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Selection of a bioindicator toolbox for monitoring effects of plant protection product residues

Part 1 - Linking ecological soil functions and soil organisms

Commissioned by the Federal Office for the Environment (FOEN)

Final Report [April 2023]

Imprint

Publisher

Swiss Centre for Applied Ecotoxicology, 8600 Dübendorf / 1015 Lausanne, Switzerland

Commissioned by

FOEN, Federal Office for the Environment, Soil and Biotechnology Division, Soil Section, 3003 Bern, Switzerland

Coordinators of the Measure 6.3.3.7 of the Action Plan for Plant Protection Products

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Acknowledgement

This project was funded by the Federal Office for the Environment. The authors would like to acknowledge Gudrun Schwilch and Bettina Hitzfeld from the FOEN and Michael Zimmermann and Katja Knauer from the FOAG for the discussions along the project and for their valuable comments on the report. The authors would like to thank all the persons listed under scientific support for the exchange we had and the advice that we received.

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Citation Proposal

Gilda Dell'Ambrogio, Mathieu Renaud, Sophie Campiche, Mireia Marti-Roura, Benoit J.D. Ferrari. 2023 Selection of a bioindicator toolbox for monitoring effects of plant protection product residues. Part 1 - Linking ecological soil functions and soil organisms. Swiss Centre for Applied Ecotoxicology, Dübendorf and Lausanne, Switzerland; 56 pp.

Cover photo: Gilda Dell'Ambrogio, Swiss Centre for Applied Ecotoxicology

Summary

The Swiss Action Plan on plant protection products (AP-PPP) includes a measure for long-term monitoring of PPP residues in agricultural soils. Within this measure, the ConSoil project was created with the aim of assessing the risk of PPP residues on soil fertility. Work package 2 of the ConSoil project includes the selection of a toolbox of bioindicators.

To select suitable bioindicators for soil fertility, first the actors (i.e., soil organisms) responsible for ecological soil functions supporting soil fertility need to be identified. The present report aims at compiling the links between soil actors and their respective ecological soil functions. The links were mainly collected from four key aggregating references and integrated under a common framework, i.e., the Common International Classification of Ecosystem Services (CICES).

The final product is a table linking actors to Processes, Ecosystem Services, and ultimately to ecological soil functions (Actor to Ecological Soil Functions, AESF table). The AESF table will serve as a basis for the second part of the work package 2 and will aid in the selection of a bioindicator toolbox, aimed at protecting long-term fertility.

Content

1 Introduction

1.1 Background and objectives

In September 2017, the Federal Council adopted an Action Plan, which aimed to reduce the risks of plant protection products (PPP) in half by 2027 and promote their sustainable use [1]. Objective 5.7 of the Action Plan (AP-PPP) “aims at ensuring that the use of PPP has no long-term adverse effects on soil fertility and at reducing the use of PPP with a high risk potential for soil". Objective 5.7 is associated to measure 6.3.3.7 of the AP-PPP, which includes the development of a monitoring program for PPP residues in agricultural soils. To meet the objectives of measure 6.3.3.7, the ConSoil project was mandated to develop (1) risk-based reference values for the assessment of PPP residues in soil (ConSoil - work package 1 [2]), as well as (2) indicators for evaluating their effects on soil fertility (ConSoil - work package 2). The present report describes the first part in the development of work package 2 and aims at identifying the soil actors which support soil fertility. The collected information will provide the basis for the selection of bioindicators, in a second part of work package 2.

Soil organisms play an important role in soil fertility [1] as essential actors in the supply of multiple soil functions (also referred to as soil multifunctionality [3]). To protect soil fertility from the effects of PPP residues, the soil organisms responsible for ecological soil functions related to soil fertility must be preserved [4]. As such, it is important that the specific actors contributing to these ecological soil functions are identified.

Many definitions and interpretations of soil functions exist in the literature. In the context of the AP-PPP, soil fertility is defined in the Swiss Ordinance relating to Impacts on the Soil (OIS; SR 814.12) [5] and is based on three specific ecological soil functions, i.e., the “habitat”, the “production”, and the “regulating” functions [6,7]. The definitions of the three ecological soil functions supporting soil fertility according to the Swiss National Soil Strategy [6] are presented in Box 1.

Box 1: Ecological soil functions supporting soil fertility according to the Swiss National Soil Strategy (2020):

• **Habitat function:** The ability of soil to sustain organisms and to maintain the diversity of ecosystems, species and their gene pool. The habitat function also covers soil’s suitability as a habitat for organisms and as a location for plants.

• **Regulating function:** The ability of soil to regulate, buffer or filter water and energy cycles, as well as to transform substances.

• **Production function:** The ability of soil to produce biomass, i.e. food and feedstuffs, as well as wood and other fibres.

In addition to functions, which are more focused on the ecosystem, the concept of Ecosystem Services (ES) is sometimes preferred for communication purposes (e.g. for policy makers), to refer to the contributions that ecosystems make specifically to human well-being [8]. ES have also been used in the scientific literature to classify the role of organisms in the ecosystem functioning [e.g., 11]. Like for functions, different classifications exist for ES and have evolved over time. One of the most known classifications was developed in the early 2000’s by the Millennium Ecosystem Assessment [10]. Since, different perspectives have been developed around the ES approach. To help harmonize the different existing classifications and refine according to the most recent literature, an expert meeting was hosted by the European Environmental Agency. As a result, the Common International Classification of Ecosystem Services (CICES) was developed [8], which is still actively maintained, with the latest version published in 2018 (V5.1, freely and publicly available at https://cices.eu/).

The links between soil functions/ES and organisms are multiple and complex [e.g., 8] and the exact quantifiable contribution of each organism to functions/ES is not currently known. Despite the lack of knowledge on their quantifiable contribution, some progress has been made to qualitatively identify the role of actors in the ecosystems. Recently, some publications have conducted extensive reviews and aggregated several years of experience and information from the scientific literature. While some studies are specific and do not give a full overview, we identified four recent key publications in particular, which provided a relatively complete list of ecological functions or

ES and identified and described the link with the responsible (soil) actors, in a systematic way, allowing the extraction of the information [3,9,12,13]. These will be referred to as key references in the remainder of this report and are briefly described below:

- Two Scientific Opinions produced by the EFSA Panel on Plant Protection Products and their Residues (EFSA PPR) with the aim of updating the prospective risk assessment of PPP in the agricultural landscape. EFSA PPR reviewed the role played by in-soil organisms [13] and plants [12] in the provisioning of ES relevant to the agricultural landscape. The classification used for ES was based on the Millennium Ecosystem Assessment [10].
- Faber et al. [9] provided an overview on the quantifiable ES provided by organisms across all compartments (soil, water, air), using the CICES as framework. For each ES identified, the study suggests currently available tools to measure how organisms are impacted by chemicals.
- Creamer et al. [3] proposed an integrative framework based on soil functions, using however a different classification than the one provided in the Swiss National Soil Strategy [6] (see Box 1), namely “water regulation and purification”, “nutrient cycling”, “carbon and climate regulation”, and “disease and pest regulation”. Soil functions are broken down into subfunctions and then into processes, which are ultimately linked to soil organisms. The framework is proposed as a flexible tool to select relevant biological indicators for monitoring soil quality under different contexts and spatial scales.

The objective of this report is to identify which soil organisms, based on the current knowledge, provide the ecological soil functions that support long term soil fertility. Instead of performing an extensive review of the literature, the qualitative links between organisms and functions/ES already identified in the above-mentioned four key references are compiled.

Since the key references have different contexts, goals and frameworks, a common framework, i.e., the CICES, is selected for the integration of literature data in this report. Next, the information provided in the key references is collected, evaluated, harmonized and merged under the selected framework. In addition to functions/ES, the key references often describe the role of actors through the concept of ecological processes. Because the aim of this report is to compile information rather than performing an extensive review, no detailed descriptions are provided for the different concepts (functions, ES, and processes) used in the key references. For specific definitions, the reader is referred to the original references. However, some additional Processes and actors, not identified in the key references, were identified in the scientific literature. For these entries, designated as “own entries” a more detailed description is provided.

The final result is the Actors to Ecological Soil Functions (AESF) table, which compiles the links between soil organisms, Processes, ES, and ultimately ecological soil functions, in light of these key references and with focus on soil fertility under the scope of the AP-PPP (measure 6.3.3.7). The present report describes the procedure applied to build the AESF table, based on literature data.

1.2 Organization of the report

This report provides first a general description of the steps performed to design the AESF table as well as a summarized AESF table (chapter 2). At the end of this chapter (section 2.8) an outlook is provided, describing how the AESF table will be used for the second part of the ConSoil project - work package 2. After that, the above-mentioned steps are described more in detail, including specific considerations and adaptations, as well as the description of own entries (chapter 3). Because of the complexity of the subject and the partial lack of consistent terminology across the scientific literature, a glossary is provided in chapter 6 summarizing essential information and the working definition for Processes used in the AESF table. Finally, the complete AESF table is provided in Appendix 1.

2 General description of the AESF table design

The design of the AESF table was based on four key references, namely Creamer et al. [3], EFSA PPR [12,13], and Faber et al. [9], which used different frameworks and classifications to show the links between soil actors and functions/ES (see chapter 1).

The framework chosen to integrate the information from the key references into the AESF table is the Common Classification of Ecosystem Services (CICES) [8]. The CICES follows a hierarchical structure providing several levels of detail, which allows selecting different and most appropriate levels of detail for comparing and integrating the information from the key references (see Section 3.1 for more information on the CICES framework).

2.1 Step 1: Associating ecological soil functions to ES Sections

For the first step of the AESF table design (see Fig. 1 for a summary of all the steps), the ecological soil functions supporting soil fertility were linked to ES, more specifically to the ES Sections, which represents the upper hierarchical level of the CICES framework (see section 3.1 for more information on the framework).

2.2 Step 2: Screening for relevant ES Classes

In the CICES framework, ES Sections are divided into different subcategories, each with a higher level of detail than the previous category. The subcategory ES Class was the most comparable to the classifications used in the key references and was the most appropriate working level within the CICES hierarchy. The final selection of the bioindicators should be framed into the specific requirements of the AP-PPP (measure 6.3.3.7). Since ES Classes cover a broader context, not all of them were relevant to the scope of the AP-PPP. Only ES Classes provided by soil organisms were considered relevant. In addition, only ES Classes occurring in-crop of agricultural fields and allowing the functioning of soil ecosystem and the provisioning of terrestrial plants were retained. The specific definitions considered for soil organisms and in-crop are provided in the glossary.

As a result, from a total of 90 ES Classes described in the CICES hierarchy, only 16 were considered relevant for the selection process of bioindicators (further information in section 3.3).

2.3 Step 3: Integrating ES Classes from key references

The soil functions and/or ES described in the key references are quite comparable to the ES Class adopted for the AESF table. However, some conversions were still necessary to be integrated into the AESF table.

Creamer et al. [3] describe three functions, which were considered relevant for the AESF table. Since a different framework (functions instead of ES) is used in this key reference, the terminology was adapted and converted into ES Classes (see section 3.4.1 for more details). Unlike Creamer et al. [3], the EFSA PPR [12,13] follows an ES framework but uses a different classification than the CICES, thus some conversion was also necessary at the ES Class level (specific adaptations applied are described in 3.4.2). Finally, Faber et al. [9] already uses the CICES framework and no conversion was necessary.

2.4 Step 4: Integrating Processes from key references

An additional category named Process, not included in the original CICES framework, was added to the AESF table. The Process category was based on the work of Creamer et al. [3] and was used in the AESF table to break down ES Classes, into a higher level of detail aiding in the attribution of actors. Processes were useful for the attribution of actors under the "regulation and maintenance" ES Section. For the “provisioning” ES Section, only crop production (i.e., plants) was considered.

Since Processes were based on the work of Creamer et al. [3], for this key reference, Processes were easily included in the AESF table with only slight adaptations. In the other key references (EFSA PPR [12,13] and Faber et al. [9]), Processes are not defined as an own category per se, but were inferred from descriptions in the text.

The adaptation and modifications at the Process category level for the key references are described in section 3.5.

2.5 Step 5: Attributing actors from key references

The last step of the procedure for integrating key references was the attribution of actors to Processes. Because the terminology is not always the same in the four key references, actors' names were first harmonized according to a common nomenclature before they were attributed to Processes, based on the links provided in the key references. The modification of actor's name is described in section 3.6 and the final link between Processes and actors is provided in the AESF table (Appendix 1).

2.6 Step 6: Additional Processes and actors

During the design of the AESF table and the verification of specific references cited by the key references, some further Processes and actors were identified in the scientific literature. Based on expert judgement and assessment of the scientific literature, suitable Processes and actors were included in the table as "own entries". Since "own entries" were not mentioned in the key references, they are briefly described in sections 3.7.1 (for Processes) and 3.7.2 (for actors), with some supporting references from the literature.

2.7 Summary of the procedure and of the AESF table

The Procedure used to build the AESF table is summarized in Fig. 1 and the AESF table compiling all information is illustrated in Appendix 1. Tab. 1: provides a summary of the critical information provided by the AESF table, such as the number of Processes, the actors responsible for those Processes and the ecological soil functions, to which the different processes belong. In addition, as Processes can occur more than once in the AESF table, associated to different ES Classes, the number (n) of occurrences of each Process in also represented in Tab. 1:. Finally, for each actor, the total number of connections to Processes is provided.

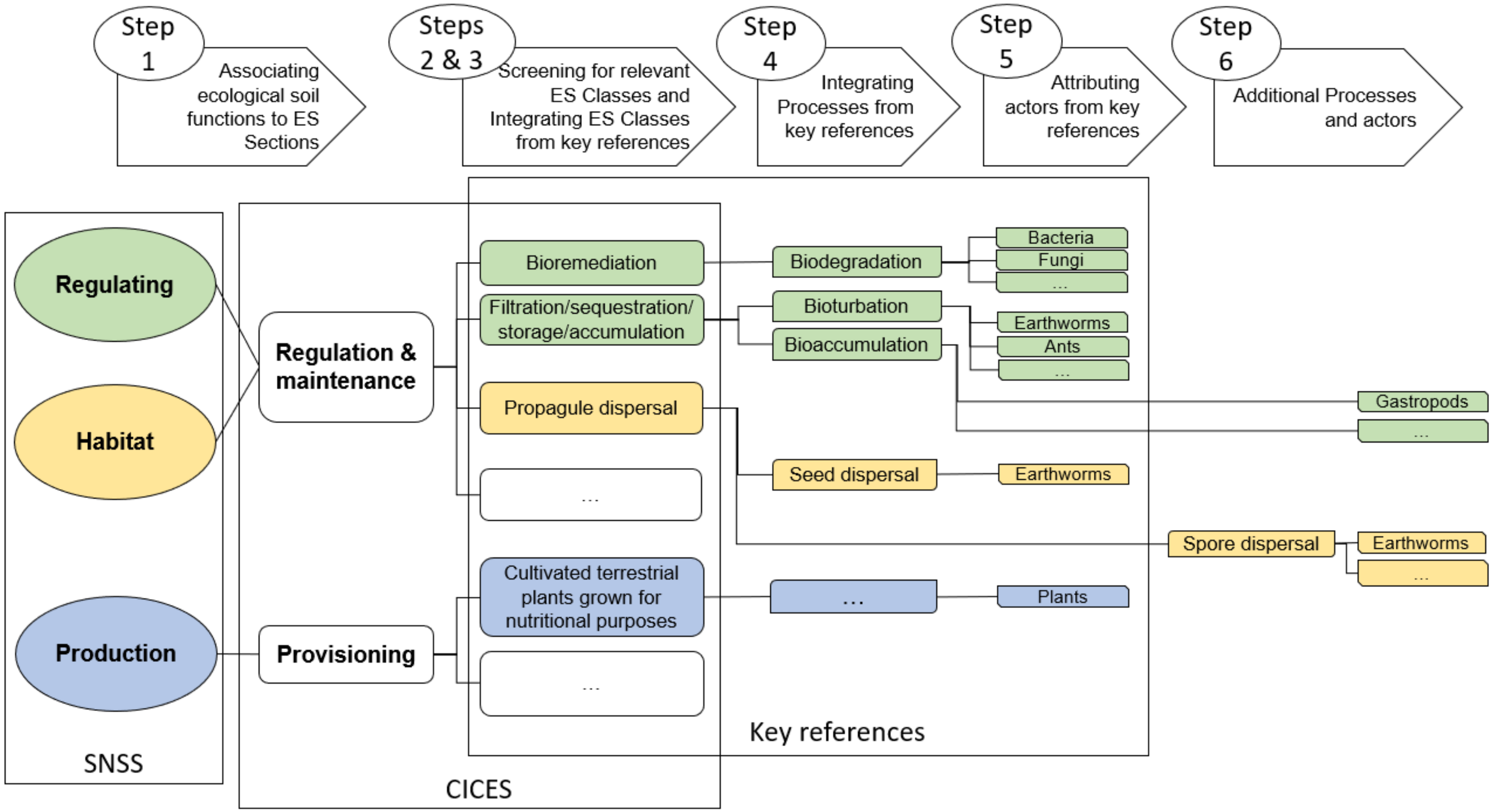

Fig. 1: Illustration of the stepwise procedure for the conception of the Actors to Ecological Soil Functions (AESF) table. SNSS: Swiss National Soil Strategy [6], CICES: Common International Classification of Ecosystem Services [8] (available at https://cices.eu/), key references: [3,9,12,13].

Tab. 1: Summary of the AESF table including the Processes and the actors responsible for providing these Processes. The link between Processes to ecological soil functions is provided by colour coding (yellow – "habitat" function, green – "regulating" function, and blue – "production" function). The number of occurrences of each Process in the AESF table under different ES Classes is indicated in the first column (n). In the last row, the total number of connections that each actor has in the AESF table (i.e. the number of Processes to which the actor is connected) is indicated.

Process		Actor																			
	n	Acari	Ants	Archaea	Bacteria	Coleoptera	Collembola	Diplopoda	Earthworms	Enchytraeid	Fungi	Gastropods	Insect	Isopod	Microalgae	Mycorrhiza	Nematodes	Plants	Protozoa	Spider	Virus
Aggregation	*3*		✓		✓		✓		✓	✓	✓				✓	✓		✓			
Bioaccumulation	*2*		✓		✓	✓	✓		✓	✓	✓	✓				✓		✓			
Biocide production	*1*				✓						✓							✓			
Biodegradation	*1*				✓				✓		✓					✓	✓	✓			
Biodiversity support	*1*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Bioturbation	*4*		✓						✓	✓											
Bioweathering	*1*				✓						✓					✓		✓			
Competition	*1*				✓						✓					✓	✓				
Crop production	*2*																	✓			
Food web assimilation	*1*	✓			✓		✓		✓	✓	✓						✓		✓		
Fragmentation	*2*	✓					✓	✓	✓	✓				✓							
Litter deposition	*1*																	✓			
Microbial food web assimilation	*1*				✓						✓										
Microbial grazing	*2*	✓					✓		✓	✓							✓		✓		
Mineralization	*1*				✓						✓										
Mycorrhizal acquisition	*2*															✓					
Mycotoxin dispersal and degradation	*1*						✓		✓								✓				
Nutrient transformation	*1*			✓	✓						✓							✓			
Parasitism	*1*				✓						✓		✓				✓		✓		✓
Plant metabolism enhancement	*1*			✓	✓						✓							✓	✓		
Plant resistance and defence	*1*				✓				✓		✓					✓					
Predation	*1*	✓	✓		✓		✓				✓		✓				✓		✓	✓	

Root foraging	*2*																	✓			
Seed dispersal	*1*								✓												
Soil pore creation	*2*		✓						✓	✓								✓			
Spore dispersal	*1*	✓				✓	✓	✓	✓	✓				✓			✓				
Stimulation of pollination	*1*				✓											✓					
Vegetation cover	*1*																	✓			
Total number of connections		**8**	**12**	**3**	**19**	**4**	**14**	**4**	**21**	**17**	**18**	**3**	**3**	**4**	**4**	**13**	**10**	**19**	**7**	**2**	**2**

2.8 **Outlook**

The AESF table provides an overall link between ecological soil functions and actors (soil organisms) using the ES framework and ecological Processes as tools to describe links. However, not all of the ES Classes and Processes have the same importance to soil fertility and the compilation produced in this report was based on scientific judgment aiming at providing a list of all potentially relevant ES Classes. The produced table will serve as the basis for the selection of bioindicators to monitor the impacts of PPP residues on soil fertility. As such, it is foreseen to rank the actors for their importance in two steps:

- A stakeholder evaluation and scoring of the ES Classes identified.
- The degree of connectiveness of the actors to the scored ES Classes.

The ranking of ES classes will allow the prioritization of the most important ecological Processes and actors for soil fertility and to determine and select bioindicator tools that represent key actors (threshold for selection of key actors not yet defined) from available standardized guidelines or well-established test methods. The selection of the bioindicator toolbox will be performed in consultation with international experts for each key actor group.

3 Detailed description of the AESF table design

The present chapter provides a more detailed description of the stepwise procedure followed to build the AESF table. First, a more detailed description of the selected CICES framework is provided (section 3.1). In the following sections (3.2 to 3.7), each step of the procedure, already summarized in chapter 2 (2.1 to 2.6), is further developed providing additional information on the modifications and considerations applied. At the end of each intermediate step, the conversions applied are summarized in a figure.

3.1 CICES framework

For the sake of harmonization, consistency, and aligned with most of the current scientific research, the ES framework was used as a keystone to better integrate and merge information from different sources. ES are defined as the contributions that ecosystems make to human well-being [8]. For the soil compartment, ES are delivered by soil functions [14]. Like for soil functions, many classifications and interpretations of ES exist and have been used depending on the different authors and sources. In this report, the most recent framework proposed by the European Environment Agency, the Common International Classification of Ecosystem Services (CICES, V5.1 – available at https://cices.eu/) [8]), and already used by some recent studies identifying actors and their link to ES (e.g. [9]), was adopted.

The CICES follows a hierarchical structure, going from low to high level of detail, i.e., from ES Section to Class type level (see example in Fig. 2). The hierarchical structure of the CICES is also a useful tool in dissecting and deconstructing the ecological soil functions, down to more specific services, where the link to actors is more feasible. ES are classified as abiotic and biotic: while the first ones are driven by physical and chemical parameters, the second ones result from the activity of organisms. For this project, abiotic, as well as cultural ES were considered out of scope. A simplified version of the CICES table (i.e., after removing abiotic and cultural ES) is available in Appendix 2.

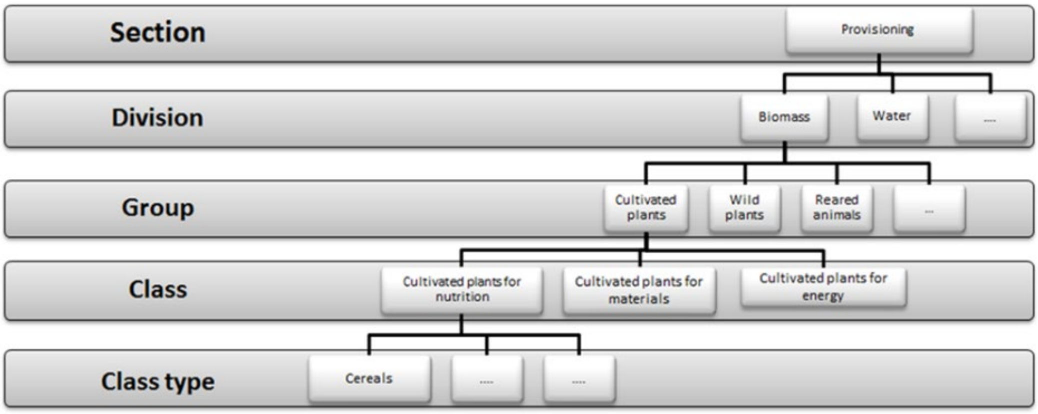

Fig. 2: Illustration of the hierarchical structure proposed by CICES V5.1 with the example of the provisioning Ecosystem Service Group "Cultivated plants" [8].

3.2 Step 1: Associating ecological soil functions to ES Sections

For the first step of the table design, the three ecological soil functions under the Swiss National Soil Strategy [6] (see Section 1.1 of the report, Box 1) were compared and associated to their corresponding ES according to the CICES (see Fig. 3).

The upper level of the CICES hierarchical structure (ES section) includes the "provisioning", the "regulation and maintenance" and the "cultural" ES Sections. The "regulating" and "production" functions defined in the Swiss National Soil Strategy [6] can be directly linked to the "regulation and maintenance" and to the "provisioning" ES Sections, respectively. However, the "habitat" function does not exist as an ES Section *per se* under the CICES but is rather included within the "regulation and maintenance" Section under the specific ES Class "maintaining nursery populations and habitats" (see Appendix 2, CICES code 2.2.2.3). "Cultural" services listed by the CICES were not included in the AESF table, since they are out of the scope of the measure 6.3.3.7 of the AP-PPP.

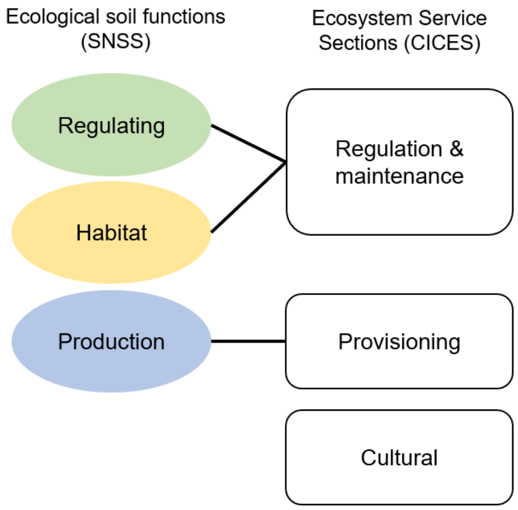

Fig. 3: Link between ecological soil functions, as described in Swiss National Soil Strategy [6]*, and Ecosystem Service Sections as classified by CICES* [8].

3.3 Step 2: Screening for relevant ES Classes

The two ES Sections ("regulation and maintenance", and "provisioning") include 73 ES Classes. Since the CICES covers all compartments (e.g., air, water, soil), as well as abiotic components (i.e., ES not performed by living organisms), and it does not focus specifically on soil fertility, a screening of relevant ES Classes was necessary. As such, ES Classes were considered relevant when linked to the role of soil organisms in supporting soil fertility in in-crop of agricultural fields (see section 2.2 for the additional context). The screening was performed as follows:

- All abiotic ES Classes were excluded, since they are not driven by soil organisms.
- Only ES Classes occurring in the soil compartment were retained.
- In the "provisioning" ES Section, only ES Classes linked to agricultural production of terrestrial crop plants were selected.

Although some ES Classes do not exclusively cover the context of the measure 6.3.3.7 of the AP-PPP, they were still considered relevant. For those, some more clarification is provided below:

- The ES Class "regulation of chemical condition of freshwater" is focused on water quality and corresponds to the ability of soil to regulate the chemical status of freshwaters. Although this is not specifically linked to soil fertility, it is important to preserve the ability of soil to filter soil-pore water which can help reducing the exposure of soil organisms to

PPP which could indirectly affect soil fertility. In addition, this ES Class allows the maintenance of freshwater quality, which, while not specific to measure 6.3.3.7, is also an objective of the AP-PPP.

- The ES Class “filtration/sequestration/storage/accumulation” was considered in the context of the role organisms play in the distribution and partitioning of contaminants in soil. Specifically, in the accumulation of contaminants by soil organisms but also their mobilization and redistribution in the soil compartment promoted by soil organisms. The Processes under this ES class can impact the spatial distribution and storage of contaminants within soil, their ability of soils to sequester contaminants as well as their partitioning to other compartments (air and water), including soil pore-water.

From the screening, a total of 16 ES Classes were selected containing all potentially relevant ES Classes. After screening, some modifications and simplifications were made to the CICES terminology when integrated in the AESF table. The list of selected ES Classes after screening as well as modifications to terminology are depicted in Fig. 4. For some modifications further context is provided below. For the full list of biotic ES Classes belonging to the “provisioning” and to the “regulation and maintenance” Sections of the CICES, see Appendix 2.

- The ES Classes 1.1.1.1, 1.1.1.2, and 1.1.1.3 were merged into a unique ES Class “Cultivated terrestrial plants, fibres or other materials from cultivated plants grown for nutritional purposes, for direct use or processing, or as a source of energy” for simplification and to focus on the context of the AP-PPP (measure 6.3.3.7).
- The ES Class 2.2.2.2 was changed to the broader term “dispersal of propagules” in order to include the transport of both spores and seeds.
- The ES Classes 2.2.3.1 and 2.2.3.2 were merged into a unique ES Class “pest and disease regulation” to be aligned with most references from the literature [3,12,13].

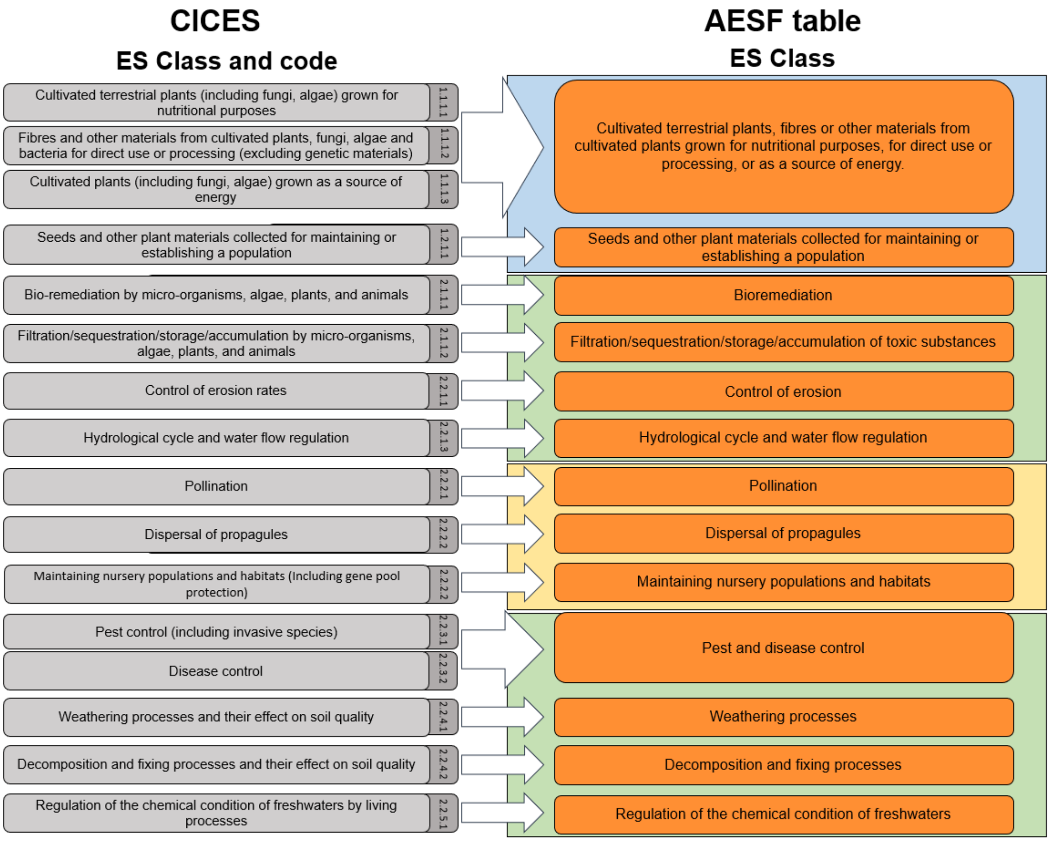

Fig. 4: Ecosystem Service (ES) Class classifications in the CICES [8]*, their respective codes and the adapted name in the AESF table and their link to ecological soil functions, In blue, ES Classes related to the "production" function; in green, to the "regulating" function; in yellow, to the "habitat" function, based on the definition of ecological soil functions provided in the Swiss National Soil Strategy* [6].

3.4 Step 3: Integrating ES Classes from key references

Since the AESF table was built using the CICES framework, the information from the key references was converted to the CICES format before being assessed and integrated in the AESF table. Details on the conversions for the concerned key references are described below.

3.4.1 ES Class adaptations for Creamer et al. [3]

Creamer et al. [3] do not follow the ES classification but rather describe four soil functions, using different definitions than the ones of the Swiss National Soil Strategy [6]. The four functions are "water regulation and purification", "nutrient cycling", "carbon and climate regulation", and "disease and pest regulation". In this key reference, each soil function is further broken down in subfunctions which, in the AESF table, were merged with functions into the category ES Class.

Modification and adaptations of soil functions and subfunctions from Creamer et al. [3] for the AESF table are visually depicted in Fig. 5.

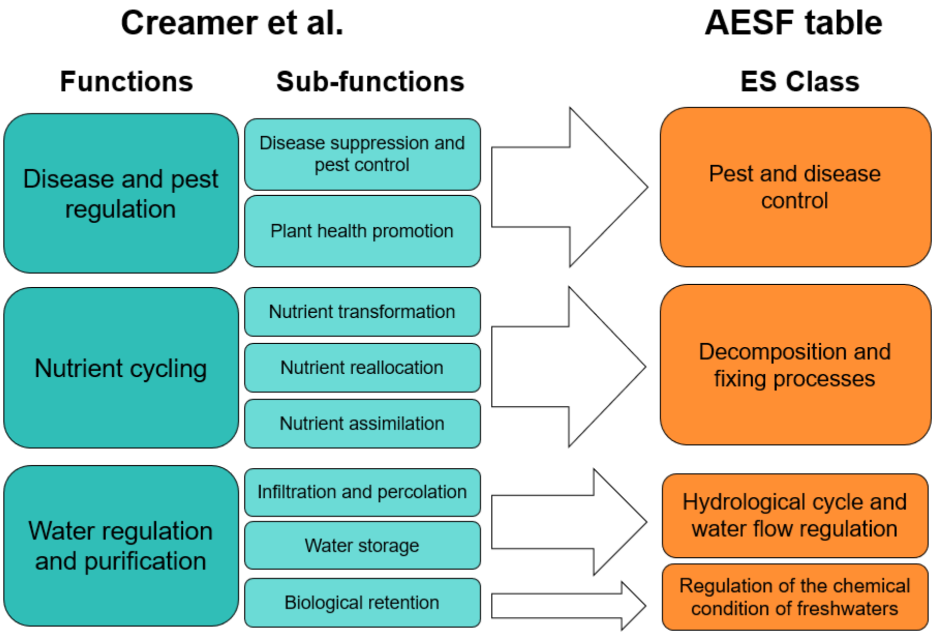

Fig. 5: Integration of soil functions and sub-functions as described in Creamer et al. [3] into Ecosystem Services (ES) Classes under the "regulation and maintenance" ES Section, used in the AESF table.

3.4.2 **ES Class adaptations for EFSA PPR** [12,13]

The EFSA PPR [12,13] describes ES provided by soil organisms based on the classification of the Millennium Ecosystem Assessment framework [10], which is partially aligned with the CICES at the Section level. However, some conversions were necessary at the level of the ES Class. Conversion of ES from EFSA PPR classification to the AESF table are visually depicted in Fig. 6. Cultural services listed in EFSA PPR [12,13] were not considered relevant in the context of the AP-PPP (measure 6.3.3.7) and not included in the AESF table.

For the ES "food provision, food web support" additional explanation is provided as it has slightly different definitions depending on the actor and the key reference. For plants specifically, this ES includes primary production and provision of food and habitat [12], while for in-soil organisms, it includes secondary production and biodiversity support [13]. As a result, the ES food provision and food web support was integrated, for all soil organisms, under the ES Class "maintaining nursery population and habitats" (which covers both provision of food and habitat, and biodiversity support) and, for plants specifically, also under the ES Class "cultivated terrestrial plants grown for nutritional purposes" in the "provisioning" ES Section (which covers primary production).

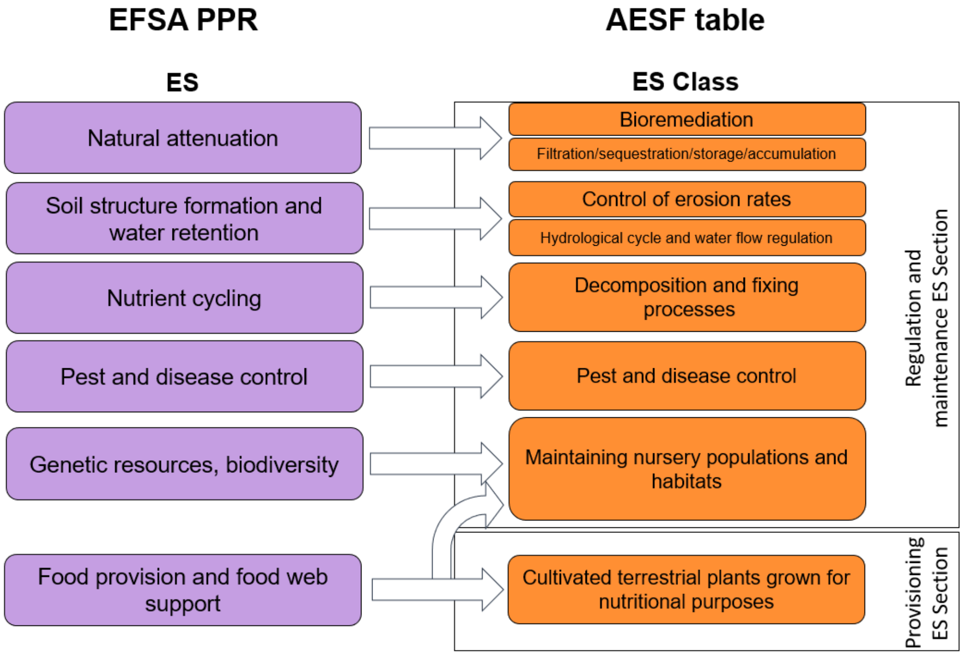

Fig. 6: Integration of Ecosystem Services (ES) considered by EFSA PPR [12,13] *into ES Classes used in the AESF table under both "regulation and maintenance" and "provisioning" ES Sections.*

3.5 Step 4: Integrating Processes from key references

For most ES Classes, the attribution of actors is difficult to perform because the ES class is not defined in sufficient detail to link to the actions of specific soil organisms. As such, to aid in the attribution of actors, Processes were added that break down ES Classes into a higher level of detail.

In the following sections, a description of modifications and adaptations is provided on how Processes were integrated from key references. The integration of Processes exclusively concerns the "regulation and maintenance" ES Section. The full list of Processes used in the AESF tables and their working definition are provided in the glossary.

3.5.1 Processes from Creamer et al. [3]

Processes that Creamer et al. [3] associated to soil functions were attributed directly to the respective ES Class in the AESF table, but some modifications were made to simplify information. Modifications include grouping or splitting Processes, or broadening their definition. All Process modifications from Creamer et al. [3] are visually depicted in Fig. 7 and some complementary information is provided below.

- The Process "antibiosis", which exclusively considers microorganisms as actors, was modified to the broader term "biocide production" in order to include also non-microbial actors.
- The general Process "nutrient transformations" was established to allow the inclusion of other nutrient cycles, not considered by Creamer et al. [3]. Under this key reference, only nitrogen and sulphur are considered, since they are the two cycles where soil biota contributions are most prevalent. However, soil organisms also play an important role in the cycling of other nutrients, such as phosphorus, essential for plant productivity, but also carbon and iron. The transformations of nitrogen and sulphur are also the only Processes with this level of specificity (linked to a particular element), thus grouping them under the Process "nutrient transformations" is better aligned with the remaining Processes.

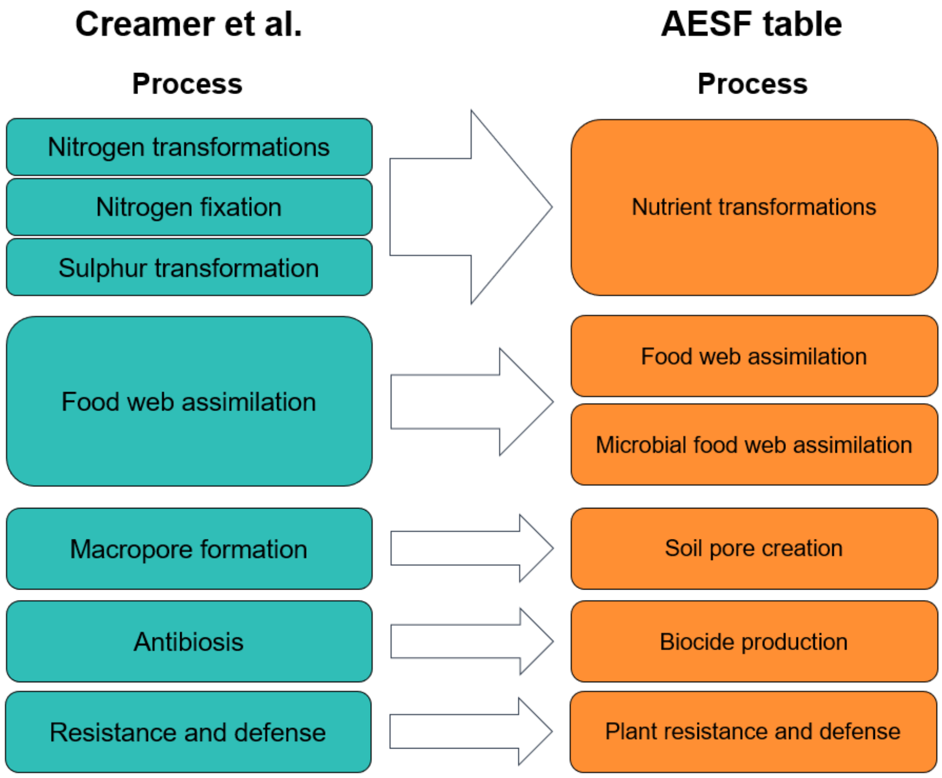

Fig. 7: Processes modified from Creamer et al. [3] when used for the AESF table.

3.5.2 **Processes from EFSA PPR [12,13] and Faber et al. [9]**

Differently from Creamer et al. [3], EFSA PPR [12,13] and Faber et al. [9] did not explicitly define Processes as a proper category, but rather linked actors directly to ES. However, most Processes are mentioned in the running text [12,13] or in the supplementary information [9] of these three key references. As such, Processes had to be attributed for the ES Classes collected from these two key references. In most cases, a Process already identified by Creamer et al. [3] could be used, but when this was not possible, a new Process was sought, supported by the information provided by EFSA PPR [12,13] and Faber et al. [9]. All the Processes added to the different ES Classes, based on Faber et al. [9] and EFSA PPR [12,13] are depicted in Fig. 8, and described in the glossary. However, some Processes need further clarifications or notes of concern which are provided below.

- Process: Bioaccumulation

  For the creation of the table, in general, positive trade-offs from soil organisms to soil fertility were considered. Bioaccumulation is per se a positive process for soil fertility, because contaminants are retrieved from the soil matrix (at least until the organisms' death). However, from the point of view of soil organisms themselves, the impact might be considered negative, because the contaminants can accumulate in organisms, causing toxic effects and even be transferred through the trophic chain, leading to potential effects to higher organisms. For this reason, this Process needs to be considered with circumspection.

- Processes: Aggregation; Soil pore creation

  In EFSA PPR [13], it is mentioned that Processes important for soil structure formation and water retention (ES Class "hydrological cycle and water flow regulation") can also play a role in the control of erosion rates (ES Classes “control of erosion rates”) but these Processes are not defined specifically. Based on a literature search, two Processes, also described by Creamer et al. [3], are important in the control of soil erosion from both water and wind, namely “soil aggregation” and “soil pore creation” [15–19]. These two Processes were therefore added to the ES Class “control of erosion rates” as well.

- Process: Biodiversity support

The ES Class “maintaining nursery population and habitats” is well aligned with the ES “genetic resources”, “biodiversity” and “food web support” defined by EFSA PPR [12,13]. Consequently, a Process named “biodiversity support” has been defined.

- Process: Bioweathering

EFSA PPR [12,13] and Faber et al. [9] provide actors contributing to weathering processes, intended as the erosion, decay and decomposition, of rocks and minerals. However, the Processes contributing to this ES Class are not specifically named. Based on a literature search, the process “bioweathering” was defined to indicate weathering performed by living organisms [20].

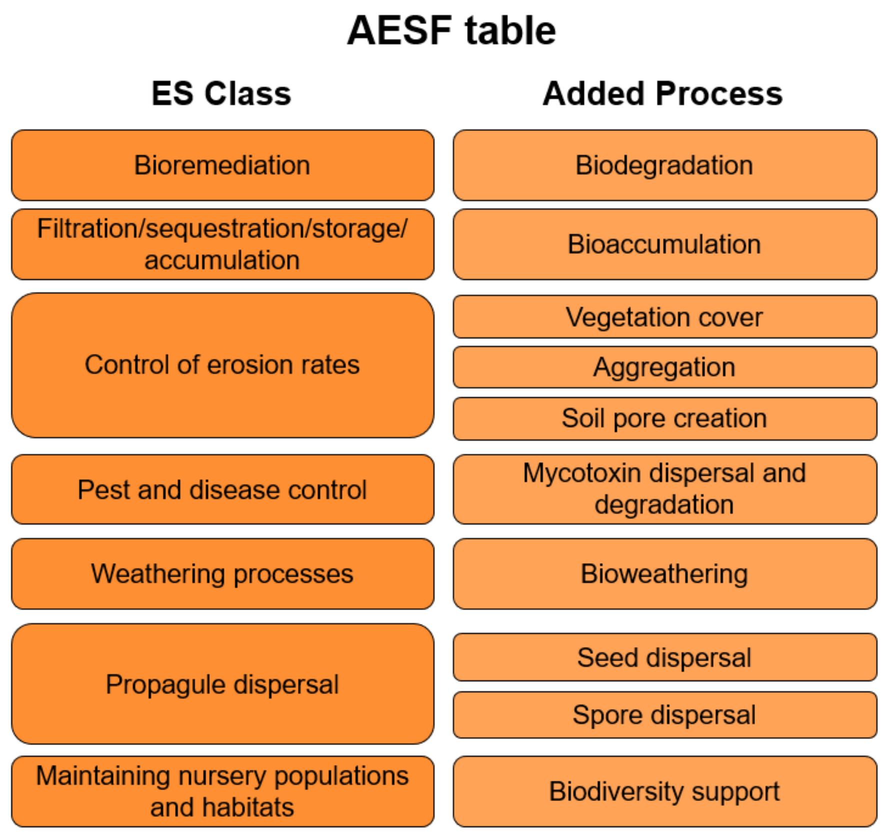

Fig. 8: Processes added to Ecosystem Service (ES) Classes based on EFSA PPR [12,13] *and Faber et al.* [9]. *Processes were either already considered in Creamer et al. [3] or attributed based on descriptions from EFSA PPR* [12,13] *and Faber et al.* [9].

3.6 Step 5: Attributing actors from key references

The last step of the conception of the AESF table was to link Processes to their respective actors. Within the agricultural land use, the only relevant actors for the “provisioning” ES Section are crops (plants). Differently, for the "regulation and maintenance" ES Section, multiple actors can be involved in the same Process. Under Creamer et al. [3], actors are already linked to Processes and were thus integrated directly. For EFSA PPR [12,13] and Faber et al. [9], the actors linked by them to ES were transferred to their corresponding Process(es) on the basis of the relationship established between the ES and Process(es), as described in section 3.5.2.

In the attribution of actors, some generalizations (e.g., plant roots to plants) or specifications (e.g., microorganisms to bacteria) were also performed. The modifications and grouping of actors are represented in Fig. 9.

Some actors considered by the key references were not considered for the AESF table. The actors insect pests, plant parasitic nematodes, and parasitic oomycetes considered by Creamer et al. [3] were removed as they consider plant parasitic organisms which can represent a negative feedback for soil fertility. The actor termites were also excluded as not relevant in the context of Swiss soils.

In Creamer et al. [3], there are three processes which relate to the uptake and transfer of nutrients by soil organisms, i.e. food web assimilation, root foraging and mycorrhizal acquisition (see definition in the glossary). For root foraging and mycorrhizal acquisition, the attributed actor was not always consistent and there was at times a duplication of the actor mycorrhizae. In the AESF table, it is important that the actors linked to a Process are always the same in the different ES Classes. Therefore, for consistency and to avoid duplications, the actor plants was attributed to "root foraging" and the actor mycorrhiza to the Process "mycorrhizal acquisition". The number of actors in the AESF table remained unchanged compared to Creamer et al. [3].

In the key references, specific references are provided by the authors to support the links between actors and Processes/ES. All these specific references were verified for their adequacy. References were not considered adequate and removed from consideration when they were:

- too general: e.g., the link between actor and Process of interest was hard to infer, not clearly described, only hypothetical.
- too specific: e.g., the link was described for a specific context which could not be extended to agricultural fields in Switzerland, e.g., arid or tropical climates, urban landscapes, extreme conditions of temperature, pH, or demonstrated outside of the soil compartment.
- not available and the abstract alone did not provide enough information.

If, after verification, no specific references remained to support a specific link between actor and Process, a literature search was conducted to find adequate replacement references. Replacement references considered, were either specific studies under a more relevant context, general references describing universally the role of the actor in a Process, or review papers collating evidence from multiple specific contexts. Replacement references were added to the AESF table, together with the key reference which initially supported the link. Each replacement reference was checked for their adequacy following the criteria described above and validated though expert judgment.

During the verification of specific references and literature research, for the Processes related to contaminants (i.e., bioaccumulation and biodegradation), preference was given to references about PPPs, which are more directly linked to the AP-PPP (measure 6.3.3.7). However, when necessary, references on other organic contaminants were also considered, because it is assumed that the mechanisms leading to degradation/bioaccumulation are similar.

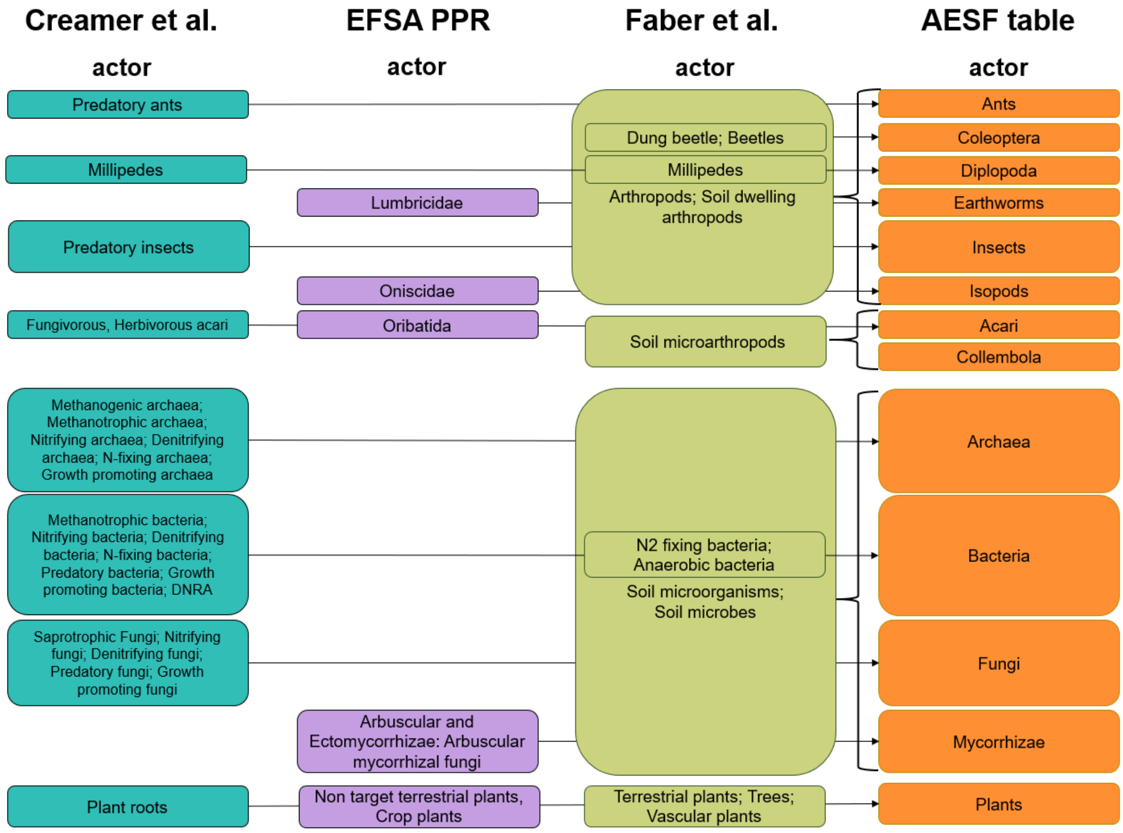

Fig. 9: Grouping and modification of actors from key references (Creamer et al. [3], EFSA PPR [12,13] *and Faber et al.* [9]*), when incorporated in the AESF table. Arrows represent conversion or generalization (e.g., predatory ants to ants, millipedes to diplopoda), brackets represent specifications (e.g., soil microarthropods to acari and collembola).*

3.7 Step 6: Additional Processes and actors

During the verification of specific references, some additional actors and Processes were identified, and were included in the table as “own entries”. Since these “own entries” were not mentioned in the key references, they are briefly described in the next two sections with some supporting references. In these sections, only added Processes and actors are depicted. The full list of Processes and actors used in the AESF table and a definition of each Process are provided in the glossary.

3.7.1 Additional Processes identified

Additional Processes not identified in the key references added to the AESF table are detailed below, for each ES Class and visually depicted in Fig. 10.

- ES Class: Decomposition and fixing process
  - Process: Litter deposition

The input and quality of organic matter is a keystone process allowing the maintenance of soil food webs, represents the starting point of decomposition and allows the functioning of linked processes [21]. To represent the input and quality of organic matter added to the soil, a Process named litter deposition was added to the AESF table.

- ES Class: Filtration/sequestration/storage/bioaccumulation of toxic substances

- Process: Bioturbation

In addition to bioaccumulation, already identified in section 3.5, bioturbation, i.e., the displacement of soil particles leading to a profound mixing of this media, was also found to play an important role under this ES Class. Bioturbation plays an important role in the re-distribution and mixing of contaminants in soil [22–24]. For this reason, bioturbation was added as Process to the ES Class “filtration/sequestration/storage/bioaccumulation”.

Bioturbation can on one hand reduce contaminants concentration in surface layers, but it can on the other hand lead to an increase of those contaminants in deeper layers. As a result, and similarly to bioaccumulation, bioturbation can have both positive and negative impacts and needs to be considered with circumspection.

- ES Class: Pollination
    - Process: Stimulation of pollination

The contribution of soil organisms to the pollination process (e.g. ants or beetles) is in general considered not significant or not sufficiently documented [25–29]. However, pollination can be influenced indirectly by microorganisms who can stimulate and increase pollination success [30,31]. Therefore, a Process named stimulation of pollination was included in the table.

AESF table

ES Class	Added Process
Decomposition and fixing processes	Litter deposition
Filtration/sequestration/storage/bioaccumulation	Bioturbation
Pollination	Stimulation of pollination

Fig. 10: Additional Processes attributed to Ecosystem Service (ES) Classes included in the AESF table, identified during literature search for specific references.

3.7.2 **Additional actors identified**

This section concerns additional actors identified for both existing Processes (from section 3.5) and additional Processes (from section 3.7.1). Newly attributed actors and the supporting references are briefly described below. The visual depiction of added actors is provided in Fig. 11.

- Process: Bioaccumulation
    - Actor: Gastropods; Mycorrhiza; Plants

Gastropods, mycorrhiza and plants are not mentioned by the key references as actors for bioaccumulation. However, during the verification of specific references, they were identified as additional actors playing an important role in the bioaccumulation of contaminants. As mentioned previously, bioaccumulation, while playing an important role in the detoxification of soil, might have negative consequences globally and could represent a negative feedback loop in overall ecosystem functioning.

Gastropods have been shown to accumulate legacy PPPs, such as the organochlorine pesticide DDT [32], as well as more recent and some still currently used PPPs (glyphosate, tebuconazole and pyraclostrobin) [33]. In fact, the proficiency of gastropods in accumulating contaminants is such that it has led to a standardized method for *in-situ* caging of the indicator species *Cantareus asperses* to assess effective bioavailability of contaminants and their bioaccumulation [34].

For mycorrhiza, most studies focus on the accumulation of polycyclic aromatic hydrocarbons (PAH) and show that mycorrhizal fungi can take up and immobilize phenanthrene, leading to its removal from the soil without translocation to the plant [35]. A similar process was identified for anthracene but without evidence of immobilization where anthracene was also detected in plant tissues [36].

Plants can accumulate a range of different chemicals from soil. Several studies established bio-concentration factors such that a database has been developed to quantify the uptake of organic chemicals by plants [37]. In one specific case, wheat was found to uptake a range of eleven different PPPs, but with different levels of accumulation, and where the partitioning of PPP to root lipids was identified as a key factor [38]. More recently, machine learning models have been used to understand and predict root concentration factors for organic contaminants [39].

- Process: Aggregation
    - Actor: Microalgae

Microalgae are described in the literature as having an important role in soil aggregation. In agricultural soils, microalgae can account for up to 27% of the total biomass [40] and play an important role in soil aggregation. The most prominent mechanism for aggregation is the formation and release of extra cellular polysaccharides, as well as the formation of soil biological crusts [41]. As a result, microalgae were added as an actor for aggregation.

- Process: Spore dispersal
    - Actor: Isopods; Diplopoda; Coleoptera; Earthworms; Acari; Collembola; Enchytraeids; Nematodes

Macroarthropods, namely isopods, diplopoda and coleoptera (carabid beetles), can play an important role in the transport of mycorrhizal fungi by ingesting spores and/or sporocarps [42,43]. Even through the process of ingestion, many spores can remain viable and initiate mycorrhizal infection [42], leading to the dispersal of mycorrhizal fungus spores within a soil microhabitat. Microarthropod promoted dispersal can positively influence the diversity of fungal symbionts and directly affect processes of nutrient cycling and plant uptake [43].

Macrofaunal actors, such as earthworms, can also greatly impact the mycorrhiza – plant relationship through hyphal grazing, spore ingestion and dispersal [42]. Mycorrhizal spores have been frequently detected and isolated from the digestive track of earthworms as well as in their casts and in greater diversity and abundance than other macroinvertebrate groups [42].

Mesofauna (collembola, mites, enchytraeids) can also play an important role in the vertical and horizontal redistribution of propagules within litter layers [44].

For collembola, the transport of conidia from three different entomopathogenic fungi (*Beauveria bassiana*, *B. brongniartii* and *Metarhizium anisopliae*) was observed for three different species (*Folsomia fimetaria*, *Hypogastrura assimilis* and *Proisotoma minuta*) both in the gut and on their cuticle [45]. A similar transport is also observed for mycorrhizal spores of *Glomus mossea* and *G. intraradices* by *Folsomia candida* and *Sinella coeca* but with different collembola dispersal efficiencies [46]. Finally, *F. candida* was shown to be attracted to the odours produced by *Streptomyces* colonies and when in contact was able to ingest and disseminate spores of *Streptomyces* either in faecal pellets or on its cuticle [47].

Dispersal of fungal spores was observed as well for oribatid mites but limited to ubiquitous taxa which points to a non-specialized role with little co-evolution [48]. Dispersal was also mostly limited to cosmopolitan and parasitic fungi with no mycorrhizal fungi identified. In a more specific study, the astigmatid mite *Sancassania phyllognathi* was found to play a role in passive dispersal of enthomopathogenic fungi, resisting infection of *Beauveria bassiana* and promoting its vertical and horizontal dispersal in soil [49].

Enchytraeids also play an important role in spore dispersal. Enchytraeids were demonstrated as efficient vectors of horizontal dispersal of saprophytic fungi [50]. More specifically, *Cognettia sphagnetorum* is known to disperse spores of *Mortierella isabellina* through its feeding behaviour [51].

Finally, in the microfauna, nematodes have shown to play a role in the dispersal of fungal spores with research considerably focusing on entomopathogenic fungi and its implication for pest control. Specifically, two species of nematodes (*Steinernema feltiae* and *Heterorhabditis bacteriophora*) were found to significantly enhance the dispersal of conidia and blastospores of the entomopathogenic fungi *Isaria fumosorosea* [52]. Nematodes were also found to play an important role in the ecology of the bacterial entomopathogen *Bacillus thuringiensis* including its dispersal in soil, which is designated as phoresy [53].

- Process: Stimulation of pollination
    - Actor: Bacteria; Mycorrhiza

In-soil microorganisms, namely bacteria and mycorrhiza can play an important role in the stimulation of pollination [30,31]. Mycorrhizal fungi and nitrifying bacteria can stimulate pollination by influencing plant traits that attract pollinators, such as the number and size of flowers as well as nectar and pollen production [30,31].

- Process: Biocide production
    - Actor: Plants

Plants were found to play an important role in the production of biocidal substances, most research focusing on its agronomic applications. Plants can naturally produce a range of compounds with biocidal action which can reduce the prevalence of pests of which glucosinolates, saponins and terpenoids are important examples [54,55]. Many of these compounds are produced by crop species from families such as *Leguminosae* (i.e. pea, beans)*, Alliaceae* (i.e. onion), *Asteraceae* (i.e. artichoke, sunflower), Brassicaceae (i.e. canola, Mustard) [54,55]. The incorporation of plant biomass, containing these compounds, into soil can lead to the release of these natural biocidal compounds leading to the suppression of pests [54,55].

- Process: Bioweathering
    - Actors: Plants

The root system of plants is involved in several mechanisms of weathering. Mineral dissolution is promoted by the formation of carbonic acid in the rhizosphere, release of root exudates (i.e. low molecular weight organic acids), selective uptake of dissolution products maintaining a favourable disequilibrium towards dissolution, modulating the redox environment, and regulating water flow [56,57]. In addition, plant root growth contributes to mechanical weathering [56,57].

- Process: Litter deposition
    - Actor: Plants

In terms of organic matter addition, plants were included as the main actor as they are the most important primary producers of litter entering into the soil [21,58]. Contributions to soil organic matter come from both the above ground portions [58] but also root biomass in the below-ground portion [59,60]. In fact, roots can contribute more to organic matter inputs to soil [61] and are expected to be especially important in agricultural systems, where above ground portions can be removed during harvest [60].

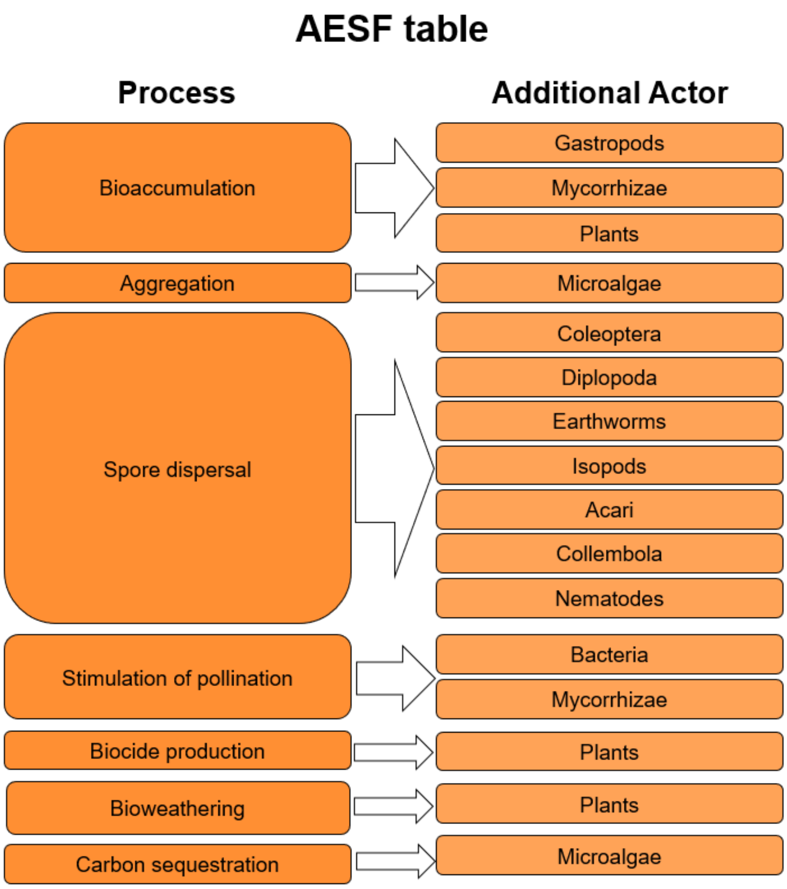

Fig. 11: Additional actors attributed to Processes in the AESF table identified during literature search for specific references.

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5 Abbreviations

AESF	Actor to Ecological Soil Function
AP-PPP	Action Plan on Plant Protection Products
CICES	Common International Classification of Ecosystem Services
ES	Ecosystem Service
EFSA PPR	European Food Safety Authority Panel on Plant Protection Products and their Residues
PPP	Plant Protection Products

6 Glossary

The definitions in the glossary were adapted to best represent the working definition under the specific context of the ConSoil project but might have, under other contexts, a broader definition.

Actor	Broader term to define different ecological and taxonomical groupings of soil organisms, e.g., plants, earthworms, bacteria.
Aggregation	Soil aggregation involves the binding together of several soil particles into three-dimensional arrangement of organic/mineral complexes, mediated by soil biota.
Biocide production	Biological interaction between two or more organisms (microorganisms or plants) that is detrimental to at least one of them, due to the secretion of a metabolic substance produced by the other one.
Bioaccumulation	Net accumulation of the uptake, distribution and elimination of a substance in an organism due to exposure through all routes, i.e., air, water, soil and food.
Biodegradation	Biologically catalysed reduction in complexity of contaminants, performed by the direct and indirect action of soil organisms.
Biodiversity support	Biotic aspects of the habitat, allowing a sustainable biodiversity which includes the support of soil food webs at different trophic levels.
Bioturbation	Displacement of soil particles carried out by soil fauna, essentially invertebrates, leading to a profound mixing of this media.
Bioweathering	Erosion, decay and decomposition, of rocks and minerals mediated by living organisms through biomechanical and biochemical mechanisms.
Carbon sequestration	Process of capturing, securing and storing atmospheric CO2 in soils.
Competition	Exploitation of a common and limiting resource by two or more species.
Crop production	Any crops, fruits or cultivated terrestrial plant grown by humans for food or used as raw material for non-nutritional purposes or as source of energy.
Decomposition	Decomposition and breakdown of organic matter, from macromolecules to smaller molecules, their transformation and uptake by organisms (adapted from). Represented by processes of fragmentation, nutrient transformations, food web assimilation, root foraging and mineralization.
Food web assimilation	Nutrient incorporation into biomass by soil biota.
Fragmentation	Involves the physical comminution and partial digestion of plant litter by soil meso- and macrofauna, after which the residues can be decomposed and/or become stabilized, contributing to soil organic matter formation and water storage.
In-crop area	Areas where a crop is grown, which can follow either a natural (e.g. vegetables, cereals), or a systematic spatial heterogeneity (e.g. orchards, vineyards) (see Fig. 12).

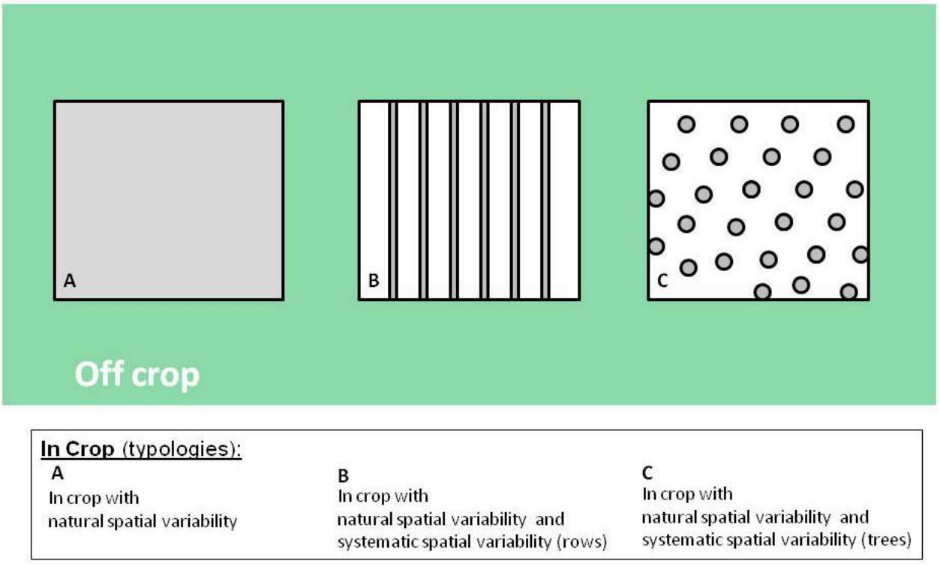

Fig. 12: Typologies of in-crop areas as defined in EFSA PPR [62]*, colours represent different spatial heterogeneity patterns, grey: cultivated crop, white: uncultivated space between crops.*

In-soil organisms	Species that dwell primarily in the soil and soil litter (including soil invertebrates and microorganisms).
Litter deposition	Refers to the input of plant residues onto (surface litter) or into (root litter) soils).
Maintaining genetic resources	Genetic material (i.e., any material of plant, animal, microbial or other origin containing functional units of heredity) of actual or potential value.
Microbial food web assimilation	The microbial assimilation of nutrients into microbial biomass.
Microbial grazing	Grazing or feeding on microbial biomass performed by non-microbial soil invertebrates.
Mineralization	Transformation of organic nutrients to inorganic form by soil bacteria and fungi.
Mycotoxin dispersal and degradation	The role played by soil biota in mycotoxin regulation and suppression.
Mycorrhizal acquisition	Plant uptake of mineral nutrients from the soil by mycorrhizal fungi.
Nutrient transformation	Soil biological processes which lead to changes in the chemical or physical status of nutrient resources, such as nitrogen, phosphorous, sulphur, carbon, iron, excluding fragmentation, mineralization and assimilation processes.
Parasitism	Interaction between species where individuals of one species live in or on a living host, sapping the host's resources for a relatively prolonged period, and exerting a negative, but not necessarily a fatal, effect on the host.
Plant metabolism enhancement	Activities performed by soil organisms which enhances the ability of plants to endure pathogens and pests.
Predation	Interaction between two organisms where individuals of one species, the predator, actively seeks, kills and eats individual of another species, the prey.

Plant resistance and defence	Interaction between plants and a soil organism which activates the plant's defence mechanisms directed against pathogens/pests.
Root foraging	Uptake of nutrients by plants for plant growth.
Seed dispersal	Departure and transport of a seed from the parent plant performed and mediated by soil organisms.
Soil pore creation	Refers to the formation of pore spaces in the soil matrix, resulting from the biological activity of soil organisms.
Spore dispersal	Discharge and transport of spores from the spore producing individual performed and mediated by soil organisms.
Stimulation of pollination	Activities of soil organisms that positively influence plant traits associated with pollinator attraction (e.g., increased flower number and size, increased pollen and nectar production) and therefore improve pollinator efficiency.
Vegetation cover	Area of ground covered by the vertical projection of the aerial parts of plants of one or more species.

7 Indices

7.1 List of Figures

7.2 List of Tables

Appendix 1 AESF Table

Appendix table 1 – AESF Table Illustrating Ecosystem Service (ES) Section, ES Class, and Process, and their link with Actors, as well as key and specific references supporting this link. In blue, ES Classes, Processes, and Actors related to the “production” function; in green, to the “regulating” function; in yellow, to the “habitat” function, based on the definition of ecological soil functions provided in the Swiss Soil National Strategy (SNSS) [1].

SNSS Function	ES Section	ES Class	Process	Actor	Key references	Specific references
Production	Provisioning	Cultivated terrestrial plants, fibres or other materials from cultivated plants grown for nutritional purposes, for direct use or processing, or as a source of energy	Crop production	**Plants**	[2,3]	No reference provided
		Seeds, and other plant materials collected for maintaining or establishing a population	Crop production	**Plants**	[2,3]	No reference provided
Habitat	Regulation and maintenance	Pollination	Stimulation of pollina-tion	**Bacteria**	Own entry	[4]
				Mycorrhizae	Own entry	[4,5]
		Dispersal of propagules	Seed dispersal	**Earthworms**	Own entry	[6–8]
			Spore dispersal	**Coleoptera**	Own entry	[9]
				Diplopoda	Own entry	[9]
				Earthworms	Own entry	[9]
				Isopods	Own entry	[9,10]
				Enchytraeids	Own entry	[11]
				Collembola	Own entry	[11–14]
				Acari	Own entry	[11,15,16]
				Nematodes	Own entry	[17,18]
		Maintaining nursery populations and habitats	Biodiversity support	**All - Biodiver-sity**	[3,19]	No reference provided
Regulating		Bioremediation	Biodegradation	**Earthworms**	[2,19]	[20–26]
				Nematodes	[19]	[27]
				Bacteria	[2,19]	[28–31]
				Fungi	[2,19]	[29–33]
				Mycorrhiza	[19]	[34–36]
				Plants	[2]	[37–40]
		Filtration/sequestration/storage/ accumulation of toxic substances	Bioturbation	**Ants**	[19,41]	[42–44]
				Earthworms	[2,19,41]	[20,42,43,45–48]
				Enchytraeids	[41]	[49]
			Bioaccumulation	**Ants**	[41]	[50]

SNSS Function	ES Section	ES Class	Process	Actor	Key references	Specific references
		Filtration/sequestration/storage/ accumulation of toxic substances	Bioaccumulation	**Coleoptera**	[41]	[51]
				Earthworms	[41]	[52–54]
				Gastropods	Own entry	[55,56]
				Collembola	[41]	[57]
				Enchytraeids	[41]	[58,59]
				Bacteria	[2,19,41]	[60,61]
				Fungi	[19]	[62–65]
				Mycorrhizae	Own entry	[36,66]
				Plants	[2]	[67–69]
		Control of erosion rates	Aggregation	**Ants**	[19]	[44,70,71]
				Earthworms	[2,19,41]	[20,45,70–75]
				Collembola	[19]	[76]
				Enchytraeids	[19,41]	[77–79]
				Bacteria	[19,41]	[80–83]
				Fungi	[2,19,41]	[76,81,83–91]
				Mycorrhizae	[2,19]	[76,85,86,88–92]
				Plants	[41]	[70,74,92]
				Microalgae	Own entry	[80]
			Soil pore creation	**Ants**	[19,41]	[44,70]
				Earthworms	[2,19,41]	[20,45,46,70,71, 75,82,93–95]
				Enchytraeids	[19]	[78,79]
				Plants	[41]	[70,96]
			Vegetation cover	**Plants**	[2]	[97–101]
		Hydrological cycle and water flow regulation	Aggregation	**Ants**	[19]	[44,70,71]
				Earthworms	[2,19,41]	[20,45,70–75]
				Collembola	[19]	[76]
				Enchytraeids	[19,41]	[77–79]
				Bacteria	[19,41]	[80–83]
				Fungi	[2,19,41]	[76,81,83–91]
				Mycorrhizae	[2,19]	[76,85,86,88–92]
				Plants	[41]	[70,74,92]
				Microalgae	Own entry	[80]
			Bioturbation	**Ants**	[19,41]	[42–44]
				Earthworms	[2,19,41]	[20,42,43,45–48]
				Enchytraeids	[41]	[49]

SNSS Function	ES Section	ES Class	Process	Actor	Key references	Specific references
		Hydrological cycle and water flow regulation	Fragmentation	**Diplopoda**	[19,41]	[102–104]
				Earthworms	[2,19,41]	[20,46,71,105]
				Isopods	[2,19,41]	[103,104]
				Acari	[2,19,41]	[106–108]
				Collembola	[2,19]	[106,107,109]
				Enchytraeids	[2,19,41]	[110,111]
			Soil pore creation	**Ants**	[19,41]	[44,70]
				Earthworms	[2,19,41]	[20,45,46,70,71, 75,82,93–95]
				Enchytraeids	[19]	[78,79]
				Plants	[41]	[70,96]
		Pest and disease control	Biocide production	**Bacteria**	[2,19,41]	[112–117]
				Fungi	[2,19,41]	[116–119]
				Plants	Own entry	[120,121]
			Competition	**Nematodes**	[19]	[122,123]
				Bacteria	[19,41]	[115,117]
				Fungi	[2,19,41]	[115,117,119]
				Mycorrhizae	[2,19]	[124,125]
			Microbial grazing	**Earthworms**	[2,19]	[11,71,126,127]
				Acari	[19,41]	[11,128–130]
				Collembola	[2,19,41]	[11,127,129–136]
				Enchytraeids	[19]	[11]
				Nematodes	[19,41]	[11,82,127,135, 137–141]
				Protozoa	[19,41]	[139,142]
			Parasitism	**Insects**	[41]	[143]
				Nematodes	[19,41]	[143,144]
				Protozoa	[41]	[145]
				Bacteria	[19,41]	[146]
				Fungi	[19,41]	[119,146]
				Viruses	[41]	[119]
			Predation	**Ants**	[41]	[147–149]
				Insects	[41]	[150]
				Spiders	[41]	[150]
				Acari	[41]	[130]
				Collembola	[41]	[130,132]

SNSS Function	ES Section	ES Class	Process	Actor	Key references	Specific references
		Pest and disease control	Predation	**Nematodes**	[19,41]	[151,152]
				Protozoa	[19,41]	[142,145]
				Bacteria	[19,41]	[153,154]
				Fungi	[19,41]	[153]
			Mycotoxin dispersal and degradation	**Earthworms**	[2,19]	[126,127,155,15]
				Collembola	[2,19]	[127,135,136]
				Nematodes	[2,19]	[127,135,136]
			Plant metabolism en-hancement	**Protozoa**	[41]	[142]
				Archaea	[19,41]	[157,158]
				Bacteria	[2,19,41]	[116,159]
				Fungi	[19,41]	[116,159]
				Plants	[41]	[160]
			Plant resistance and defence	**Earthworms**	[2]	[126]
				Bacteria	[19,41]	[115,117,159,16]
				Fungi	[19,41]	[117,159]
				Mycorrhizae	[2,19]	[124,125,162]
		Weathering processes	Bioweathering	**Bacteria**	[2,19]	[163–166]
				Fungi	[2,19]	[163,167–170]
				Mycorrhizae	[2]	[163]
				Plants	Own entry	[163,165,171]
		Decomposition and fixing processes	Litter deposition	**Plants**	Own entry	[172–176]
			Fragmentation	**Diplopoda**	[19,41]	[102–104]
				Earthworms	[2,19,41]	[20,46,71,105]
				Isopods	[2,19,41]	[103,104]
				Acari	[2,19,41]	[106–108]
				Collembola	[2,19]	[106,107,109]
				Enchytraeids	[2,19,41]	[110,111]
			Nutrient transformation	**Archaea**	[19,41]	[177–181]
				Bacteria	[2,19,41]	[80,180–189]
				Fungi	[2,19,41]	[182,184,186,190,191]
				Plants	[2,19]	[192–197]
			Mineralization	**Bacteria**	[19,41]	[184,187]
				Fungi	[19,41]	[175,184,198]
			Aggregation	**Ants**	[19]	[44,70,71]
				Earthworms	[2,19,41]	[20,45,70–75]

SNSS Function	ES Section	ES Class	Process	Actor	Key references	Specific references
		Decomposition and fixing processes	Aggregation	**Collembola**	[19]	[76]
				Enchytraeids	[19,41]	[77–79]
				Bacteria	[19,41]	[80–83]
				Fungi	[2,19,41]	[76,81,83–91]
				Mycorrhizae	[2,19]	[76,85,86,88–92]
				Plants	[41]	[70,74,92]
				Microalgae	Own entry	[80]
			Bioturbation	**Ants**	[19,41]	[42–44]
				Earthworms	[2,19,41]	[20,42,43,45–48]
				Enchytraeids	[41]	[49]
			Food web assimilation	**Earthworms**	[41]	[199]
				Acari	[41]	[199]
				Collembola	[41]	[199]
				Enchytraeids	[41]	[199]
				Nematodes	[41]	[199]
				Protozoa	[41]	[199]
				Bacteria	[41]	[199]
				Fungi	[41]	[199]
			Root foraging	**Plants**	[2,19]	[192,194,196,200–203]
			Mycorrhizal acquisition	**Mycorrhizae**	[19,41]	[204–209]
			Microbial grazing	**Earthworms**	[2,19]	[11,71,126,127]
				Acari	[19,41]	[11,128–130]
				Collembola	[2,19,41]	[11,127,129–136]
				Enchytraeids	[19]	[11]
				Nematodes	[19,41]	[11,82,127,135, 137–141]
				Protozoa	[19,41]	[139,142]
		Regulation of the chemical condition of freshwaters	Bioaccumulation	**Ants**	[41]	[50]
				Coleoptera	[41]	[51]
				Earthworms	[41]	[52–54]
				Gastropods	Own entry	[55,56]
				Collembola	[41]	[57]
				Enchytraeids	[41]	[58,59]
				Bacteria	[2,19,41]	[60,61]
				Fungi	[19]	[62–65]

SNSS Function	ES Section	ES Class	Process	Actor	Key references	Specific references
		Regulation of the chemical condition of freshwaters	Bioaccumulation	**Mycorrhizae**	Own entry	[36,66]
				Plants	[2]	[67–69]
			Microbial food web assimilation	**Bacteria**	[41]	[199]
				Fungi	[41]	[199]
			Root foraging	**Plants**	[2,19]	[192,194,196,200–203]
			Mycorrhizal acquisition	**Mycorrhizae**	[19,41]	[204–209]

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Appendix 2 Simplified CICES list

Appendix table 2 – Simplified CICES list for biotic Ecosystem Services (ES). ES Classes in bold were retained under the ConSoil project, other ES Classes were not retained. The full list of ES considered under the CICES can be found under https://cices.eu/resources/ (Version 5.1).

Section	Division	Group	Class	Code
Provisioning (Biotic)	Biomass	Cultivated terrestrial plants for nutrition, materials or energy	**Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes**	**1.1.1.1**
			Fibres and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials)	**1.1.1.2**
			Cultivated plants (including fungi, algae) grown as a source of energy	**1.1.1.3**
		Cultivated aquatic plants for nutrition, materials or energy	Plants cultivated by in- situ aquaculture grown for nutritional purposes	1.1.2.1
			Fibres and other materials from in-situ aquaculture for direct use or processing (excluding genetic materials)	1.1.2.2
			Plants cultivated by in- situ aquaculture grown as an energy source	1.1.2.3
		Reared animals for nutrition, materials or energy	Animals reared for nutritional purposes	1.1.3.1
			Fibres and other materials from reared animals for direct use or processing (excluding genetic materials)	1.1.3.2
			Animals reared to provide energy (including mechanical)	1.1.3.3
		Reared aquatic animals for nutrition, materials or energy	Animals reared by in-situ aquaculture for nutritional purposes	1.1.4.1
			Fibres and other materials from animals grown by in-situ aquaculture for direct use or processing (excluding genetic materials)	1.1.4.2
			Animals reared by in-situ aquaculture as an energy source	1.1.4.3
		Wild plants (terrestrial and aquatic) for nutrition, materials or energy	Wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition	1.1.5.1
			Fibres and other materials from wild plants for direct use or processing (excluding genetic materials)	1.1.5.2

Section	Division	Group	Class	Code
			Wild plants (terrestrial and aquatic, including fungi, algae) used as a source of energy	1.1.5.3
		Wild animals (terrestrial and aquatic) for nutrition, materials or energy	Wild animals (terrestrial and aquatic) used for nutritional purposes	1.1.6.1
			Fibres and other materials from wild animals for direct use or processing (excluding genetic materials)	1.1.6.2
			Wild animals (terrestrial and aquatic) used as a source of energy	1.1.6.3
	Genetic material from all biota (including seed, spore or gamete production)	Genetic material from plants, algae or fungi	**Seeds, spores and other plant materials collected for maintaining or establishing a population**	**1.2.1.1**
			Higher and lower plants (whole organisms) used to breed new strains or varieties	1.2.1.2
			Individual genes extracted from higher and lower plants for the design and construction of new biological entities	1.2.1.3
		Genetic material from animals	Animal material collected for the purposes of maintaining or establishing a population	1.2.2.1
			Wild animals (whole organisms) used to breed new strains or varieties	1.2.2.2
		Genetic material from organisms	Individual genes extracted from organisms for the design and construction of new biological entities	1.2.2.3
	Other types of provisioning service from biotic sources	Other	Other	1.3.X.X
Regulation & Maintenance (Biotic)	Transformation of biochemical or physical inputs to ecosystems	Mediation of wastes or toxic substances of anthropogenic origin by living processes	**Bio-remediation by micro-organisms, algae, plants, and animals**	**2.1.1.1**
			Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals	**2.1.1.2**
			Smell reduction	2.1.2.1

Section	Division	Group	Class	Code
		Mediation of nuisances of anthropogenic origin	Noise attenuation	2.1.2.2
			Visual screening	2.1.2.3
	Regulation of physical, chemical, biological conditions	Regulation of baseline flows and extreme events	**Control of erosion rates**	**2.2.1.1**
			Buffering and attenuation of mass movement	2.2.1.2
			Hydrological cycle and water flow regulation (Including flood control, and coastal protection)	**2.2.1.3**
			Wind protection	2.2.1.4
			Fire protection	2.2.1.5
		Lifecycle maintenance, habitat and gene pool protection	**Pollination (or 'gamete' dispersal in a marine context)**	**2.2.2.1**
			Seed dispersal	**2.2.2.2**
			Maintaining nursery populations and habitats (Including gene pool protection)	**2.2.2.3**
		Pest and disease control	**Pest control (including invasive species)**	**2.2.3.1**
			Disease control	**2.2.3.2**
		Regulation of soil quality	**Weathering processes and their effect on soil quality**	**2.2.4.1**
			Decomposition and fixing processes and their effect on soil quality	**2.2.4.2**
		Water conditions	**Regulation of the chemical condition of freshwaters by living processes**	**2.2.5.1**
			Regulation of the chemical condition of salt waters by living processes	2.2.5.2

Section	Division	Group	Class	Code
		Atmospheric composition and conditions	**Regulation of chemical composition of atmosphere and oceans**	**2.2.6.1**
			Regulation of temperature and humidity, including ventilation and transpiration	2.2.6.2
	Other types of regulation and maintenance service by living processes	Other	Other	2.3.X.X