Towards climate-smart sustainable management of agricultural soils

SERENA Deliverable D2.3.1

Towards a cookbook to evaluate soil threats, soil-based ecosystem services and their associated bundles over scenarios of changes: a first identification of indicators for harmonisation at EU level

Due date of deliverable: M14(35)
Actual submission date: 13.01.2023

GENERAL DATA

Grant Agreement: 862695
Project acronym: EJP SOIL
Project title: Towards climate-smart sustainable management of agricultural soils
Project website: www.ejpsoil.eu

Start date of the project: February 1st, 2020
Project duration: 60 months
Name of lead contractor: INRAE

Funding source: H2020-SFS-2018-2020 / H2020-SFS-2019-1
Type of action: European Joint Project COFUND

DELIVERABLE NUMBER:	D2.3.1
DELIVERABLE TITLE:	Towards a cookbook to evaluate soil threats, soil-based ecosystem services and their associated bundles over scenarios of changes: a first identification of indicators for harmonisation at EU level
DELIVERABLE TYPE:	Report
WORK PACKAGE N:	WP2
WORK PACKAGE TITLE:	Definitions, conceptual Framework, and harmonised methodologies
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REVIEWERS	Sophie Cornu; Rudi Hessel; Erik van den Elsen
DISSEMINATION LEVEL:	CO/PU

Suggested citation:
Montagne, D., Buttafuoco, G., Scammacca, O., Calzolari, C., Pindral, S., Foldal, C., Laborczi, A., Kukk, L., Antón, R., Medina, E., Stefanova, M., Oorts, K., Klimkowicz-Pawlas, A., Niedźwiecki, J., Borůvka, L., (2023). Towards a cookbook to evaluate soil threats, soil-based ecosystem services and their associated bundles over scenarios of changes: a first identification of indicators for harmonisation at EU level. EJP Soil Internal Project SERENA, Deliverable D.2.3.1, 47 pp.

Abstract

In the last decades, there has been a growing awareness that soils are a vital non-renewable natural resource that provide essential environmental, economic and social benefits to society when they are healthy. At the same time, soils are threatened by human activities and are, for most of them, already degraded. This double observation has led to numerous attempts to assess and map either the threats to soils or the ecosystem services they provide to society. However, most of these assessment or mapping exercises have been developed for a specific threat or services, at a regional to national level and independently of each other so that they differ by various ways and their results are poorly comparable or consistent. Methodologies for assessing soil threats and services must first be harmonized in order to provide a consistent vision across Europe that can be used to implement the European transition towards healthy soils. In that objective, this report provides i) a tiered approach for harmonising at EU level the assessment of STs, SESs and their associated bundles; ii) an explicit procedure to score and rank indicators for soil threats and services according to their “scientific soundness”, their “availability” and their “ability to convey information” and finally iii) an application of the ranking procedure to a first subset of indicators used for assessing soil threats and services at EU level. The developed strategy towards harmonization recognised four successive steps of increasing complexity: i) the harmonisation of the framework and definitions; ii) the harmonisation of the indicators for threats and services; iii) the harmonisation of the models used to assess the selected indicators and iv) the harmonisation of the data used to run the selected models. With regard to the harmonisation of indicators, the selection of indicators is more advanced for soils threats than for soil services, probably due to the longer history in assessing soil threats. In any case, this first application of the developed procedure for selecting and harmonising indicators for soil threats and services and its resulting list of indicators for harmonisation still need to be extended to a larger range of threats and services and to indicators used at national or regional levels.

Acknowledgements

The authors gratefully thanks Jessica Reyes-Rojas and Joao-Augusto Coblinski for providing the list of indicators used for assessing soil threats and soil services at the EU level and the corresponding references on which part of this report is based. The authors also gratefully thanks S. Cornu, R. Hessel and E. van den Elsen for helpfully reviewing an earlier version of this report

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 862695

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List of acronyms and abbreviations

AFP	Air-Filled Porosity
CEC	Cation Exchange Capacity
DC	Degree of Compaction
EEA	European Environment Agency
EJP	European Joint Programme
ES(s)	Ecosystem service(s)
EU	European Union
JRC	Joint Research Center
MS	Member State
NEP	Net Ecosystem Productivity
NPP	Net Primary Production
NPPpot	Potential Net Primary Production
NUTS	Nomenclature of Territorial Units for Statistics
OM	Organic matter
RECARE	Preventing and Remediating degradation of soils in Europe through Land Care
RND	Relative Normalized Density
SERENA	Soil Ecosystem seRvices and soil threats modelling aNd mApping
SES(s)	Soil-based ecosystem services

SIREN	Stocktaking for Agricultural Soil Quality and Ecosystem Services Indicators and their Reference Values
SOC	Soil organic Carbon
SS	Soil Stress
ST(s)	Soil threat(s)
WLCC	Wheel Load Carrying Capacity
WP	Work Package

1. Introduction

The Thematic Strategy for Soil Protection (EU 2006) established common principles for soil protection throughout the EU according to which MS will be able to decide how to protect soils as good as possible and how to use them sustainably on their territory. Seven possible threats to soil were defined in the strategy: soil compaction, soil erosion, soil salinisation, soil organic matter decline, landslides, pollution and sealing. The last two threats (pollution and sealing) depend on external factors not related to specific soil conditions and therefore require a general or national protection strategy (European Commission, 2006). Other EU documents have updated the Thematic Strategy for Soil Protection, including the EU Soil Strategy for 2030 (European Commission, 2021), which renewed the European Soil Strategy with the aim of exploiting the benefits of healthy soils for people, food, nature and climate. This renewed Soil Strategy requires the establishment of a framework and concrete measures for the protection, restoration and sustainable use of soil that simultaneously mobilises the commitment of society, makes available the necessary financial resources, shared knowledge, sustainable practices and monitors the achievement of common goals. The EU vision for soil by 2050 is anchored in the EU biodiversity strategy for 2030 (European Commission, 2020) and in the Climate Adaption Strategy (European Commission, 2021) and is aimed at contributing significantly to several objectives of the European Green Deal and Sustainable Development Goal 15.3 (UN 2015). This vision is aimed at achieving that all soil ecosystems are in a healthy condition and hence more resilient to global change and able to provide as many of SESs as possible.

Vulnerability to STs and the capacity of soil to deliver SESs depend on specific environmental conditions, therefore both (STs and SESs) require to be assessed using explicit and appropriate methodologies. There is a rich literature on methodology for assessing STs and SESs. However, there are still large discrepancies in the definitions of STs and ESs, in the indicators used to assess them, in the procedures for assessing such indicators, in the type and origin of the primary data mobilised in these procedures and finally in the spatial (and temporal) extent and resolution at which the STs and ESs are provided (van Beek et al., 2010; Faber et al., 2022). This prevents a consistent assessment of both vulnerabilities related to STs and SESs at the EU level. Achieving the objectives of the EU Soil Strategy, and all those related to it, requires that different methods and procedures of evaluation are comparable and consistent. An easy way forward would be a standardization of methods using identical assessment procedures for every ST/SES in the EU and thus the selection of a single assessment methodology for all MS (van Beek et al., 2010). That is not always possible and, therefore, there is a need for a harmonisation procedure to ensure comparability and consistency of results from different methods (van Beek et al., 2010).

The Task 2.3 of the SERENA project is thus aimed at developing harmonised methodologies to evaluate bundles of soil threats (STs) and soil-based ecosystem services (SESs) at different levels. For this purpose, a global strategy towards the harmonisation of the assessment of STs and SESs at the EU level was first developed (Chapter 3). This strategy includes four successive steps: i) the harmonisation of the conceptual framework for assessment and definitions; ii) the harmonisation of STs and SESs indicators; iii) the harmonisation of methods used in the assessment of STs and SESs indicators, and finally iv) the harmonisation of the input data necessary to use the selected methods. The first step of the proposed approach was extensively addressed in Deliverables D2.1 and D2.2 whose main inputs are briefly summarised below (Chapter 2) and to which the readers are referred for further details. This report develops the second step of the global strategy for harmonisation and is mainly focused on the selection of indicators for the harmonised assessment of a first subset of STs and SESs at the EU level. The process designed to select STs and SESs indicators is described in Chapter 4 and its application to some STs, namely soil organic carbon loss, soil erosion, soil compaction and soil sealing, and to some SESs, namely primary biomass production, greenhouse gas and climate regulation including carbon sequestration, and erosion control is the subject of the fifth chapter.

2. Inputs from other Work Packages, tasks and projects

Task 2.3 activity is largely based on inputs from other SERENA tasks and projects. These inputs are directly related to the contribution of Task 2.3 to the achievement of some objectives of the SERENA project. This can be summarized as follows:

1. Obj. 2.3 (to be dealt with the T2.2 working group): to provide a list of STs and SESs of interest for the SERENA project, with the indicators and thresholds/reference values to evaluate them.
2. Obj. 2.4: to provide a methodology to evaluate bundles at different scales (local, national, European).
3. Obj. 2.5: to provide methodologies to evaluate STs, SESs and their associated bundles over scenarios of change.

2.1. Links between Task 2.3 and other Work Packages and tasks

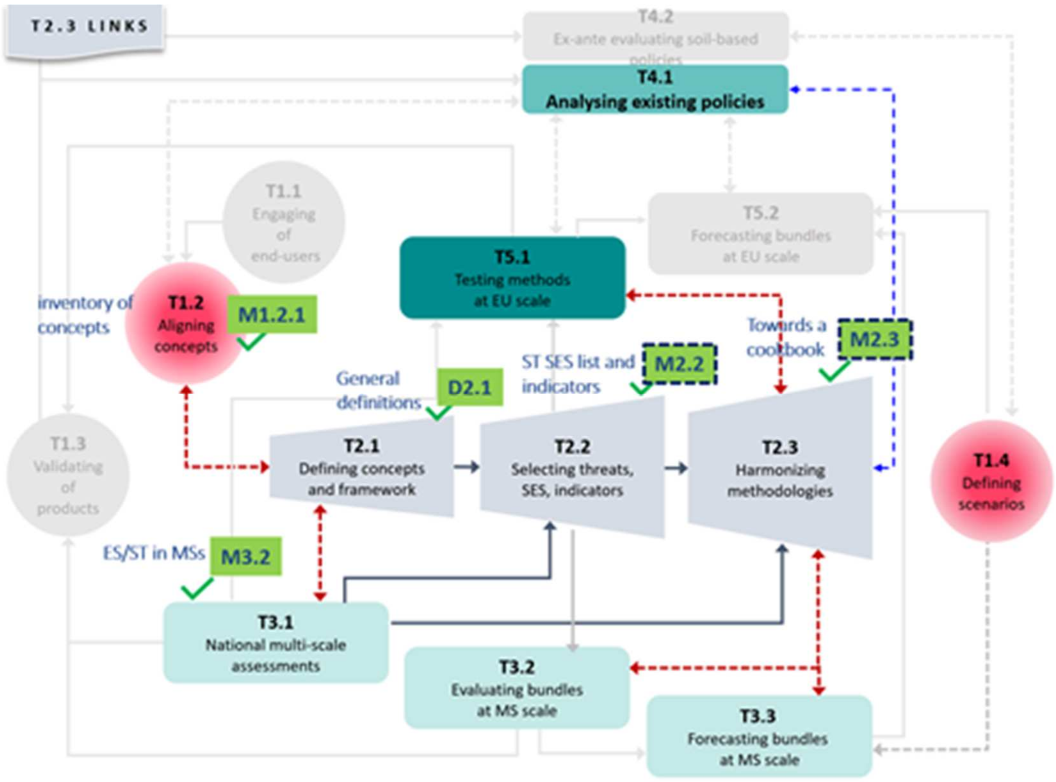

Figure D2.3.1.1: Links between WP2 tasks and other WP tasks

As a task of the WP 3, The SERENA Task 2.3 is directly linked to the task T2.2 (Fig. D2.3.1.1). However, Task 2.3 is indirectly related as well to the inputs of Task 2.1 in relation to the definition of the main

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 862695

concepts used in SERENA and the conceptual framework linking them as reported in the SERENA Deliverable D2.1 entitled "A framework to assess soil threats, soil functions and soil-based ecosystem services" to which the reader is invited to refer as only the main points directly linked to the development of the harmonised methodology are briefly summarised below.

Task 2.3 is also linked to Task 3.1 and Task 5.1 that perform a comprehensive review on existing data (maps, databases, reports, etc.) on STs and SESs in each MS and at the EU level respectively, with the aim of providing a critical analysis of existing experiences at different levels (field/farm, local, regional, national and European).

In turn, Task 2.3 should provide input to Tasks 3.2, 3.3 and 5.1. In particular, Task 3.2 will have to test the indicators for assessing STs and SESs at the MS scale included in the cookbook of harmonised estimation methods produced by Task 2.3. Similarly, Task 5.1 will have to test the same harmonised methods for assessing indicators of STs and SESs at the EU scale.

Task 2.3 is finally closely related to Task 3.3 and Task 5.2 to forecast the effect of change scenarios on the levels of STs and SESs. This will be done particularly for bundles of STs and SESs.

2.1.1. Conceptual framework and definitions: consequences for harmonisation

First of all, being based on the cascade model by Potschin and Haines-Young (2011), the SERENA conceptual framework (Fig. D2.3.1.2) recognised ESs as integral parts of the natural (eco)system. Within the natural system, ESs are distinguished from functions by their direct or indirect, total or partial contribution to human well-being (when combined with other inputs). SESs are finally defined as the subset of the ESs that are directly and quantifiably controlled by the soil physical, chemical or biological properties through the classical production chain: properties, processes, functions and ultimately services. STs are in turn defined as the set of processes able to degrade the soil conditions, their functions and the delivery of (some of) the SESs. According to these definitions, indicators of services have to be clearly distinguished from indicators of soil condition and soil functions whereas indicators of STs have to be distinguished from pressure or impacts indicators.

The SERENA framework also highlights the link between land use and soil management and the supply of the SESs, either through an ameliorative management increasing the soil quality or through an unsustainable management leading to soil degradation. Indicators of STs and SESs are then expected to be responsive to changes in land use and land management. A practical way to ensure the sensitivity of ST and SES indicators to soil use and management is to select indicators that are not only based on inherent soil properties but also on manageable soil properties (Dominati et al., 2010).

Finally, bundles may concern SESs as commonly defined in most of the literature, STs, or the combination of the two and are defined as the STs and SESs that appear together in time or space. Consequently, bundles are not constituted by the a priori selection of STs or SESs whose joint distribution is to be described but by a posteriori selection of the subset of STs and SESs that appear together from the known distributions of individual STs and SESs.

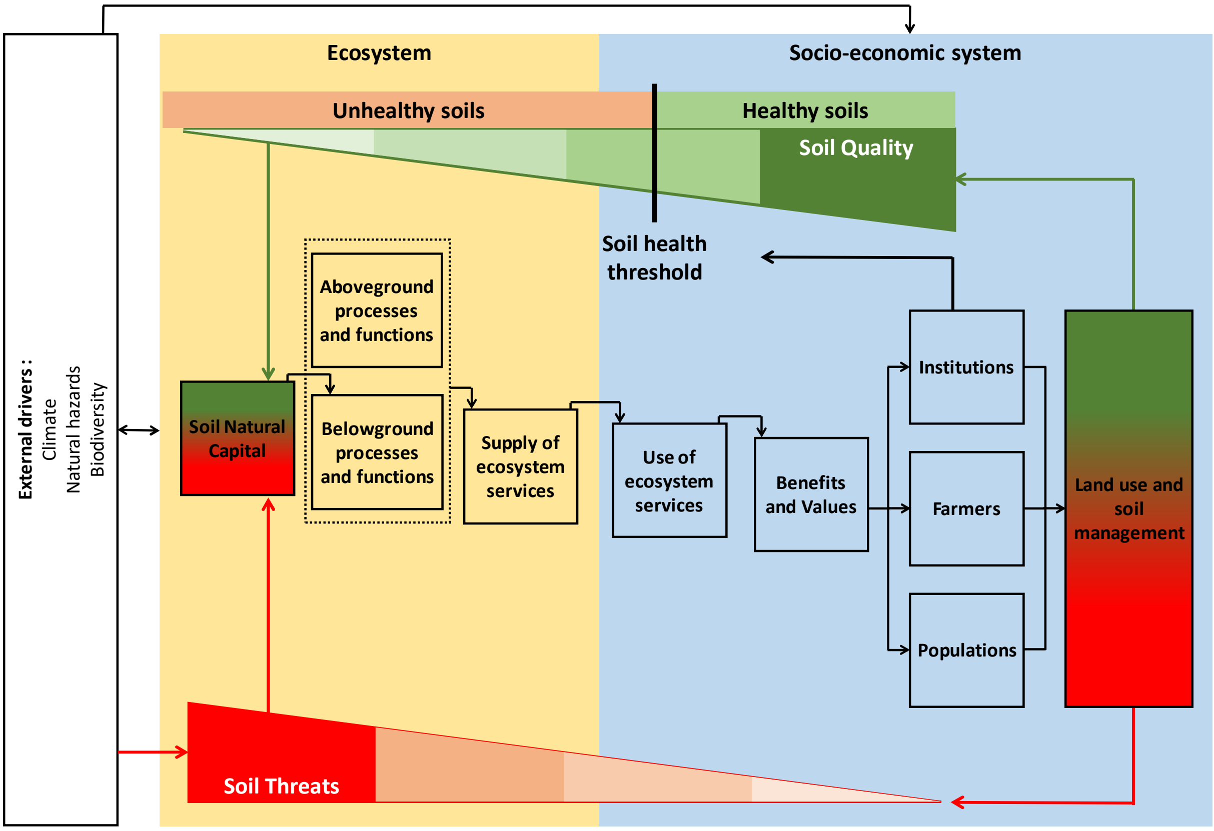

Figure D2.3.1.2: The SERENA conceptual framework under development (23 August 2022 version)

2.1.2. Between interest and implementation at the EU level, the selection of a list of soil threats and soil-based ecosystem services for first implementation in T2.3

Four STs and three SESs have been selected for the development and testing of the indicator harmonisation procedure according to two complementary criteria. The first one refers to the high interest of SERENA's partners for these STs and SESs, as indicated in the D2.2 deliverable. The second one is the identification by T5.1 and T5.2 of previous work that has assessed these particular STs and SESs at EU level. The selected STs and SESs are:

- For STs: soil erosion; soil organic carbon loss; soil compaction; and soil sealing;
- For SESs: primary biomass production; erosion control; and greenhouse gas and climate regulation including carbon sequestration;

However, it is clear that the procedure for selecting an indicator for harmonisation, developed and tested here for a subset of STs and SESs, will be extended to the whole set of STs and SESs of interest in SERENA. Besides the STs and SESs of the highest interest and assessed at least once at the EU level, threats like nutrient imbalance, soil acidification, salinization, soil contamination or loss of soil biodiversity as well as services like water provision and regulation will be considered in the future and integrated in the following milestones and deliverables.

2.2. Links between T2.3 task and other projects

Task 2.3 is closely related to the EJP SOIL Internal Project SIREN that produced a synthesis of policy-relevant soil quality indicators with high potential for harmonised application in national and EU monitoring based on literature, international policy, international stakeholder opinions, wide application in national soil monitoring and EU projects. Moreover, in SIREN a comprehensive conceptual framework linking soil quality to SESs has been developed from the review of scientific literature by unifying various concepts associated with soil quality and SESs.

Other important links are found between Task 2.3 and the project Preventing and Remediating degradation of soils in Europe through Land Care (RECARE) (www.recare-hub.eu). This project was funded by the European Commission FP7 Programme, ENV.2013.6.2-4 'Sustainable land care in Europe'. The most relevant RECARE result for Task 2.3 is the framework developed in the Work Package 2 (Base for RECARE data collection and methods), which provides an overview of existing information on STs and soil degradation at the EU scale. The STs considered by RECARE were: (1) soil erosion by water, (2) decline of organic matter (OM) in peat, (3) decline of OM in minerals soils, (4) soil compaction, (5) soil sealing, (6) soil contamination, (7) soil salinization, (8) desertification, (9) flooding and landslides, and (10) decline in soil biodiversity. Each ST was defined, described, and related to the soil processes involved, the state of the soil degradation by each ST was provided together with drivers/pressures (including climate, human activities, policies) for their occurrence. In addition, key ST indicators and methods for their assessment were listed, along with the effects of each of them on other STs and soil functions.

3. A tiered approach for harmonisation

Developing an assessment of bundles of STs and SESs fully harmonised at the EU level was conceptualized in four successive steps, as described in Figure D2.3.1.3

The first step is to harmonise the conceptual framework and associated definitions. Although the harmonisation of main concepts and specific definitions has long been recognised as a mandatory initial step for harmonisation (Boyd and Banzhaf, 2007; Nahlik et al., 2012), the EJP SOIL Internal Project Stocktaking for Agricultural Soil Quality and Ecosystem Services Indicators and their Reference Values (SIREN, https://ejpsoil.eu/soil-research/siren/) still identified large differences in the definitions of the most commonly used terms (e.g., soil health, soil quality, etc.) or in the definition of individual STs and SES (Faber et al., 2022). In the SERENA project, the harmonisation of the conceptual framework and definitions of related concepts was achieved in task T2.1, while the harmonisation of the definition of the individual ST and SES was achieved in task T2.2.

The second step was to harmonise the indicators used to measure the levels of individual ST and SES, hereafter called STs or SESs indicators. Reflecting the diversity of STs and SESs definitions as well as the diversity of environmental, political and social conditions, or, more simply, the availability of primary data, a huge diversity of indicators is currently used to infer particular ST or SES across countries or, within countries, across regional and local studies (Faber et al., 2022). Such diversity considerably limits the comparability of assessments within or among countries. In that respect, harmonising indicators will increase the comparability of assessments, especially of trends over time. Leaving open the choice and the practical implementation of specific approaches to assess these "harmonised" indicators will allow each country to make the best use of the data and expertise at its disposal. If the variables used to measure specific STs or SESs are supposed to be harmonised at this stage, this is not the case for the interpretation of the indicators that would require the harmonisation of reference and target values. Apart from being impossible to harmonise due to the use of different exact methods, reference and target values should probably not be harmonised but used to reflect the diversity of climatic, soil or land use and management conditions among or within countries.

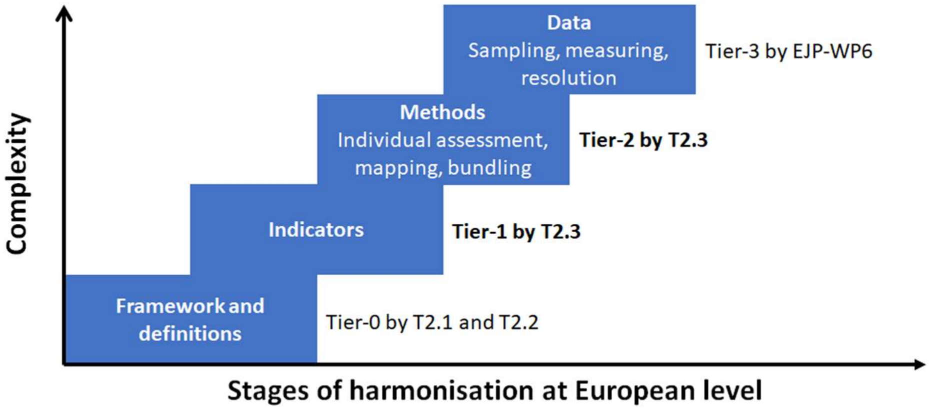

Figure D2.3.1.3: A tiered approach to harmonise the assessment of soil threats and soil-based ES at the EU Level

The third step was to harmonise the tools or methods used for the assessment of individual ST and SES indicators, for the mapping of these indicators as well as methods for the identification (and mapping) of bundles of STs and SESs. At this step, only the tools and models used are harmonised but not the input data used to run these tools and models that are still allowed to vary among or within countries. Such harmonisation of the methods is an important step towards the comparability of actual status of STs and SESs among countries. The main challenge is to find the right balance between complex but potentially accurate approaches and simpler but less accurate approaches (Bagstad et al., 2013).

The final step was to harmonise the input data used to run the tools and models harmonised in the previous step in terms of sampling, analytical methods and spatio-temporal resolution. It is highly unlikely that all countries change their own well-established programme of acquisition and monitoring of primary data needed to maintain long term monitoring of environmental conditions. The set of tools/models selected at the previous stage could, however, be run on datasets harmonised at European or global level, such as the dataset under preparation in Work Package 6 of the EJP SOIL. The development of such a harmonised dataset goes largely beyond the objectives of the task T2.3. Such final step in harmonisation will insure the complete comparability of the status and trends of STs and SESs among countries, but very likely, at the expense of the spatio-temporal resolution achievable in most countries with available data at national scale.

Given that EU countries are moving at different speeds, and with different levels of detail, a fully harmonised methodology for the assessment of STs and SESs at the EU level will inevitably deviate from the most recent scientific advances. On short time scales, the comparison of the fully harmonised methodology with such up to date methodologies will be very helpful to develop comparative studies (Bagstad et al., 2013; Vorstius and Spray, 2015) and ultimately to indicate how the cookbook could be improved. On longer time scales, the preliminary harmonisation of indicators will pave the way for step-by-step refinement of tools, models and spatio-temporal resolutions as capacity is built in the different countries.

4. Towards indicator harmonisation: a procedure for selecting indicators

The first step towards the harmonisation of the individual assessment and mapping of STs and SESs consists in harmonising the indicators used in the individual assessment of ST and SES (Fig. D.2.3.1.3).

It requires: i) to identify potential indicators and; ii) to rank them according to their suitability for a harmonised assessment of STs and SESs at EU level.

4.1. Identifying and listing potential indicators for harmonisation

Table D.2.3.1.1: List of indicators used to assess selected soil threats and soil-based ecosystem services at the EU level (adapted from SERENA T5.1 and T5.2)

Indicator	Unit	Example of references
ST - Soil organic carbon (SOC) loss		
SOC content	kgC kg^{-1}	JRC et al., 2015
SOC stock	kgC ha^{-1}	JRC et al., 2015
SOC stock loss	kgC ha^{-1} yr^{-1}	Grace and Robertson, 2021
ST - Soil erosion		
SOC decrease	kgC ha^{-1} yr^{-1}	Lugato et al., 2016
Gully erosion	Number of occurrences	Borrelli et al., 2022
Soil loss by water (potential)	t ha^{-1} yr^{-1}	Cerdan et al., 2010
Soil loss by water (actual)	t ha^{-1} yr^{-1}	Panagos et al., 2020
Soil loss by wind	t ha^{-1} yr^{-1}	Borrelli et al., 2017
Soil loss by crop harvesting	t ha^{-1} $harvest^{-1}$	Panagos et al., 2019
Soil loss by water and tillage	t ha^{-1} yr^{-1}	Van Oost et al., 2009
ST - Soil compaction		
Wheel load carrying capacity	kN	Lamande et al., 2018
Soil stress	kPa	Lamande et al., 2018
Degree of compaction	%	Piccoli et al., 2022
Relative normalized density	%	Piccoli et al., 2022
Air-filled porosity	%	Piccoli et al., 2022
ST - Soil sealing		
Degree of soil sealing	%	
Imperviousness	%	EEA, 2018
Land take	km^2	EEA, 2021
SES - Greenhouse gas and climate regulation including carbon sequestration		
Net ecosystem productivity	kgC km^{-2} yr^{-1}	JRC et al., 2011
Carbon offset	%	Schulp et al., 2012
Carbon stocks (in living materials)	kgC ha^{-1}	JRC et al., 2011
SES - Primary biomass production		
Potential net primary production	kg (dry matter) ha^{-1} yr^{-1}	Mayer et al., 2021
Used biomass harvest	kg (dry matter) ha^{-1} yr^{-1}	Mayer et al., 2021
Proportion of biomass harvest	%	Mayer et al., 2021
Energy output from agricultural biomass	J ha^{-1} yr^{-1}	Mouchet et al., 2017
Volume of stemwood	m^3 km^{-2} (forest) yr^{-1}	Mouchet et al., 2017
SES - Erosion control		
Capacity of vegetation to reduce erosion risk	dimensionless	Schulp et al., 2012
Decrease of erosion risk by vegetation	dimensionless	Schulp et al., 2012
Capacity of ecosystem to avoid soil loss	dimensionless	Rendon et al., 2022
Total amount of soil not eroded	t ha^{-1} yr^{-1}	Rendon et al., 2021
Surface area of natural vegetation with a function of erosion control	ha (weighed by erosion risk) ha^{-1} (NUTS area)	JRC et al., 2011
Surface area of forest with a protective function		Holting et al., 2019

The identification of potential indicators for STs and SESs was done in three successive steps. As a first step, only the indicators already used to map STs or SESs at EU level were considered. Indeed, by

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definition, these indicators met two important criteria for indicator selection (Rendon et al., 2022): they are quantifiable (i.e., they can be quantified from available existing data in Europe) and available [i.e., they are either spatially explicit or available at NUTS (Nomenclature of Territorial Units for Statistics) (EU, 2020) 2 level maximum]. Assuming that these indicators also fulfil criteria such as relevance (i.e., they adequately quantified the threat or service of interest according to its specific definition) or communicability (see Table D2.3.1.2 for the full list of criteria) and that the models currently used to quantify them at the EU level are relevant, the assessments at EU level of these STs or SESs can be considered as "ready-to-be-harmonised" data. The indicators used, at least once, for the assessment of the STs and SESs of interest in SERENA have been reviewed and listed by T5.1 and T5.2 (Table D2.3.1.1).

While this first list contains a significant diversity of potential indicators for some STs (e.g., soil erosion) or SESs (e.g., biomass production or erosion control), only a few indicators could be identified for other STs (e.g., soil organic carbon loss or soil sealing) or SESs (e.g., the greenhouse gas and climate regulation including carbon sequestration). This list of indicators used for the assessment at EU level of STs and SESs will be complemented in a second step with indicators used at national level by the different MS involved in the SERENA project. The indicators used at the national level in the different MS involved in the SERENA project have already been stocktaken by T3.1. If none of the indicators currently used in the assessment of STs and SESs at the EU or MS levels are selected to be the “harmonised indicator” at the EU level, an in-depth literature review will be carried out by T2.2 and T2.3 in order to complement the first two lists with indicators used at sub-national levels and/or outside MS involved in the SERENA project.

This deliverable only deals with the first list of indicators, i.e., indicators already used at EU level. Indicators used at the national, sub-national levels and/or outside MS States involved in the SERENA project will be successively taken into account in the following milestones or deliverables in order to cover the full range of STs and SESs of interest in SERENA. It is however highly likely that their application at the EU level will be all the more limited as these indicators have been developed for small areas.

4.2. Development of a framework for indicators’ ranking

A template was developed to score and rank the indicators selected for each ST and SES according to multiple criteria (Table D2.3.1.2). The development of the template was based on the existing literature (OCDE, 2002; Feld et al., 2010; Layke et al., 2012; Muller and Burkhard, 2012; van Oudenhoven et al., 2012; Faber et al., 2013; Stone et al., 2016; van Oudenhoven et al., 2018; Thakur et al., 2022) in order to highlight the main criteria currently used by the scientific community to select and assess the suitability of indicators to provide information related to a given SES or ST. For instance, Layke et al., (2012) propose two main criteria to evaluate the adequacy of indicators: i) the availability of data that should fit multiple spatio-temporal scales, be accessible and normalized; ii) the ability of the indicator to convey information, which means that the indicator should be intuitive, sensitive and widely accepted. Other authors suggested the importance of the object represented by the indicator, which can for example refer to the supply of the service, its use, demand or interests by human societies (Geijzerdorffer et al., 2017). Finally, van Oudenhoven et al., (2012 and 2018) proposed exhaustive lists of multiple criteria, which also integrate as well the importance of stakeholder’s and user’s objectives, focusing on the flexibility and inclusivity of the selection process of the indicators.

A total of seven criteria divided in three main families were finally selected (Table D.2.3.1.2):

1. **Scientific soundness**. This family of criteria estimates the adequacy of the representation of the targeted object according to three complementary criteria: i) the scientific adequacy and suitability of the indicators in fitting the purpose and object of the assessment (fitness-to-purpose, 1); ii) the possibility and ease of spatial and temporal comparison (interpretability, 2); and iii) the sensitivity to changes in external conditions (sensitivity, 3);
2. **Availability of data**. It estimates the feasibility of using a particular indicator according to two criteria: i) the availability and measurability of the indicator (measurability, 4); and ii) the existence of past applications of the indicator, especially at the EU level (scalability, 5);
3. **Ability to convey information**. It estimates the suitability of the indicator to the objectives that stakeholders expect from its application. This is assessed through two criteria: i) understandability of the indicator by various stakeholders (intuitivity, 6); and ii) their implementation in current environmental policies (policy-relevance, 7).

Scoring levels ranging from 0 (i.e., lowest score) to 12 (i.e., highest score) were finally defined for each of these indicators. The 0 to 12 scale was chosen to give the same weight to all the criteria classified on 3, 4, 5 or 6 different levels. For instance, the score corresponding to the fitness of a SES indicator varies whether the indicator refers to a soil condition (score 1), an ecosystem function (score 4), an ecosystem good or impact (score 8), the capacity of the ecosystem to deliver the considered SES (score 10) or the actual flow of SES (score 12). As another example, if the indicator is not measurable, a score equal to zero will be attributed to it, while if it is modellable, indirectly measurable, directly measurable or measurable, scores of 3, 6, 9, 12 respectively will be associated to it.

This list of criteria and their corresponding levels have been consolidated through a continuous improvement loop. A first list of criteria and levels was proposed and tested by a small group of reviewers. The criteria and their levels were then individually discussed within the T2.3 working group according to the feedbacks from the first reviewers, synthesized and traced in a “reporting” sheet. Once validated, three to seven different volunteers from the T2.3 working group individually ranked the different indicators used to assess each selected ST or SES against the final list of criteria and corresponding levels. To limit subjectivity, discussions were held between the evaluators of each ST and SES to share their understanding and to limit inconsistencies among individual ratings. Finally, for each criterion, a mean value of the scores provided by each reviewer was obtained. The indicator scores were finally represented graphically through radar charts to better identify the “weak” and “strong” features of each indicator.

Table D.2.3.1.2: A template for ranking ST/SES indicators for use at EU scale, criteria, levels, and scores

Family	**Criterion**		**Level**		
	Name	**Description**	**Score**	**Name**	**Description**
Scientific soundness	**Fitness-to-purpose**	Rate the nature of the object targeted by the indicator considering that SERENA aims at quantifying STs and SESs	0	Other	ST: the indicator represents objects other than the following SES: the indicator represents object other than the following
			1	Condition	ST: the indicator represents current soil conditions SES: the indicator represents current soil conditions
			4	Driver	ST: the indicator represents the drivers/pressures controlling the considered ST
				Function	SES: the indicator represents an ecosystem function that do not, or only indirectly, benefit to humans
			8	Impact	ST: The indicators represent an impact of the considered ST on particular ecosystem conditions or functions
				Good	SES: The indicator represents tangible (goods) or intangible (benefits) ecosystem outputs combined with built, human or social capitals
			10	Capacity	ST: The indicator represents the potential risk for a threat under current conditions and type of use SES: the indicator represents the potential of the ecosystem to deliver a service (i.e. the contribution of the natural system to human well-being before the addition of built, human or social capitals) under current conditions and type of use
			12	Flow	ST: the indicator represents the actual risk for a threat under current conditions and type of use. SES: the indicator represents the amount of a service (i.e. the contribution of the natural system to human well-being before the addition of built, human or social capital) used or experienced by people under current conditions and type of use.
	Interpretability	Rate how the variable is expressed according to the possibility and the ease of spatial and temporal comparison and interpretation	0	Categorical	Variables that can have two or more categories without systematic ordering within these categories
			4	Semi-quantitative	Ordered categorical or quantitative variable but on an arbitrary scale
			8	Quantitative	Quantitative variable
			12	Referenced	Quantitative variable for which reference, thresholds or target values are politically or scientifically defined

	Sensitivity	Rate the sensitivity of the indicator to changes in climate, soil, use and/or management conditions	0	No	The assessment of the indicator does not depend on climate, soil, land-use and land-management conditions
			3	Limited	The assessment of the indicator depends on one of the conditions mentioned
			6	Moderated	The assessment of the indicator depends on any combination of two of the four conditions mentioned
			9	High	The assessment of the indicator depends on any combination of three of the four conditions mentioned
			12	Full	The assessment of the indicator depends on all the conditions mentioned
Data Availability	**Measurability**	Rate the availability of the indicator into formats widely used and made available for easy access. When not available, it rates the possibility and the ease in measuring the indicator	0	No	Variables not contained in databases, that cannot be measured with adequate resolution in space and time or mechanistically modelled
			3	Modellable	Variables not contained in databases, that cannot be measured with adequate resolution in space and time but that can be mechanistically modelled
			6	Indirectly measurable	Variables not contained in databases but that can be measured through proxy or remote sensing approaches
			9	Directly measurable	Variables not contained in databases but that can be directly measured at an adequate resolution in space and time
			12	Measured	Variable currently available in databases
	Scalability	Rate the current applications of the indicator from local to EU levels and, when applied at the EU level, the type of spatial and temporal coverage	0	Local (< 1,000 km^2)	The indicator has been applied in local studies but seems difficult to apply at the EU level (in the framework of the SERENA project)
			3	Regional (1,000 - 100,000 km^2)	The indicator has been applied in regional studies but seems difficult to apply at the EU level (in the framework of the SERENA project)
			6	National	The indicator has been applied in national studies but seems difficult to apply at the EU level (in the framework of the SERENA project)
			9	European (limited)	The indicator has been applied at the EU level but its application is limited by data availability to particular time periods and/or particular level of aggregation (physiographic, land-use/land cover, administrative unit, etc.)
			12	European (full)	The indicator has been applied at the EU level, is spatial exhaustive (no spatial division) and refers to one of the last five years (at least)
Ability to convey information	**Intuitivity**	Rate the understandability of the indicator by policy	0	Low	The indicator is not understood by policy makers or non-technical audiences
			6	Moderate	The indicator is understood by policy makers or non-technical audiences but ambiguity remains

	makers and non-technical audiences	12	High	The indicator is easily and clearly understood by policy makers or non-technical audiences
Policy implementation	Rate the current use of the indicator for addressing the key environmental issues faced by governments and other stakeholders (according to WP4)	0	No	The indicator is not implemented in the environmental policies of any of the MS
		4	National	The indicator is implemented in the environmental policies of few MS (from one to five)
		8	Sub-European	The indicator is implemented in the environmental policies of a large number of MS (more than five)
		12	European	The indicator is implemented in the EU environmental policies or in most of the MS (all minus a maximum of five)

5. The ranking of soil threats and soil-based ecosystem services indicators.

5.1. Soil threats

5.1.1. Soil organic carbon loss

According to D2.2, Soil organic carbon (SOC) loss is defined as the decrease in soil organic carbon stocks or content of specific soil layers.

It is considered as a key soil threat in EU that influence both food security and climate change (European Commission, 2021). Due to the dynamic changes in the environment throughout the year, the method of assessment of SOC loss should be harmonised. According to Stolte et al. (2015) the SOC loss should be considered slightly different in mineral and organic soils.

The biggest losses of SOC are observed in peat soils being under agricultural use. They are affected by the drainage (causing oxidation), degradation of its natural structure or devastation linked to the peat excavation. The mineralization of organic soils (Histosols) lead to the large decline of OM. For the EU organic soils, the losses can be equal 10–20 tonnes OM per hectare per year and these negative changes cause emissions of CO_2 up to 20–40 tonnes of CO_2 per hectare per year (Stolte et al., 2015). This is why all the MS should include organic soils as protected areas to limit their degradation and devastation.

For the mineral soils, the proper soil management techniques should be applied to prevent SOC loss. In previous years, SOC losses in cropland were reported in many MS (e.g. Fantappié et al., 2011; Goidts and van Wesemael, 2007; Heikkinen et al. 2013). The intensive agriculture and unsustainable land management is the biggest cause of the SOC loss in EU soils. The main drivers of this threat can be soil tillage, leaving soils as a bare fallow, using too many mineral fertilisers and not enough organic fertilizers, using too much pesticides, applying simple crop rotation, deforestation, or biomass burning, (Stolte et al., 2015).

Several indicators have been already used to assess the soil organic carbon loss:

- **SOC content** (g C kg^{-1})

SOC contents are the simplest and one of the most frequently used indicators for assessing SOC loss threat (Joint Research Center et al., 2015). Measures of SOC contents are indeed relatively cheap and easy. Moreover, various databases containing SOC contents can be mobilised to prepare maps of SOC content at various scales among which, the GEMAS agricultural soil database (Reimann et al. 2014a, 2014b), LUCAS database (Fernandez-Ugalde et al. 2022), OCTOP topsoil SOC content database (Jones et al. 2005), etc. However, SOC contents are mainly available for topsoil horizons, are measured on various depths as for example 0–20 or 0–30 cm (Fernandez-Ugalde et al. 2022; Jones et al. 2005; Panagos et al. 2013) or with various analytical methods.

- **SOC stock** (kg C ha^{-1}).

SOC stocks are another common indicator for assessing the soil organic carbon loss. SOC stocks are generally estimated according to Wiesmeier et al., (2012):

$$SOC_{stock,soil} = \sum_{i=1}^{n} \left\{ SOC_i \; x \; BD_i \; x \; h_i \; x \; \left(1 - \frac{SC_i}{100}\right) \right\}$$

where, $SOC_{stock,soil}$ is the total SOC stock (g m^{-2}) of the *n* soil horizons considered, SOC_i is the SOC content (g kg^{-1}) of the fine earth of horizon *i*, BD_i is the bulk density (kg m^{-3}) of the fine earth of horizon *i*, h_i is the thickness (m) of horizon *i*, and SC_i is the volumetric fraction of coarse fragments of horizon *i*. The assessment of SOC stocks requires several soil parameters in addition to SOC contents, including the bulk density, which is rarely measured directly but estimated using various pedotransfer functions (Wiesmeier et al., 2012). Similarly to SOC contents, the estimation of SOC stocks is generally limited to 30-cm depth although the amount of SOC stored deeper easily exceeds 50% (Wiesmeier et al., 2012).

- **Change in SOC stock** (kg C ha^{-1} yr^{-1})

The change in SOC stocks is generally estimated using one of the numerous SOC dynamic models as for example SOCRATES (King et al. 1997; Grace and Robertson 2021), Century (Smith et al. 2009), RothC (Bleuler et al. 2017; Farina et al. 2016) or others. Such modelling usually requires a lot of input data including climatic data (temperature, precipitations…), soil data (clay and SOC contents, pH, Cation Exchange Capacity (CEC) etc.) as well as land use and land management data. As for the previous indicators, changes in SOC stocks are modelled for topsoil horizons (0–30 cm) with a designated time frame (e.g. 20 years).

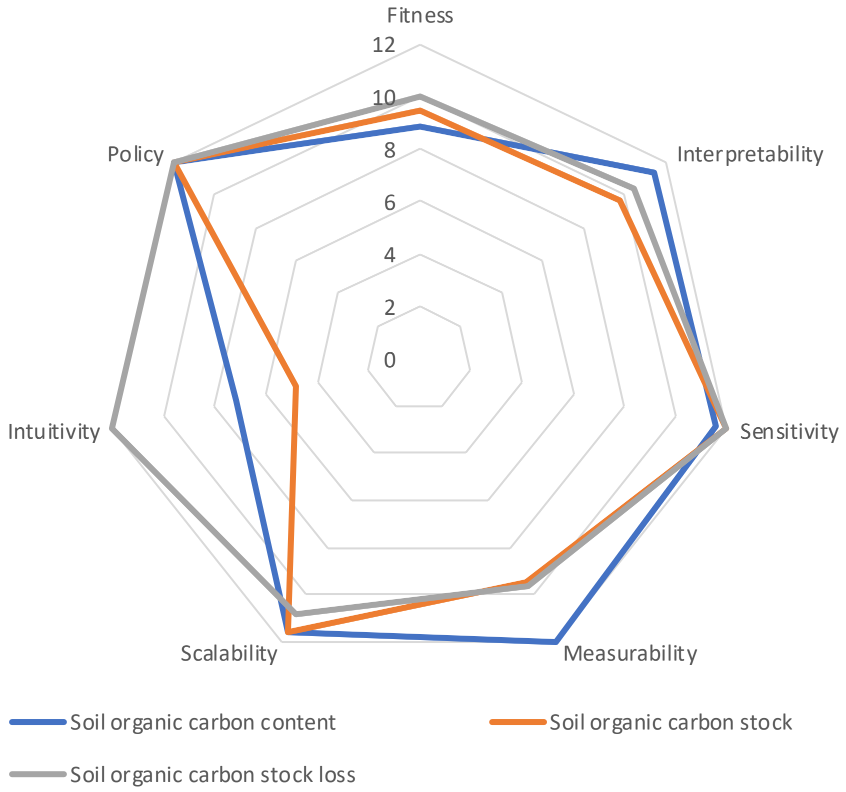

Figure D2.3.1.3: Radar chart summarizing the results of indicators ranking for soil organic carbon loss

Due to the conducted evaluation of indicators, all presented indices are well fitted for the SOC losses calculation (Fig. D.2.3.1.3.). Based on the relatively high scores in most of the evaluated aspects (mean scores from 10 to 12) we can conclude that the listed indicators are good enough to be used in further work. The indicator rating however underlines a balance between fitness and measurability. Indeed, the change in carbon stocks most closely represents the threat of soil organic carbon loss but has a difficulty in measurability due to the complexity of input parameters and datasets requirements. On the opposite, carbon contents are easily measurable, already contained in various databases, but represent the result of soil organic carbon losses cumulated over time rather than the knowledge of present soil organic carbon loss. In addition, while these indicators may be equally useful in assessing SOC loss, the choice of one or the other will ultimately affect the relationships between SOC loss and other threats and services. Indeed, while SOC contents in topsoil horizons are expected to be closely (positively or negatively) related to other STs such as soil compaction and soil erosion or to SESs such as biomass production and control of erosion, changes in SOC stocks over the entire soil depth may be more related to greenhouse gases and climate regulation.

All mentioned indicators can be calculated using the LUCAS database. There is a difficulty in SOC stock calculation due to the lack of soil bulk density data at the EU scale. This can be solved by the application or creation of pedotransfer functions for the bulk density estimation based on other soil properties (texture, water condition, SOC content, soil types, etc.). Considering SOC stock, harmonised methodology for inclusion of coarse fragments at EU scale is required. Also, there is a variation in actual soil depths to be considered in SOC stock modelling. Therefore, there is a significant level of uncertainty in modelling SOC stock and it`s change at EU scale due to different modelling approaches (incl. pedotransfer functions) and/or uncertainties in the input datasets. It is important that one model and methodology will be proposed in the cookbook for SOC stock calculations for all partners of SERENA.

The LUCAS database is a good starting point for Europe but for some countries there are not enough LUCAS points for a correct estimation of SOC contents and stocks. In many countries, additional data are available on SOC contents and SOC stocks. It is important to take these data into account for the estimation of the SOC loss in Europe.

5.1.2. Soil erosion

According to D2.2. soil erosion is a soil degradation process consisting in the detachment, disintegration and transport of soil particles by erosive agents, such as water (water erosion), wind (wind erosion), ploughing (erosion by tillage) or ice (glacial erosion).

Soil erosion is considered a very important soil threat among most SERENA member states, and it is regarded as a regional problem, especially in hilly regions with loamy soils. The concern involves either the on-site (e.g., loss of SOC and fertility) and off-sites effects (e.g., reservoir siltation) of erosion.

Various erosion types exist, depending on the main drivers, water, wind or tillage, mostly acting in combination. Also, other soil erosion processes are important at more limited scale, such as soil erosion due to crop harvesting, erosion by piping and by snow melt, among others. Extreme events and droughts have a major impact on erosion processes and on their extent, which poses substantial concerns when climate change scenarios are considered. Sustainable agricultural management practices can reduce, mitigate or solve soil erosion impacts. On the other hand, unstainable practices may exacerbate the problem. Whatever the erosion type considered, soil erosion is usually measured in tons (or Mg) per hectare per year.

USLE-based models, i.e., models using the Universal Soil Loss Equation (USLE) concept or incorporating USLE factors, are the most popular for assessing water erosion, including USLE, RUSLE, WATEM/SEDEM among others. These have been widely used at every scale, included the EU one, with differences in used databases and in models for estimating the USLE equation factors (Borrelli et al., 2021).

The amount of soil loss per year by water erosion, sheet and rill, is a pertinent indicator of erosion threat as it allows estimating actual risk (and potential either) of the ST given the current conditions. The indicator is easily interpretable as continuous values are estimated which allows setting thresholds, tailored to local conditions and policy needs, and has a good sensitivity considering all the environmental conditions (climate, soil, land use, land management). However, this depends on data availability that can be limited for example for land management. As it has been widely used at every scale, the indicator is well known, understandable and used to a certain extent at political level. USLE type models do not estimate gully erosion, and only one approach has been applied at EU scale so far, based on visually assessed gullies associated to LUCAS monitoring sites. This restricts the possibility to use the approach for modelling the ST due to lack of reliable data in many MS. Neither is deposition modelled in USLE type models, but this can be overcome either by coupling them with sediment transport routines, or by making an assumption on delivery ratio (e.g. Borselli et al., 2008).

The examples of wind erosion assessments are less numerous in Europe and limited to specific areas. This implies a minor intuitivity of the estimates and minor consideration in MSs policies. The same applies to soil loss due to harvesting or tillage erosion.

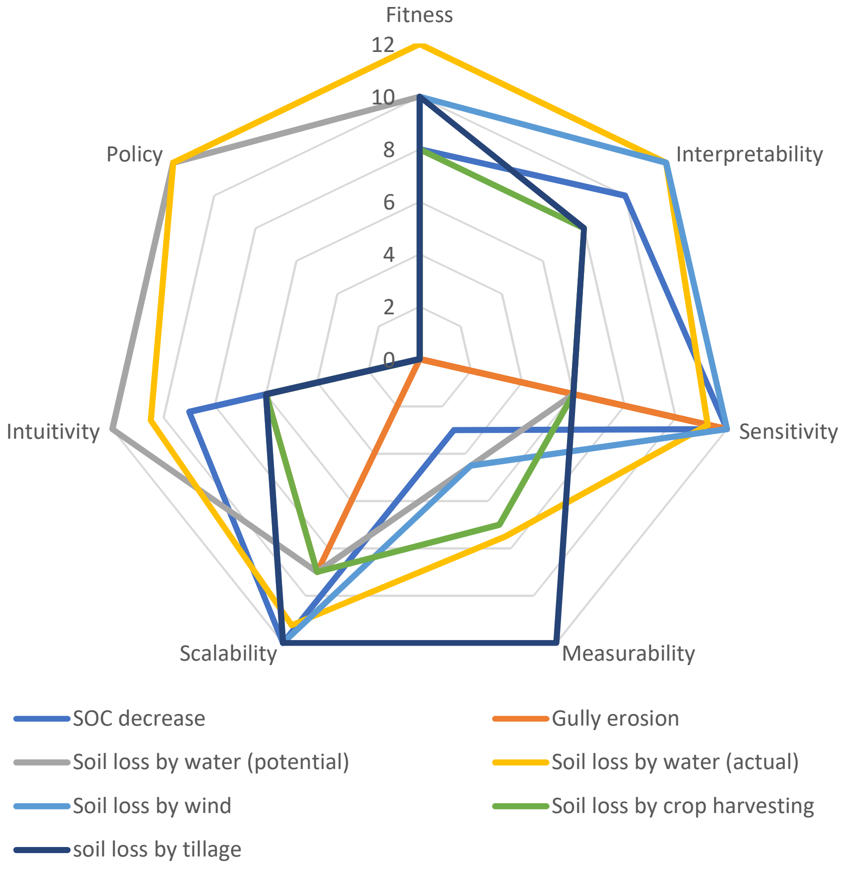

Figure D2.3.1.4: Radar chart summarizing the results of indicators ranking for soil erosion.

Soil loss by water has been subject of numerous studies and applications all around Europe. The models used for assessments are consolidated and databases exist for USLE factor estimations (used also in WATEM/SEDEM models). Several examples exist also at EU scale, together with relevant available databases. The suggestion is to concentrate on water erosion, using well tested models (possibly including deposition modelling) and the best available databases for the estimation of the erosion factors. Wind erosion assessment, which is an important soil threat in several European areas, could be associated in sensitive areas.

Worth to be noted is the forthcoming project by the FAO- Global Soil Partnership, which aims to assess soil erosion (water, wind, tillage) on a global scale. As GSP members have been invited to participate in the project, the GSP cookbooks could be used as such or modified within SERENA project.

5.1.3. Soil compaction

According to D2.2, soil compaction is defined as the densification and distortion of soil by which total and air-filled porosity are reduced, causing deterioration or loss of one or more soil functions.

Soil compaction is manifested by an increase in bulk density. Some soil horizons may be naturally compacted. For example, subsoil horizons have commonly a higher bulk density than topsoil horizons. Human-induced compaction is caused by frequent traffic with machinery of increasing weight or by the trampling of animals. It is problematic as soil compaction is hardly visible, cumulative and persistent, especially in subsoil horizons that are not loosened by tillage.

Two indicators linked to the assessment of soil compaction at the EU level have been identified: the soil stress (SS) and the wheel load carrying capacity (WLCC) (Lamandé et al., 2018). In addition, three supplementary indicators, namely the degree of compaction (DC), the relative normalized density (RND), and the air-filled porosity (AFP) have been used by Piccoli and co-authors (2022) to estimate soil compaction at five sites across Europe.

The **soil stress** (SS, kPa) is the pressure applied on the soil by machinery. It is estimated from the stress distribution at soil contact and the stress propagation in depth (Lamandé et al., 2018), which are predicted from machinery characteristics and by the Söhne summation procedure respectively (Lamandé et al., 2018).

The **wheel load carrying capacity** (WLCC) is the maximum wheel load, expressed in kN, that can be carried by a specific machinery without inducing permanent soil deformation. It is computed from a comparison of soil stress with the inherent susceptibility of soil to compaction, called soil strength, at 0.35 meter deep and for a soil water potential of –50hPa (Lamandé et al., 2018). The soil strength was estimated from the clay content and the dry bulk density using the pedotransfer function established by Schjønning and Lamandé (2018).

The **degree of compaction** (DC, %) and the Relative Normalized density (RND, %) measure the ratios, expressed in percent, between the field bulk density and a reference bulk density (Piccoli et al., 2022). For the degree of compaction, the reference bulk density is derived from the pedotransfer function established by Keller and Håkansson (2010). For the relative normalized density, it is 1.6 g cm^{-3} for soils with a clay content up to 16.7 % or the bulk density estimated with the pedotransfer function of van den Akker and Hoogland (2010) when the clay concentration is higher.

Finally, **the air-filled porosity** (AFP, %) is calculated as the difference between the total porosity and the volumetric water content at the time of sampling

Among the identified indicators of soil compaction (Fig. D2.3.1.5), none assesses the threat of soil compaction directly. The soil stress (SS) measures the pressure applied to the soil, the wheel load carrying capacity (WLCC) measures the threshold above which there is a risk of permanent soil compaction, the degree of compaction (DC) and the relative normalized density (RND) measure the current state of compaction and the air-filled porosity measures the soil condition at the time of sampling (Fig. D2.3.1.5, Fitness-to-purpose).

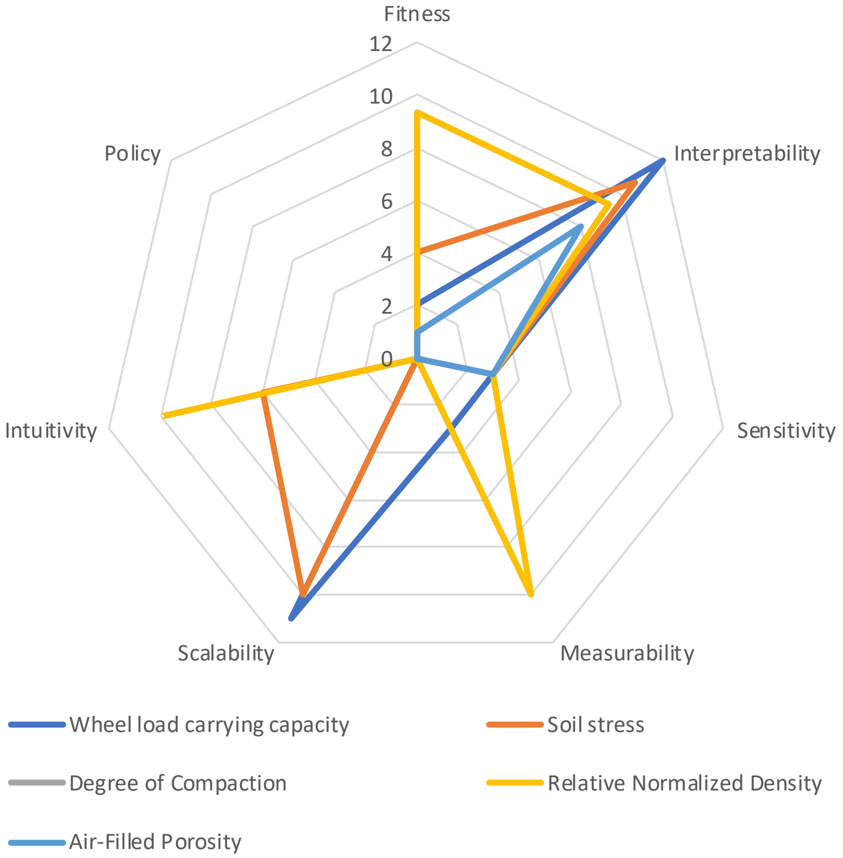

Figure D2.3.1.5: Radar chart summarizing the results of indicators ranking for soil compaction.

Measuring the cumulative impact of past soil compaction and remediation practices, DC and RND are the two indicators most closely related to the ST “soil compaction”. Although all these indicators are quantitative and various reference, threshold, or target values have been defined for most of them (Fig. D2.3.1.5, Interpretability), these values are generally not applicable to all pedoclimatic conditions especially for the DC, RND and AFP indicators (Piccoli et al., 2022). Being calculated from machinery characteristics (SS, WLCC) or from soil characteristics like soil bulk density (WLCC, DC, RND, AFP); clay, silt or sand contents (WLCC, RND, DC); or OM contents (DC), these indicators are sensitive to change in soil conditions but cannot be used to predict the impact of changes in climate, soil use, or soil management conditions with the exception of machinery changes for SS and WLCC (Fig. D2.3.1.5, Sensitivity). To our knowledge, these indicators are not contained in classical databases (Fig. D2.3.1.5, Measurability). The dry bulk density, which is involved is the computation of WLCC, DC, RD, and AFP, is easily measurable. However, it is highly unlikely that bulk density will be measured with sufficient spatial and temporal coverage to allow regular use of these indicators except at a local scale (Fig. D2.3.1.5, Measurability). This is why DC, RND and AFP have only been applied at a local scale or why SS and WLCC were only calculated at a relatively coarse scale (1: 1 000 000) using bulk densities from the SPADE database. If the DC and RND are supposed to be relatively easily understood by policy makers and non-technical audiences, this would likely not be the case for SS, WLCC or AFP (Fig. D2.3.1.5, Intuitivity). Finally, no current implementation of these indicators in the environment policies of one or more MS were known by the evaluators of these indicators (Fig. D2.3.1.5, Policy implementation).

It was concluded that the indicators evaluated so far are not suitable to be used in the cookbook. Some of them like the potential wheel load carrying capacity offer information on limits to compressive load, but not direct information on the process of densification. Indicators that are related to the process of changes in soil volume as a result of compression such as the degree of compaction require the definition of references for non-compacted soils that are difficult to obtain within the framework of an exercise having the spatial scope of SERENA. It is recommended to continue the search for indicators of compaction that better satisfy the definition of the threat stated in D2.2 with a focus on indicators that have been used at national or regional level to favour measurability and scalability. A potential candidate may be the change in bulk density over time. Such an indicator corresponds closely to the definition of soil compaction. However, it seems difficult to measure with sufficient and temporal coverage and is probably not sensitive enough to changes in climate, land uses or management changes when modelled with pedotransfer functions based mainly on soil texture or SOC contents.

5.1.4. Soil sealing

According to D2.2, Soil sealing is defined as: the permanent covering of soils by buildings, constructions and layers of completely or partly impermeable artificial material (asphalt, concrete, etc.). It is the most intense form of land take and is a hardly reversible process. Soil sealing is causing loss of essential soil ecosystem functions.

Soil sealing is considered one of the main environmental issues of our decade (Peroni et al., 2022) and a major soil threat in most of the SERENA's MS. Indeed, when soil is sealed, soil ecosystem services dramatically decrease or are even nullified (Peroni et al., 2022). Soil sealing has been assessed at national and regional scales in numerous studies and is monitored at EU level by European Environmental Agency (EEA) every three years using the high-resolution Copernicus imperviousness datasets (https://www.eea.europa.eu/data-and-maps/dashboards/imperviousness-in-europe)

We identified three different indicators, which, depending on the context, status or changes in soil sealing are given in absolute (ha or km^2) or in relative (%) amount of soil sealed, land taken or impervious surface.

In principle, all three indicators are well established in scientific and policy reports (e.g., Soil health; Green Deal). As shown in Fig. D2.3.1.6, the indicators are i) regarded as efficient for quantifying the ST (Fitness-to-purpose), ii) already used and iii) available in national and EU databases (Measurability; Scalability). However, we can distinguish between the indicators, as follows:

The **degree of soil sealing is** the percentage of area where the nature and/or condition of the soil surface has been altered by the application of artificial, (semi-)impermeable materials resulting in the loss of essential soil ecosystem functions. It describes the averaged sealing on a given dimension (pixel; ha; area of municipality; etc.). This indicator includes soils which are completely or partly covered by impermeable artificial material (asphalt, concrete), like for instance buildings, parking lots or railway lines. In order to assess the ST of soil sealing it is helpful to compare the degree of soil sealing along time.

The **imperviousness** is the degree of soils covered by a complete impervious material. According to EEA: *the imperviousness indicator is defined as the yearly average imperviousness change between two dates (years), as measured by imperviousness change products. The change is aggregated for a certain reference unit and expressed relative to the size of that unit (as %). (https://www.eea.europa.eu/data-and-maps/indicators/imperviousness-change-2)*

The **Land take** in km^2 or ha describes the area of land use change from natural, semi-natural, forest or agricultural land taken for the purpose of infrastructure, housing areas, commercial zones, including not sealed soils, which continue to provide some services. Land take can result in an increase of scattered settlements in rural regions or in an expansion of urban areas around an urban nucleus (urban sprawl).

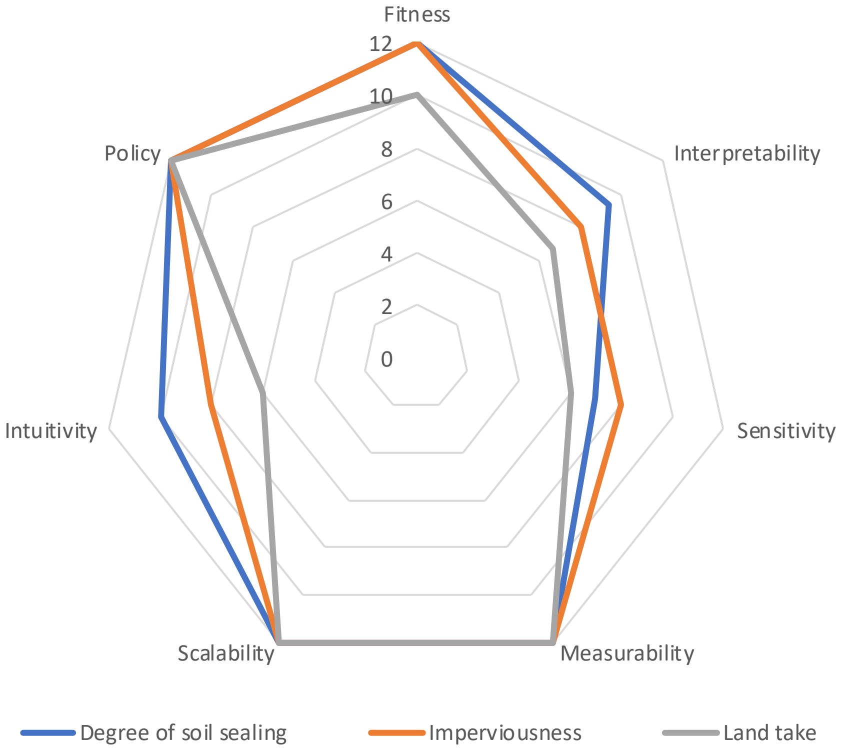

Figure D2.3.1.6: Radar chart summarizing the results of indicators ranking for soil sealing.

The existing indicators are well established and depending on the context good indicators. However, as indicator for soil sealing, we recommend: to use the degree of soil sealing and its change over time, because this indicator describes the ST most accurately. Further, we recommend to discuss the intuitivity (how well the indicator is understood by policy makers and the non-technical audience) and the interpretability (how the indicator is expressed according to the possibility and the ease of spatial comparison and interpretation) of the indicator among stakeholders.

5.2. Soil-based ecosystem services

5.2.1. Primary biomass production

According to D2.2, Primary biomass production is defined as: the capacity of soils to supply humans with food, feed, fiber, fuel, wood, pharmaceuticals and biochemicals

Biomass provision is the most relevant service to human kind provided by agricultural soils including arable land, permanent crops and managed pasture land as well as land used for urban agriculture. In addition to these, also soils supporting natural forests or pasture lands provide biomass to humankind with various uses (e.g., wood for fuels, herbs and natural plants for medicinal or food uses, grass for pasture, etc.).

Indicators fitting with the definition of a SES adopted by SERENA in D2.1 can be of relevance for new policy frameworks and strategies connected with Sustainable Development Goals (SDGs) and Agenda2030 at International, EU or national levels. For example, the new post-2022 strategy of UN for SDG12 regarding food system transformation for achieving 10 of the SDGs (United Nations, 2022), the EU Green-Deal framework and of course to implement the interlinkages between the EU Soil and Biodiversity strategy. In particular, appropriate indicators for biomass production could help in guiding the re-design of farming systems from input-based toward biodiversity-based farming, capable of using ESs as production factors (Duru et al., 2015). In this sense, they can be used in informing the agroecological transitions of EU farms (HLPE, 2019; European Commission, 2019; SCAR-AE, 2022).

The following indicators, which have been used at EU level have been analyzed so far:

- **Potential net primary production** *(*NPPpot, t dm ha^{-1} yr^{-1}). The indicator represents the net primary production (NPP) that would prevail in ecosystems without human land use. NPP denotes the balance between gross biomass production during photosynthesis and plant respiration.

- **Used biomass harvest** (t dm ha^{-1} yr^{-1}). This indicator represents the biomass which has been removed from ecosystems after harvesting. It comprises primary products as well as used harvested residues. This indicator is used in Mayer et al. (2021) to represent the biomass provisioning ES. NPPpot and Used biomass harvest indicators are part of the Human Appropriation of Net Primary Production framework, adopted by Mayer et al. (2021).

- **Proportion of biomass harvest** (%). This indicator is defined as the ratio of the used biomass harvest to the NPPpot.

- **Energy output from agricultural biomass** (MJ ha^{-1} yr^{-1}). It comprises the energy content of harvested products used for food and feed as well as other biomass that can be used for production of non-food products (Mouchet et al., 2017). The latter includes all biomass that can be harvested sustainably like straws or wood cuttings from permanent crops (vineyards, fruit, citrus or olive plantations among others) and that are already harvested in some measure as part of regular crop management activities.

- **Volume of stemwood** (m^3 km^{-2} forest yr^{-1}) (Mouchet et al., 2017). This indicator represents the average volume of stemwood extractable annually from forests for material and energy use (Mouchet et al., 2017).

These indicators are meant to represent ontologically different entities. NPPpot expresses the capability of ecosystems to produce biomass (Fig D2.3.1.7, Fitness-to-purpose). The used biomass harvest, the proportion of biomass harvest or the energy output from agricultural biomass refer to goods co-produced by humans and ecosystem (Fig D2.3.1.7, Fitness-to-purpose). The only indicator potentially aligned with the definition of SES adopted in the framework of SERENA is the volume of stemwood which refers to entities with the same ontological status as SES concept adopted by SERENA (that is benefits). However, the supply of wood may include as for other biomass production various human inputs through afforestation, forest thinning.

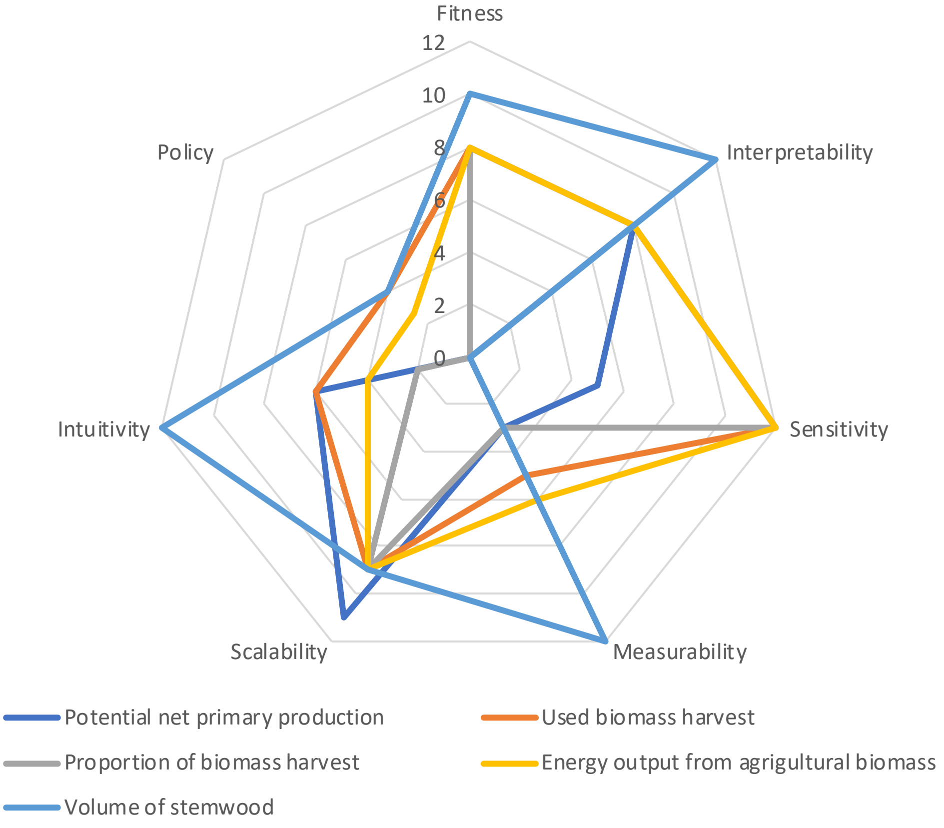

Figure D2.3.1.7: Radar chart summarizing the results of indicators ranking for primary biomass production.

Attention should be paid when using such indicators for policy informing as they do not differentiate between the contribution of the ecosystems and man-made capital to the biomass provisioning for human use (Fig. D2.3.1.7, Intuitivity). It can be misleading if such indicators are used alone since they can create incentives for intensive agricultural systems, without discriminating between the factors of intensification (e.g., exogenous inputs versus intensification in the use of ecosystem services by agriculture). Moreover, such indicators if used alone could be of little interest for policies aimed at transforming EU agriculture toward biodiversity-based agricultural models as for example, the organic agriculture model or emerging models for agroecology which explicitly aim at using ESs as productive factors (Duru et al., 2015; Garbach et al, 2016).

While all the considered indicators are quantitative, only the volume of stemwood is supposed to be supported by thresholds, references or target values (Fig. D2.3.1.7, Interpretability). The assessment of the used biomass harvest, of the proportion of biomass harvest and of the energy output from agricultural biomass require the estimation of crop yields.

When not derived from statistical databases, crop yields are commonly estimated based on simulations with crop or global vegetation models. In such cases, these indicators are sensitive to changes in climate, soil, use and management conditions (Fig. D2.3.1.7, Sensitivity). This is not the case for the volume of stemwood that is only applicable to woodlands and that was estimated in Mouchet el al., (2017) on the basis of forest inventory data and of a stemwood volume increment only (Fig. D2.3.1.7, Sensitivity). Finally, the potential net primary production is not sensitive to land use or management changes according to its definition (Fig. D2.3.1.7, Sensitivity).

Some indicators are currently available in databases (the volume of stemwood), or can be relatively easily calculated from the data available in databases (used biomass harvest, energy output from agricultural biomass), at least at the NUTS 2 level for Europe (Fig. D2.3.1.7, Measurability). Contrastingly, the potential net primary production and the proportion of biomass harvest are only modellable (Fig. D2.3.1.7, Measurability). This is also the case for the used biomass harvest or the energy output from agricultural biomass as soon as a finer resolution than the NUTS 2 level is requested (Fig. D2.3.1.7, Measurability). The ranking under the criteria for intuitiveness and policy is not sufficiently worked out and is excluded at this stage from further analyses.

In conclusion, all the above-mentioned indicators provide information on various aspects of the biomass production in cultivated or forested ecosystems. However, they cannot be recommended to be used standalone or without adaptation to the specific goals of SERENA, either because they are ontologically far from a SES, or because they do not allow differentiating the contribution of ecosystems and/or soils from the contribution of man-made capital. Especially in the case of agricultural soils this could lead to policy distortions in intensively managed industrial agricultural systems where high productivity in terms of biomass or energy output is not necessarily positively correlated with high contributions of ecosystems to the overall supply of biomass.

In the further stage of the study, other indicators should be considered too, for example, those applied in national policies. In that respect, the Energy Return on Investment (EROI) or the Net Energy Balance (NEB) may be of particular interest. The energy return on investment is defined as the energy gained divided by the energy used to get that energy and the net energy balance is defined as the energy gained minus the energy used (European Commission et al., 2016). Taking explicitly into account the external energy inputs (the denominator in the EROI formula) used to produce the energy outputs including labour, machinery, fertilizers or irrigation, such indicators are indeed good candidates to differentiate the contributions of ecosystems and human capital (Atlason et al., 2015, European Commission et al., 2016).

5.2.2. Greenhouse gas and climate regulation including carbon sequestration

According to D2.2, greenhouse gas and climate regulation including carbon sequestration is defined as the capacity of soils to reduce the amount of GHG emissions to the atmosphere.

It is an important ecosystem service performed by soil based on the influence that ecosystems have on the global climate by emitting GHG and by extracting carbon from the atmosphere (Maes et al., 2011). It is explained by the role of soils in regulating biogeochemical cycles of C and N through soil-atmosphere exchange (Ciais et al., 2013; Paustian et al., 2016), thus by the balance between the capacity of soils to sequester CO_2 and promote SOC storage, and GHG emissions from soils. Soil C sequestration can be defined by the process of transferring CO_2 from the atmosphere into the soil of a land unit, through plants, plant residues and other organic inputs which are stored or retained in the unit as part of the soil organic matter.

Three indicators have been used to assess the greenhouse gas and climate regulation including carbon sequestration SES at EU level: the net ecosystem productivity (Maes et al., 2011; Schulp et al., 2012; Hölting et al., 2019;); the carbon offset (Schulp et al., 2012); and the carbon stocks in vegetal biomass (Maes et al., 2011).

- The **Net Ecosystem Productivity** (NEP) represents the net C exchange between terrestrial ecosystems and the atmosphere. It is estimated by the difference between NPP and soil respiration, where NPP is defined as the difference between plant photosynthesis minus plant respiration, and soil respiration is C flux to the atmosphere resulting from the oxidation of soil C (Bouwman et al., 2006, Schulp et al., 2012,). Both can be estimated by different model option as IMAGE (Schulp et al., 2012) or C-Fix (Maes et al., 2011) from data on climate, soil, atmospheric CO_2 concentration, altitude, land-cover, but also C stocks and turnover rates. It is normally expressed as annual carbon fixation rates (Mg C km^{-2} y^{-1} or equivalent).

- The **carbon offset** is defined as the proportion of the annual country total CO_2 emission captured by the ecosystem by soil and vegetation (%).

- The **carbon stocks in vegetal biomass** represents the quantity of carbon stored in above- and below-ground living plant materials in Mg C km^{-2} or equivalent (Maes et al., 2011). It is estimated using remotely sensed imagery based on the methodology proposed by Olson et al. (1983, 1985). The original Olson data set was derived from vegetation patterns of pre-agricultural vegetation, while this updated data set is based on the land cover conditions in the year 2000 (GLC2000) and consequently accounts for human-induced changes in land cover (Gibbs, H. 2006).

Net ecosystem productivity represents the difference between annual C fixation by photosynthesis and annual plant and soil respiration. It therefore does not take into account the residence time of carbon stored in living plant materials, a fraction of which, especially for biomass grown for food or energy purposes, is subjected to return to the atmosphere on a time scale too short to regulate climate change. NEP consequently measures a function rather than an SES (Fig. D.2.3.1.8, Fitness-to definition). It is a quantitative variable likely not associated to particular reference or target values (Fig. D.2.3.1.8, Interpretability). Its assessment is sensitive to climate, soil and land cover changes, but not to changes in soil management (Fig. D.2.3.1.8, Sensitivity). It can be modelled or measured through proxy or remote sensing approaches at EU level depending on annual data availability (Fig. D.2.3.1.8, Measurability), and it is considered to be understandable by policy makers or the non-technical public (Fig. D.2.3.1.8, Intuitivity). Finally, no implementation in the European or MS environmental policies are known (Fig. D.2.3.1.8, Policy implementation).

Similarly to NEP, carbon offset refers to an annual C flux, with no additional information provided on long-term C storage. It represents also an ecosystem function (Fig. D.2.3.1.8, Fitness-to definition). It is a quantitative variable. Its assessment is sensitive to climate, soil and land-cover changes, but the role of soil management is not clear in this evaluation (Fig. D.2.3.1.8, Sensitivity). It is mostly modelled although it can be also measured through proxy or remote sensing approaches (Fig. D.2.3.1.8, Measurability). It is considered to be more understandable by policy makers or the non-technical public than NEP indicator, but, its level of implementation by individual MS is unclear.
Carbon stocks in plant biomass express current ecosystem conditions (Fig D2.3.1.8, Fitness-to-purpose). Its assessment is based on vegetation types. It is then sensitive to land-use changes but only indirectly to climate, soil or soil management conditions (Fig. D2.3.1.8., Sensitivity). It is a quantitative variable with some doubt about the existence of specific reference thresholds (Fig. D2.3.1.8, Interpretability). This indicator has been already applied at the EU level and is currently available in databases (Fig. D.2.3.1.8, Measurability). Finally, it is considered to be understandable by policy makers or the non-technical public but, again, its level of implementation in EU or MS environmental policies is not clear.

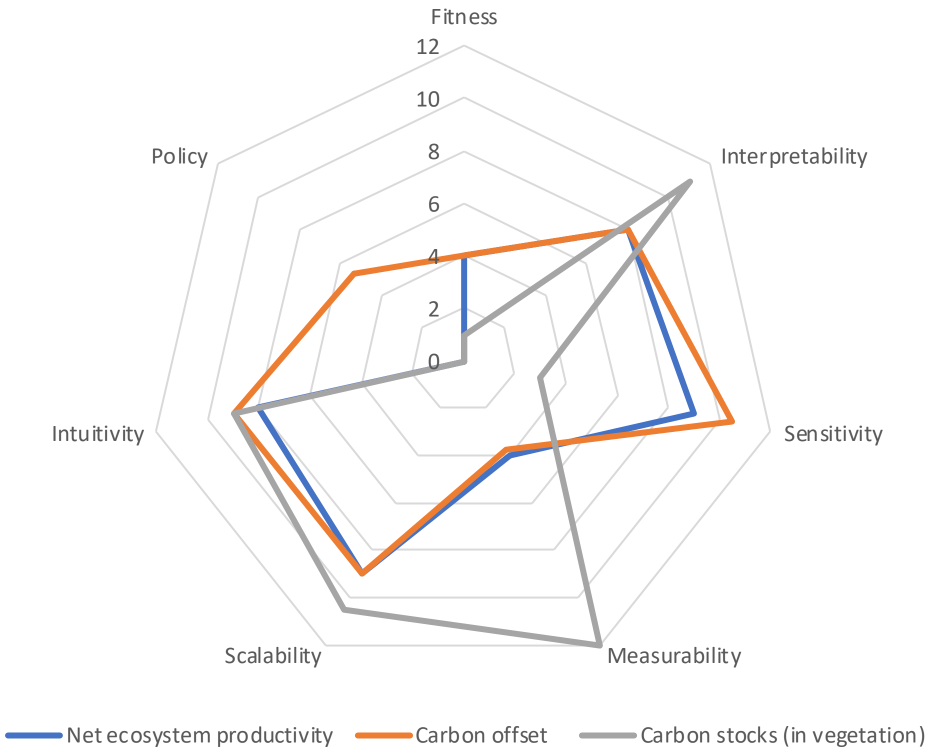

Figure D2.3.1.8: Radar chart summarizing the results of indicators ranking for greenhouse gas and climate regulation including carbon sequestration

The limited fit of all these indicators to the assessment objectives of both the climate regulation SES and the SERENA project suggest that none of them could be recommended for implementation in the framework of the project. The no evidence of long-term C stabilization and the unclear role of soil and soil management in their assessment, are the main reasons underlying this recommendation.

However, although the fit and measurability criteria scores are not correct, the indicators that most closely match the project objective would be NEP and C offset, with correct scores for the other criteria. Among them, NEP is considered to provide more complete information from a scientific point of view compared to the C offset and is therefore the reference indicator proposed in this first version of the cookbook. Further, it is recommended to discuss the policy relevance of all these indicators later in the project, when this criterion is better defined and checked with WP4.

5.2.3. Erosion control

According to D2.2, erosion control is defined as the reduction in the loss of material by virtue of the stabilising effects of the presence of plants and animal that mitigates or prevents potential damage to human use of the environment or human health and safety.

Several indicators have already been applied to assess erosion control at the EU level among which:

- The **capacity of vegetation to reduce erosion risk** represents the decrease of erosion risk by vegetation (Schulp et al., 2012) using indices ranging from 0 to 1 for the protective effects of each land-cover type as provided by Hootsmans et al. (2001).

- The **decrease of erosion risk by vegetation** in utilized areas with a high erosion risk is used by Schulp et al., (2012) to assess erosion control. It is calculated by multiplying the risk of soil erosion estimated using a 0–1 index based on the Universal Soil Loss Equation (USLE) (Batjes 1996) with the capacity of vegetation to reduce erosion risk as mentioned above.

- The **capacity of ecosystems to avoid soil erosion** is the average fraction of the total soil erosion that is mitigated by the vegetation cover. It corresponds to an adimensional gradient from 0 to 1 (Guerra et al., 2014; Hölting et al., 2016; Rendon et al., 2022). It is calculated as the reverse to 1 of the C vegetation cover factor of the RUSLE model.

- The **total amount of soil not eroded** represents the quantity of soils (t ha^{-1} y^{-1} (or equivalent)) that has not been eroded due to the protective effect of vegetation (Guerra et al., 2014; Hölting et al., 2016; Rendon et al., 2022). It is estimated as the difference between the erosion that would occur when vegetation is absent based on rainfall erositivity, soil erodibility and local topography, and the soil erosion according to the current land management options.

- The **surface area of natural vegetation with a function of erosion control** represents on a particular spatial extent, usually one square kilometre or NUTS2 area, the surface area of natural vegetation weighted by the erosion risk estimated by the erosion risk estimated with MESALES Model (Modèle d'Evaluation Spatiale de l'ALéa Erosion des Sols - Regional Modelling of Soil Erosion Risk). It consequently scores natural vegetation that are situated in areas of high erosion risk.

- The **surface area of forest with a protective function** (ha km^{-2}) is a European statistic. It estimates the area of forest or other woodland for which protection is the primary management objective. It mainly concerns the protection of soil against erosion by water and wind, the prevention of desertification, the reduction of risk of avalanches and rock or mud slides, the conservation, protection and regulation of water supply including the prevention of flooding and the protection against air and noise pollution.

The indicators related to erosion control are classified to three main categories, as far as Fitness-to-definition is concerned. ‘Capacity of vegetation to reduce erosion risk’, ‘Capacity of ecosystems to avoid soil erosion' - contrary to their name - refer to ecosystem functions considering that no erosion is needed to obtain a reduction in the erosion risk (Fig. D2.3.1.9, Fitness-to definition). 'Decrease of erosion risk by vegetation' and 'Total amount of soil not eroded' quantify a capacity rather than a flow of erosion control because they quantify the whole reduction in the loss of soil material and not only the fractions in the loss of soil material that finally result in a decrease in damages to human use of the environment or human health and safety (Fig. D2.3.1.9, Fitness-to-definition). Finally, 'Surface area of natural vegetation with a function of erosion control', and 'Surface area of forest with a protective function' got the lowest score for Fitness-to-definition, representing other level than the others (Fig. D2.3.1.9, Fitness-to-definition). Among the investigated indicators, none represents the fraction of the reduction in the loss of soil materials involved in mitigating or preventing potential damages to human use of the environment or human health and safety.

Figure D2.3.1.9: Radar chart summarizing the results of indicators ranking for erosion control

In terms of Interpretability, all indicators were scored consistently as quantitative variable (Fig. D2.3.1.9, Interpretability). The assessment of the indicators 'Decrease of erosion risk by vegetation', 'Total amount of soil not eroded', and 'Surface area of natural vegetation with a function of erosion control' are based on models like USLE and MESALES. Their assessment is consequently sensitive to changes in climate, soil, land use or land management conditions. This is not the case for the indicators 'capacity of vegetation to reduce erosion risk', 'capacity of ecosystems to avoid soil erosion' and 'surface area of forest with a protective function' that only depends on land use or land management (Fig. D2.3.1.9., Sensitivity).

In terms of measurability, all the investigated indicators can only be modelled, except ‘Surface area of forest with a protective function’, which can be measured and is currently available in international and national databases.

All of the ranked indicators have been applied or are applicable at the EU level. However, only two of them (‘Capacity of vegetation to reduce erosion risk’ and ‘Decrease of erosion risk by vegetation’) are spatial exhaustive, and have been assessed for at least one of the last five years.

Among the investigated indicators, none estimates the reduction in the loss of soil materials that mitigates or prevents potential damages to human use of the environment, human health and safety. Because the condition of human benefits is not taken into account, these indicators cannot be considered as “ideal” indicator for the SES of erosion control. However, two of them, the ‘Decrease of erosion risk by vegetation’ and ‘Total amount of soil not eroded’ estimates the overall reduction in the loss of soil materials, that is the ecosystem capacity to deliver the SES of erosion control. Among these, the latter shows relatively high scores for each of the considered criteria, with the exception of “measurability”. Therefore ‘Total amount of soil not eroded’ is recommended for implementation. Using the 'Total amount of soil not eroded' as erosion control indicator, it is proposed to take into consideration the different types of erosion by computing sub-indicators for each erosion process: water-, wind-, tillage erosion, and soil erosion due to crop harvesting.

6. Conclusions

In the past year, the T2.3 working group has:

- Built a tiered approach for harmonising at EU level the assessment of bundles of STs, SESs and their associated bundles based in four successive steps: 1) the harmonisation of the framework and definitions taken in charge by the T2.1 and T2.2 working groups; 2) the harmonisation of STs and SESs indicators on which this report focuses; 3) the harmonisation of the models used to assess these indicators and 4) the harmonisation of the data used as inputs data to run the selected models.

- Developed and tested a framework to rank and score STs and SESs indicators according to seven criteria clustered to the category “Scientific soundness”, “Availabity” and “Ability to convey information (Salience)”

- Applied the scoring and ranking procedure to a first subset of STs and SESs indicators of high interest in SERENA (as defined in D2.2) and already used to assess STs and SESs at the EU level.

Following this procedure, especially the fitness-to-definition criterion, “ideal” indicators have been identified for all the selected STs as summarized in Table D2.3.1.3. However, their assessment at the EU level is far from simple for several reasons. Firstly, three of them: i) the change in SOC stocks, ii) the change in bulk density, and iii) the change in soil sealing are defined as changes over time. The full definition of these indicators requires a time interval that remains to be defined at this point. Secondly, a balance between the fitness of the indicator to the concept of threat as defined in SERENA and its measurability has frequently been observed. This is notably the case for the change in SOC stocks or the change in soil bulk densities. When possible, alternative "realistic" indicators have been identified (Table D2.3.1.3). Finally, the available assessments of these "realistic" indicators suffer from significant limitations hindering their direct use. For example, the available assessment of the actual soil loss by water can be improved by including deposition modelling or by improving the assessment of the so-called erosion factors.

Table D2.3.1.3: List of "ideal" and "realistic" indicators of soil threats and soil-based ecosystem services selected for a harmonisation of assessment of soil threats and services at the European level

Soil threat / Soil Ecosystem Services	Ideal indicator	Realistic indicator
Soil Organic Carbon (SOC) loss	Change in SOC stocks	
Soil erosion	Soil loss	Soil loss by water
Soil compaction	Change in bulk density	
Soil sealing	Change in soil sealing	Soil sealing
Primary biomass production		
Greenhouse gas and climate regulation		Net ecosystem productivity
Erosion control	Non-eroded soil	Non-eroded soil by water

The development, and consequently the identification of "ideal" or "realistic" SESs indicators is considerably less advanced, as "ideal" or "realistic" indicators could only be identified for the SES of erosion control (Table D.2.3.1.3). The SESs indicators already used at EU level represent functions (upstream from the service in the cascade model) or goods (downstream from the service in the cascade model) rather than services. When the indicator succeeds in targeting the service, this is generally the potential rather than the current supply as beneficiaries and benefits are rarely or poorly taken into account.

This preliminary application of an explicit procedure for selecting and harmonising ST and SES indicators will be extended to the whole set of STs and SEs of interest in SERENA and to the whole set of ST and SES indicators used at the national level (as taken stock by T3.1) in order to obtain a full list of "ideal" or "realistic" indicators. Such list, corresponding to the second step in the roadmap towards the harmonisation of ST and ES assessment at EU level, will pave the way towards the development of methods (step three) and ultimately to the cookbook to evaluate indicators of ST, SES and their associated bundles.

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8. Appendix

Appendix D2.3.1.A1: List of reviewers of soil threat and soil-based ecosystem service indicators (by alphabetical order).

Anton-Sobejano, Rodrigo	INRAE, FR
Boruvka, Lubos	CZU, CZ
Buttafuoco, Gabriele	CNR, IT
Calzolari, Costanza	CNR, IT
Foldal, Cecilie	BFW, AT
Klimkowicz-Pawlas, Agnieszka	IUNG, PL
Kukk, Liia	EMU, EE
Laborczi, Annamaria	ATK, HU
Medina-Roldan, Eduardo	CNR, IT
Montagne, David	APT, FR
Niedźwiecki, Jacek	IUNG, PL
Oorts, Katrien	VPO, BE
Pindral, Sylwia	IUNG, PL
Scammacca, Ottone	APT, FR
Stefanova, Milena	ENEA, IT

Appendix D2.3.1.A2: Individual scoring of soil threat and soil-based ecosystem service indicators (12/01/2022).

ST/SES indicator	Reviewer	Scores						
		Scientific soundness			Data availability Ability to convey information			
		Fitness	Interpretability	Sensitivity	Measurability	Scalability	Intuitivity	Policy implementation
Soil threat - Soil organic carbon loss								
Soil organic carbon content	Reviewer 1	8	12	12	12	12		
	Reviewer 2	8	12	12	12	12	6	
	Reviewer 3	8	12	12	12	12		
	Reviewer 4	10	12	12	12	12	6	
	Reviewer 5	10	12	12	12	12	6	
	Reviewer 6	8	8	9	12	9	6	12
	Reviewer 7	10	12	12	12	12	12	12
Soil organic carbon stock	Reviewer 1	8	12	12	12	12		
	Reviewer 2	8	8	12	9	12	6	
	Reviewer 3	8	12	12	12	12		
	Reviewer 4	12	8	12	12	12	6	
	Reviewer 5	12	8	12	3	12	0	
	Reviewer 6	8	8	12	9	9	6	12
	Reviewer 7	10	12	12	9	12	6	12
Soil organic carbon stock loss	Reviewer 1	10	12	12	12	12	12	12
	Reviewer 2	8	12	12	12	12	12	
	Reviewer 3	10	8	12	12	12	12	
	Reviewer 4	10	8	12	9	9	12	
	Reviewer 5	12	12	12	3	9	12	12
Soil threat - Soil erosion								
Soil organic carbon decrease	Reviewer 1	8	8	12	3	12	6	0
	Reviewer 2	8	12	12	3	12	12	
Gully erosion	Reviewer 1	8	0	12	0	9	6	0
	Reviewer 2	8	0	12	0	9	6	0
Soil loss by water (potential)	Reviewer 1	10	8	6	3	9	12	12
	Reviewer 2	10	8	6	6	9	12	12
Soil loss by water (actual)	Reviewer 1	12	12	12	12	12	12	12
	Reviewer 2	12	12	9	12	12	12	12
	Reviewer 3	12	12	12	3	9	6	12
	Reviewer 4	12	12	12	3	12	12	12

Soil loss by wind	Reviewer 1	10	12	12	6	12	6	0
	Reviewer 2	10	12	12	3	12	6	0
Soil loss by crop harvesting	Reviewer 1	8	8	6	6	9	6	0
	Reviewer 2	8	8	6	6	9	6	0
	Reviewer 3	8	8	6	9	9	6	0
Soil loss by tillage	Reviewer 1	10	8	6	12	12	6	0
	Reviewer 2	10	8	6	12	12	6	0
Soil threat - Soil Compaction								
Wheel load carrying capacity	Reviewer 1	4	12	3	3	12	0	0
	Reviewer 2	1	12	3	3	9	0	0
	Reviewer 3	1	12	3	3	12	0	0
Soil stress	Reviewer 1	4	12	3	0	9	6	0
	Reviewer 2	4	12	3	0	12	6	0
	Reviewer 3	4	8	3	0	9	6	0
Degree of compaction	Reviewer 1	12	8	3	0	12	6	0
	Reviewer 2	8	12	3	9	0	12	0
	Reviewer 3	8	8	3	9	0	12	0
Relative normalized density	Reviewer 1	12	8	3	12	0	6	0
	Reviewer 2	8	12	3	9	0	12	0
	Reviewer 3	8	8	3	9	0	12	0
Air-filled porosity	Reviewer 1	1	8	3	0	0	0	0
	Reviewer 2	1	8	3	0	0	0	0
	Reviewer 3	1	8	3	0	0	0	0
Soil threat - Soil sealing								
Degree of soil sealing	Reviewer 1	12	8	9	12	12	12	12
	Reviewer 2	12	12	6	12	12	6	12
	Reviewer 3	12	8	6	12	12	12	12
Imperviousness	Reviewer 1	12	8	9	12	12	6	12
	Reviewer 2	12	8	9	12	12	6	12
	Reviewer 3	12	8	6	12	12	12	12
Land take	Reviewer 1	10	6	6	12	12	6	12
	Reviewer 2	10	6	6	12	12	6	12
	Reviewer 3	10	8	6	12	12	6	12
Soil-based ecosystem service - Greenhouse gases and climate regulation including carbon sequestration								
Net ecosystem productivity	Reviewer 1	4	8	9	3	9	12	0
	Reviewer 2	4	8	9	6	9	6	0
	Reviewer 3	4	8	9	3	9	6	0
Carbon offset	Reviewer 1	4	8	9	3	9	12	0
	Reviewer 2	4	8	12	6	9	12	8

	Reviewer 3	4	8	9	3	9	6	
	Reviewer 4	4	8	12	3		6	8
Carbon Stocks (in vegetation)	Reviewer 1	1	12	3	12	12	12	0
	Reviewer 2	1	8	3	12	9	6	0
	Reviewer 3	1	12	3	12	9	12	0
	Reviewer 4	1	12	3	12	12	6	0
Soil-based ecosystem service - Biomass production								
Potential Net Primary production	Reviewer 1	0	8	6	3	12	12	0
	Reviewer 2	0	8	6	3	12	0	0
	Reviewer 3	0	8	3	3	9	6	0
Used biomass harvest	Reviewer 1	8	8	12	3	9	6	4
	Reviewer 2	8	8	12	6	9	6	4
	Reviewer 3	8	8	12	6	9	6	4
Proportion of biomass harvest	Reviewer 1	8	8	12	3	9	0	0
	Reviewer 2	8	8	12	3	9	0	0
	Reviewer 3	8	8	12	3	9	6	0
Energy output from agricultural biomass	Reviewer 1	8	8	12	6	9	0	0
	Reviewer 2	8	8	12	6	9	6	4
	Reviewer 3	8	8	12	6	9	6	4
Volume of stemwood	Reviewer 1	10	12	0	12	9	12	4
	Reviewer 2	10	12	0	12	9	12	4
	Reviewer 3	10	12	0	12	9	12	4
Soil-based ecosystem service - erosion control								
Capacity of vegetation to reduce erosion risk	Reviewer 1	4	8	3	3	12	12	0
	Reviewer 2	4	8	3	3	12	6	
	Reviewer 3	4	8	3	3	12	6	0
Decrease of erosion risk by vegetation	Reviewer 1	10	8	12	3	12	12	8
	Reviewer 2	10	8	12	3	12	6	0
	Reviewer 3	10	8	12	3	12	6	0
Capacity of ecosystem to avoid soil erosion	Reviewer 1	4	8	6	3	9	6	0
	Reviewer 2	4	8	6	3	9	12	0
	Reviewer 3	4	8	6	3	9	12	0
Total amount of soil not eroded	Reviewer 1	10	8	12	3	9	6	0
	Reviewer 2	10	8	12	3	9	12	0
	Reviewer 3	10	8	12	3	9	12	0
Surface area of natural vegetation with a function of soil erosion	Reviewer 1	1	8	12	3	9	6	8
	Reviewer 2	1	8	12	3	9	6	0
	Reviewer 3	1	8	12	3	9	6	0

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 862695

Surface area of forest with protective function	Reviewer 1	1	8	3	12	9	6	0
	Reviewer 2	1	8	3	12	9	6	0
	Reviewer 3	1	8	3	12	9	6	0