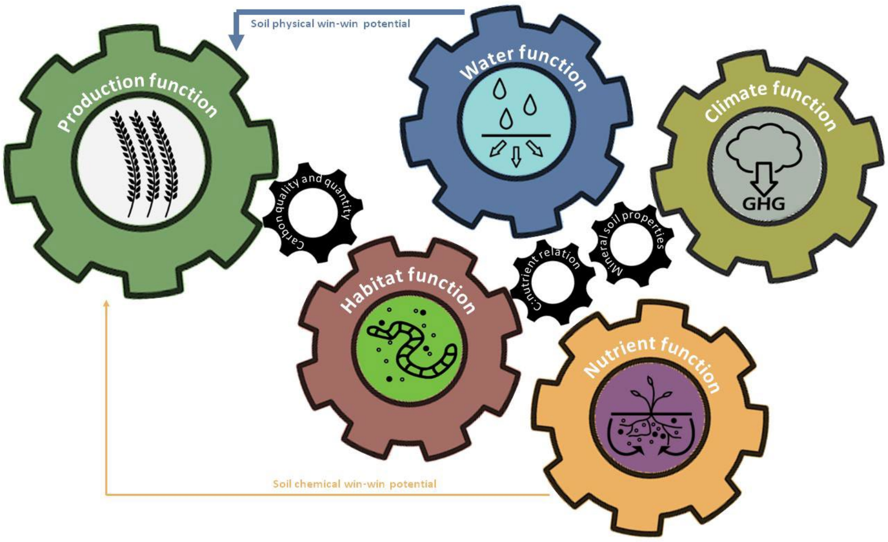

Figure 1. Soil ecosystem functions and their interrelation *(G. Bodner, unpublished)*

2.1.2 Soil indicators

For soil health assessment, measurable indicators are allocated to the single soil function. Different approaches have been proposed for clustering and scoring indicators to comprehensive soil functions, such as expert assessment (e.g. Andrews et al., 2004) and unsupervised statistical methods (e.g. factor analysis, Shukla et al., 2006).

Indicators are thus single soil properties that serve as descriptors for given soil functions and are a key component of soil health assessment and monitoring schemes. Numerous indicators have been used to capture soil health and the respective changes due to management measures. An overview of commonly used indicators is given in Bünemann et al. (2018), while Stewart et al. (2018) provide an evaluation of several indicators in terms of sensitivity to capture soil health oriented management change via cover cropping and reduced tillage.

Indicators should optimally meet two criteria:

1. Indicators should be **measurable with standard protocols** at reasonable costs in order to potentially allow large scale implementation into monitoring schemes.
2. Indicators should be **sensitive to management change** in order to capture improvement vs. degradation of soil properties.

However, due to the complex nature of soils and continuous progress in soil analytics an objective selection of soil health indicators that are most adequate for monitoring soil health is hardly possible. Thereby indicators used for soil health assessment should also reflect current scientific knowledge as well as relevant policy frameworks, in particular indicator selections made in the course of the implementation of the European Directive on Soil Monitoring and Resilience. Assessment tools should thereby facilitate implementation of novel indicators and databases, responding to the dynamic changes in the scientific and political field of soils.

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2.2 Methodology of the soil health assessment tool

The methodology of the NBS online soil health assessment tools follows the approach of the "Soil Management Assessment Framework" (Andrews et al., 2004; Wienhold et al., 2009). SMAF provides an approach for site-specific assessment of management impacts on soil functions based on measurable indicators that are combined to form a comprehensive soil quality index. The approach is comprehensively documented (Stott, 2019), validated (e.g., soil cultivation: Nunes et al. 2020; e.g., SOC accrual: Nunes et al. 2021) and is constantly being further developed (e.g., Norris et al., 2020).

Besides these strengths of SMAF, its suitability as a basis for the NBSOIL health index tool is also due to NBSOIL's orientation towards soil advisors as soil experts: The SMAF-framework takes into consideration the integration of expert knowledge and data interpretation and therefore provides a particularly useful basis for the tool developed in NBSOIL.

A key methodological component of the indicator model is scoring and indicator integration into comprehensive function. Scoring transforms a measured indicator into a dimensionless quantity to a numerical value from 0 to 1 (or any other standardized scale).We used a linear scoring system for all indicators. Since all indicators in the current version follow a more-is-better principle, the evaluated value was divided by the maximum value to obtain a score between 0 and 1. Should less-is-better indicators be used, the minimum of the indicator would be divided by the evaluated value, yielding values between 0 and 1.

Corresponding to the SMAF framework, the indicator-objective function relationships can be represented by three main curve shapes (Figure 1): (a) local optimum (e.g., optimal function), (b) more-is-better (e.g., logistic growth function), and (c) less-is -better (e.g., inverse logistic function).

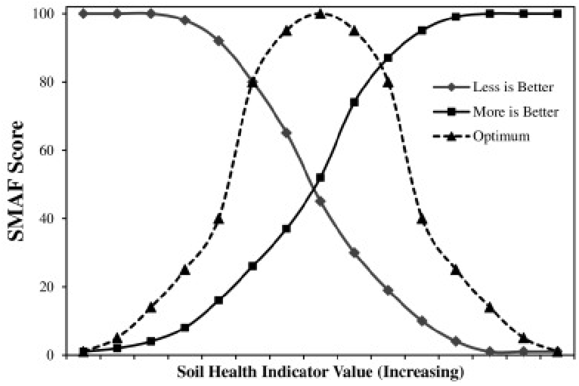

Figure 2: Scoring curves for the evaluation of measurement indicators in the SMAF (Source: Veum et al., 2017)

The general shape of the curve can be adapted to site-specific boundary conditions to take natural site constraints, in particular soil texture, into account in the definition of the scoring functions, e.g. different location of optima or maxima, differences in the course of increase or decrease of the curve. Figure 3 shows a classic example of site-specific (texture) scoring for the climate target indicator soil organic matter accrual.

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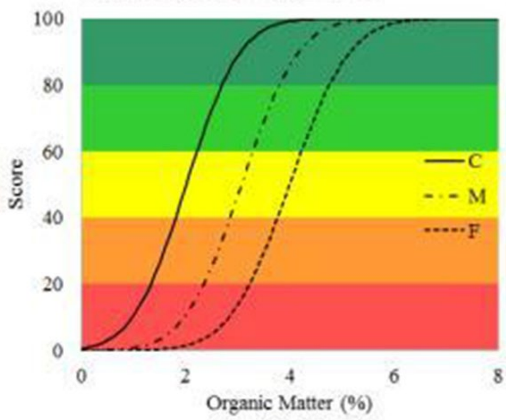

Figure 3. Example of site-specific adaptation of the course of the scoring function (score here: 0-100) for soil organic matter as a frequently used indicator for climate protection (C sequestration) for different soil texture classes (C…coarse, M…medium F…fine textured; Source: Fine et al., 2017).

Upon scoring, the individual indicators, which are allocated to a given soil function via initial expert assessment, are summed up to provide a unique value for each of the target functions. The overall assessment of a field for the achievement of a soil health is ultimately carried out by additively combining all individual indicators according to the formula (Andrews et al. 2004):

$$SF = \left(\frac{\sum_{i=1}^{n} I_i}{n}\right) \times X \qquad \textit{(Equation 1)}$$

where SF is the soil function index value for the objective function, which results from the sum of the n individual indicators and is transferred to a corresponding scale (e.g. 0-1) with a factor X (e.g. 1).

Thereby the model provides a summary indication for each of the targeted soil ecosystem functions to visualize specific strengths and weaknesses as well as a comprehensive evaluation of a field. Comparison for the management system under review can be done with the overall dataset, local averages or between individual single fields differing in management.

Overall, scoring functions are the key element of soil health assessment as they define the benchmarks for soil health assessment. Therefore, the assessment critically depends on datasets that are used for scoring, with the general rules of:

(i) Larger datasets allowing a more robust scoring.
(ii) Localized datasets allowing a more specific representation of natural site constraints in a region.

Therefore, it has to be taken into account that any indicator-based model for soil quality assessment is critically dependent on the underlying dataset and will continually improve with the amount of available data (see for example the SMAF for soil organic matter: Nunes et al. 2021).

Additional considerations regarding datasets in soil health assessments include:

i. Data quality: The accuracy and reliability of datasets are crucial, as inconsistencies or biases in measurements can significantly affect the outcomes of scoring functions.

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ii. Temporal resolution: Datasets that capture temporal changes, such as seasonal variations in soil properties, provide a more dynamic and realistic representation of soil health over time.
iii. Integration of diverse data sources: Combining traditional datasets (e.g., laboratory measurements) with modern data sources (e.g., remote sensing, on-site digital tools) enhances the comprehensiveness and applicability of soil health assessments.

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3 Middle version of NBS Soil health index tool

In the following we describe the concept, implementation and usability of the middle version of the NBS Soil health Index online tool. The overall objective of the tool is to provide an online-instrument for soil advisors to assess the status of a target field based on a series of measured indicators and compare (benchmark) the respective site with available reference data.

The online tool middle version (Figure 4) is available via: https://soilhealthindex.shinyapps.io/shiny_nbsoil/

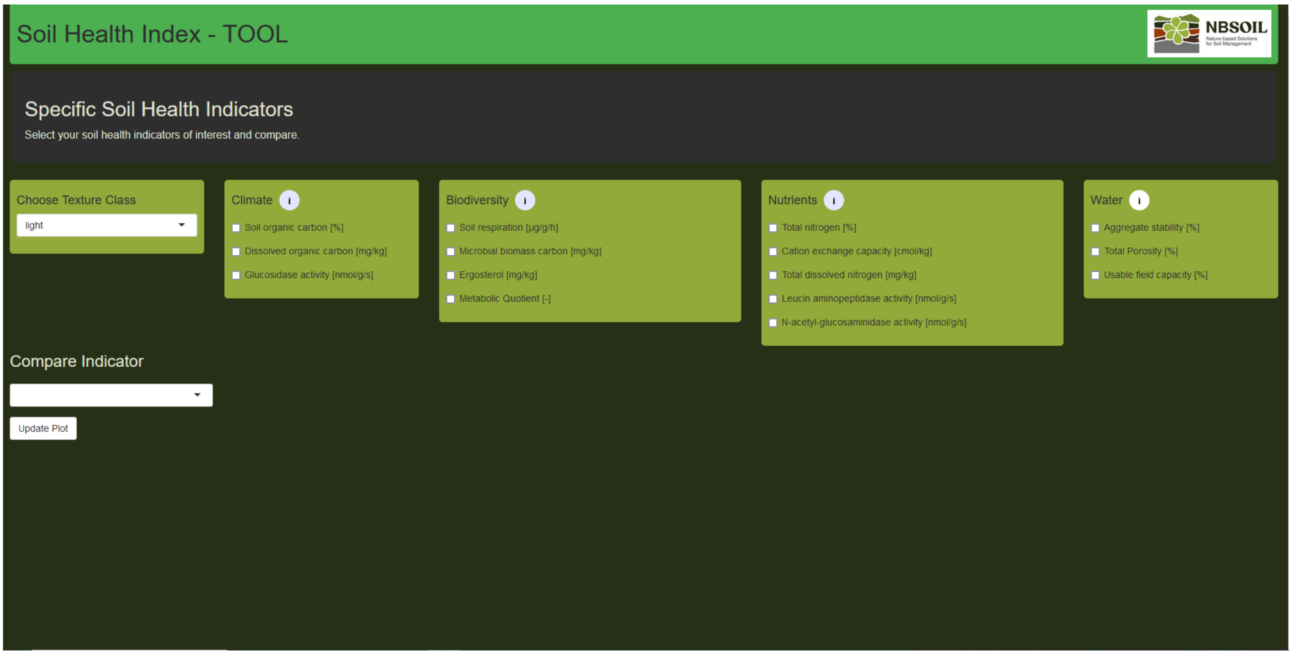

Figure 4. Online soil health index tool (middle version)

3.1 Benchmarking dataset

Assessing soil health requires suitable **benchmarking values** to evaluate a given soil sample in relation to references values that indicate the transition from a sub-optimum to an optimum state via the scoring functions pattern. While established benchmarking values exist for a range of chemical indicators from long-term soil fertilization decision support, novel indicators of high importance for the biological and/or physical state of soil health currently lack such universal benchmarking values. It is expected that upon implementation of the Soil Monitoring and Resilience Directive benchmarks will be defined for several indicators.

Deriving reasonable benchmarking critically depends on the **underlying dataset**: the larger the dataset and the better it represents local conditions (texture, soil type) and the better a given soil sample can be compared to a population of similar pedogenetic background to be ranked within the possible range of indicator values.

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It is mentioned that the specific goal of NBSOIL in Task 2.1 is to build a suitable, advisor-oriented soil health assessment tool. For this purpose, we have to largely rely on existing datasets, while only selected additional data are projected to be measured within NBSOIL for defined demonstration sites. However, the online-tool provides an open approach that allows

(1) **Integration of datasets** from other sources (e.g. other projects related to the Mission Soil implementation) to increase the number of parameters represented as well as the robustness of benchmarking.
(2) **Integration of upcoming benchmarks** into scoring functions (e.g. benchmarks from other national (e.g., SoilPioneers2050) and European projects (e.g., BENCHMARKS), benchmarks define in the course of the Soil Monitoring and Resilience Directive, updated benchmarks with increasing database implemented in the tool).

The characteristics of the dataset used to build the middle version of the project is resumed in Table 1. It originates from on-farm studies about soil health advances at agricultural soils in Austria.

Table 1: Dataset characteristics of the middle version of the Soil health index tool used for benchmarking

Dataset characteristics	Description
Number of entries	63
Geographical region	Austria
Type of soil use	Pairwise measurement of agricultural soil under conventional standard management (n=21), soil health regenerating pioneer management (n=21) and non-agriculturally used reference soil from grass vegetated field margins (n=21)
Range of texture	Clay content from 8.4 % to 51.8 %
Dominant soil types	Chernozem, Cambisol, Luvisol, Stagnosol, Pheaozem, Regosol
Indicators	**Climate** *(carbon cycle):* Soil organic carbon, dissolved organic carbon, Glucosidase activity **Nutrients** *(nitrogen cycle):* Total nitrogen, total dissolved nitrogen, leucin aminopeptidase activity, N-acetyl-glucosaminidase activity, cation exchange capacity **Biodiversity**: Microbial respiration, microbial biomass carbon, metabolic quotient, ergosterol **Water**: aggregate stability, total porosity, plant available water

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The dataset comprises a range of soil chemical, physical and biological properties which are allocated to the respective comprehensive soil functions (climate, nutrients, biodiversity, water). According to the SMAF methodology, selection of indicators for a core data set and their allocation to soil functions follows an expert-based assessment. The approach of the NBSOIL Soil health index tool can be updated for future indicators and functional allocation, taking into account e.g.:

- Available datasets from other EU projects.
- Indicators selected during the implementation of the Soil Monitoring and Resilience directive.
- National and/or European expert panels defining the allocation of indicators to soil functions.

Additionally, the tool can integrate new or emerging data sources, enhancing the adaptability of the model to evolving scientific and policy developments.

Currently there are no indicators that directly represent the soil production function. However, there is potential overlap between the role of certain indicators among soil functions (e.g. plant available water, cation exchange capacity) which are relevant for different soil functions. As SMAF represents an expert-based classification system, the allocation of indicators to functions can be continuously refined and updated through collaboration with stakeholders, ensuring the tool remains relevant and accurate.

Table 2 provides the methodical references for the measured indicators and their data range of the dataset currently used for benchmarking and building the scoring functions.

Table 2. Soil health indicators contained in the dataset, their functional allocation, methodological reference and range of data values.

Indicator	Function	Method	Range
Soil organic carbon	Climate	Elemental analysis	0.8 – 7.6 %
Dissolved organic carbon	Climate	Brandstetter et al. (1996)	11.9 – 192.2 mg kg^{-1}
Glucosidase activity	Climate	Marx et al. (2001)	9.4-1365,6 nmol g^{-1} s^{-1}
Total nitrogen	Nutrient	Elemental analysis	0.04 – 0.81 %
Total dissolved nitrogen	Nutrient	Voroney et al. (2008)	2.5 – 55.3 mg kg^{-1}
leucin aminopeptidase activity	Nutrient	Marx et al. (2001)	22.6 – 925.5 nmol g^{-1} s^{-1}

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N-acetyl-glucosaminidase activity	Nutrient	Marx et al. (2001)	0.7 – 195.7 nmol g^{-1} s^{-1}
Cation exchange capacity	Nutrient	ÖNORM L 1086-1	16.1 – 406.1 cmol kg^{-1}
Microbial biomass carbon	Biodiversity	Chloroform fumigation extraction	36.4 – 587.6 mg kg^{-1}
Microbial respiration	Biodiversity	Rosinger et al. (2025)	0.8 – 7.6 μg g^{-1} h^{-1}
Metabolic quotient	Biodiversity	Anderson and Domsch (1993).	0,002 - 0,043 mg CO_2 g^{-1}
Ergosterol	Biodiversity	Sae-Tun et al. (2020)	1.0 – 118.8 mg kg^{-1}
Total porosity	Water	250 cm^3 soil cores	32.0 – 70.2 %
Aggregate stability	Water	Kemper and Koch (1966)	10.8 – 98.0 %
Available water	Water	Schindler et al. (2010)	8.3 – 25.7 %

3.2 Indicator selection, data input and visualization

For assessing the status of a target soil based on analytical values, a soil advisor first selects the indicators to be considered and a texture class of the site. This selection depends on (1) the available indicators in the benchmarking dataset (for the current version based on a dataset available to the Task lead, *cf.* Table 2) and (2) the indicators that have been measured in the target sample. Figure 5 gives an example: SOC has been selected as the measured indicator representing the climate function of soils and a value of 2.5 % has been measured for the target sample.

As several soil indicators are strongly texture-dependent, the user also selects a texture class (coarse < 15 % clay; medium 15-25 % clay, fine > 25 % clay) to automatically filter the values of the dataset that are used for subsequent benchmarking and scoring according to texture class. More detailed filtering could be considered for larger datasets.

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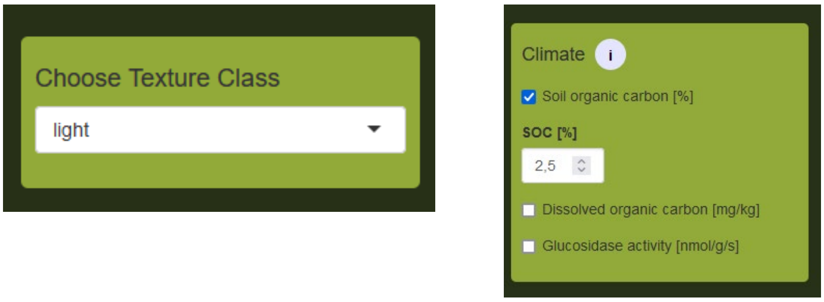

Figure 5. Step 1 chooses a texture class and the respective indicator(s) – example for SOC in light textured soil.

As a first visualization (Figure 6), the user can return a plot of all the data in the respective texture class that are contained in the dataset, ordered from lowest to highest value and showing the location of his sample. This gives a first orientation for evaluating single measurement parameters (indicators) within the range of the values in the dataset.

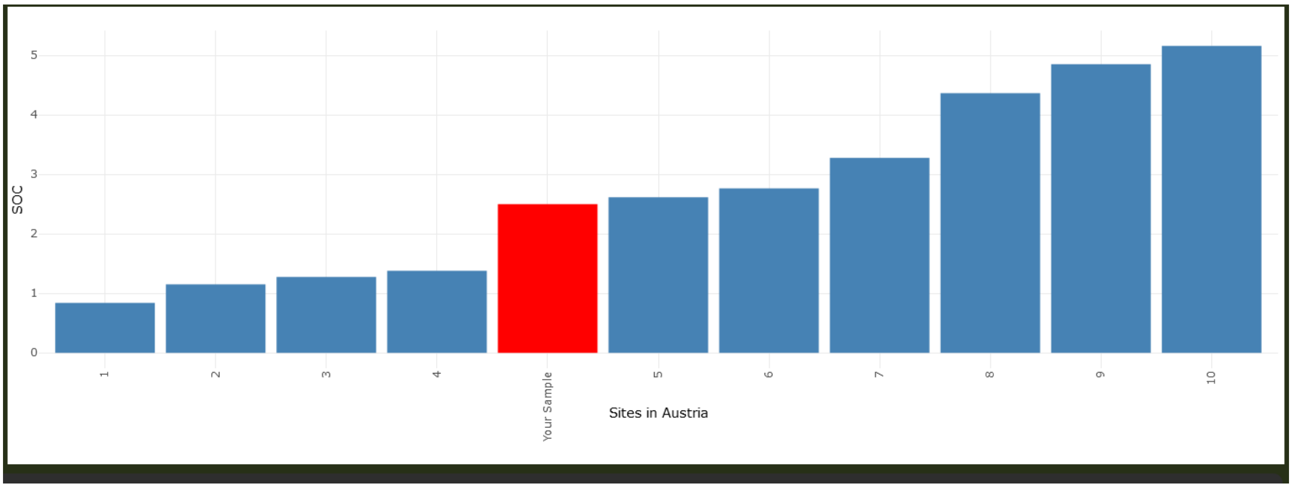

Figure 6. Step 2 shows the value of the user-sample within the range of samples in the database.

3.3 Indicator scoring and visualization of soil health status

The model then calculates a scored indicator value (0-1) according to the SMAF methodology for all the selected indicators. The scaled single indicator values are then summed to scored (0-1) soil functions and are visualized on a radar plot to provide an overview of the state of the respective soil functions base for the target sample (Figure 7). Thereby the user can see the state of the single soil functions for the target field based on his measured indicators.

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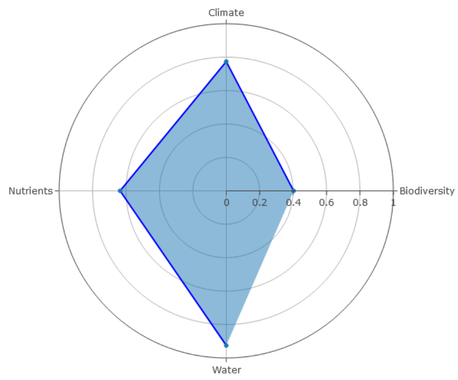

Figure 7. Step 3 shows a radar plot of single soil functions that is obtained by scoring and summing up the single indicators.

Thereafter the single indicators are compiled into an integrated soil health score for all single soil functions based on an additive function of all indicators (see Equation 1) that have been selected and where the user has inserted the individual values of the target sample (Figure 8).

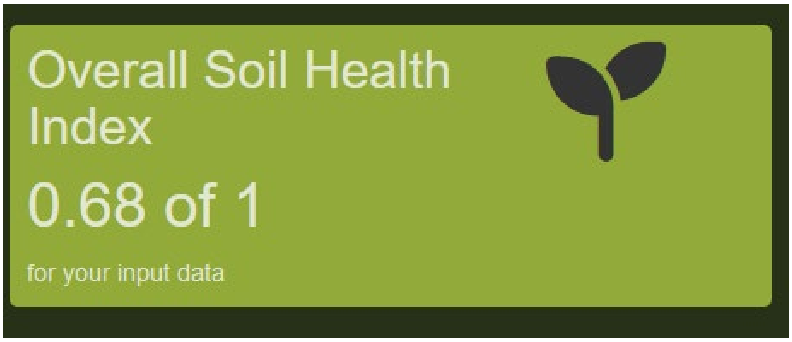

Figure 8. Overall soil health index for the site based on the measured and scored indicators.

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4 Outlook

The methodology of the soil health index tool is fully functional and available online. The next development steps will include:

- **Extension of the benchmarking dataset based on NBS demonstration site**s: Biodiversity is a core soil health indicator (e.g. Fierer et al. 2021; Labouyrie et al., 2023) where still no data are available in the currently used dataset. Similarly, an extension of the dataset towards SOC stability (e.g. Wieser at al., 2024) as well as measures for drought resilience (e.g. Martínez-Fernández et al., 2015) are key for assessing soil health and climate change mitigation and adaptation advances. Therefore, within the scheduled budget for data acquisition within NBSOIL, ***additional data on microbial diversity, SOC pools*** and ***soil moisture for NBSOIL demo sites*** will be gathered and included in the dataset for an improved evaluation of soil functions and demonstration of soil health advances via implementation of NBS measures in demo sites.
- **Integration of LUCAS data for benchmarking:** To extend the benchmarking dataset, ***LUCAS data will be integrated*** into the soil health index tool. Thereby the range of benchmarking values will be extended beyond the national dataset that is currently used. An option will be provided to allow the user selecting between the national and European dataset, thereby facilitating comparison towards regional environments with more similar pedoclimatic characteristics as well as over wider range of ecosystems with a larger span of pedoclimatic feature.
- **Land use type filtering:** Due to the strong impact of land use, a ***filter for land use type*** (agriculture, forestry, grassland, urban, peatland) will be included and made functional for those cases where sufficient data are available for benchmarking of other ecosystems beyond agriculture which are considered in NBSOIL.
- **Use cases:** For the NBSOIL demonstration sites where soil measurement data are available, use cases for evaluating the respective land use and management systems with nature-based solutions will be created and provided to the ***NBS Soil Academy for training purposes***.

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