

SPECIAL ISSUE ARTICLE

Towards a standardization of soil-related ecosystem service assessments

Carsten Paul¹  | Kristin Kuhn² | Bastian Steinhoff-Knopp² |
Peter Weißhuhn¹ | Katharina Helming^{1,3}

¹Leibniz Centre for Agricultural Landscape Research (ZALF), Muencheberg, Germany

²Institute of Physical Geography and Landscape Ecology, Leibniz University Hannover, Hannover, Germany

³Faculty of Landscape Management and Nature Conservation, University for Sustainable Development (HNEE), Eberswalde, Germany

Correspondence

Carsten Paul, Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Street 84, 15374, Muencheberg, Germany.
Email: paul@zalf.de

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Abstract

The concept of ecosystem services (ES) creates understanding of the value of ecosystems for human well-being. With regard to soils, it provides a framework for assessments of soil contributions and soil management impacts. However, a lack of standardization impedes comparisons between assessment studies and the building of synthesis information. The Common International Classification of Ecosystem Services (CICES) is an important step forward, although its application to soils is not without difficulty. CICES version 5.1 defines 83 ES classes, of which only some are relevant for soils. We compiled two subsets of CICES classes: one set of soil-related ES comprising 29 services defined as directly and quantifiably controlled by soils and their properties, processes and functions, and another set of 40 ES defined as being affected by agricultural soil management. Additionally, we conducted a systematic literature review, searching for published lists of soil-related ES that claim completeness. We identified 11 relevant lists. Of all CICES classes, 12 were included in more than 75% of the lists, whereas another 36 classes were included in 25–75% of them. Regarding the suitability of the CICES classification for addressing ES in the context of soils and their agricultural management, we identified constraints, such as overlaps, gaps, and highly specific or very broad class definitions. Close cooperation between the soil research and ES communities could ensure better consideration of soils in future CICES updates. A shortlist of 25 service classes affected by agricultural soil management facilitates a standardized approach and may function as checklists in impact assessments.

Highlights

- Standardized definitions are needed to allow meta-analysis of ecosystem service studies and improve assessments.
- CICES defines 83 detailed classes of ecosystem services, suggested as a “default list”.
- We identified 29 classes as soil related and 40 classes as affected by agricultural soil management.
- Both subsets facilitate ecosystem service assessments in soil research and comparability of results.

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KEYWORDS

agriculture, arable, CICES, impact area, impact assessment, soil functions, soil management, soil properties, standardization

1 | INTRODUCTION

Soils are of the highest importance for the well-being of societies. This is highlighted in the concept of soil functions, which first gained prominence through the proposed European Soil Thematic Strategy (European Commission, 2006). Therein, seven soil functions are defined, namely the production of biomass, the storing, filtering and transforming of nutrients, substances and water, the provision of a physical and cultural basis for humans and their activities, the provision of habitats and gene pools, the function as a source of raw materials, and the function as geological and archaeological archives. Although this classification into a small number of soil functions is well suited for enabling policy and stakeholder dialogue on the societal significance of soils, the wide definition of each function is impractical for scientific analysis of the complex and dynamic interactions between soil management and soil functioning. Additionally, the exclusive focus on soils impedes the adoption of a wider ecosystem perspective, which is indispensable for sustainability assessments of soil management. Here, the ecosystem services (ES) concept provides a relevant framework for integration (Costanza et al., 1997; Daily, 1997; Helming, Diehl, Geneletti, & Wiggering, 2013; MEA, 2005). ES are defined as the contributions of ecosystem structure and function (in combination with other inputs) to human well-being (Burkhard & Maes, 2017). The concept is well established in both research and policy making (Costanza et al., 2017; IPBES, 2019). Since Dominati, Patterson, and Mackay (2010) created a basis for analysing ES in relation to soils, an increasing body of literature dealing with the importance and conceptual integration of soils into the ES approach has been published. The subject is discussed in relation to the concept of soil functions (e.g., Adhikari & Hartemink, 2016), soil threats (Schwilch et al., 2016), soils as natural capital (e.g., Robinson, Lebron, & Vereecken, 2009), institutional economics (Bartkowski, Hansjurgens, Mockel, & Bartke, 2018), sustainable development goals (Keesstra et al., 2016) and sustainability assessments (Helming et al., 2018). The implementation of the ES concept to assess the role of soils requires a standardized approach to indicator development for soil-related ES supply. This includes the role of soil management and anthropogenic driving forces.

Defining ES supplied by soils is problematic because ES are usually the result of interactions between multiple ecosystem compartments, including soils (Adhikari & Hartemink, 2016). For example, the provision of food from agricultural crops relies on soil properties, on climatic variables such as rainfall, sunlight and temperature, and on human interventions such as sowing or fertilizing. The same example also highlights that ES controlled by soils and their agricultural management extend beyond the soil surface, as crops growing in the soil also form aboveground habitats and may determine the visual aspect of cultural landscapes. To account for the fact that ES are not exclusively provided by soils but that soils make a contribution that determines how well some services are supplied, this paper uses the term *soil-related ecosystem service*. Within a well-defined context, the supply of these services can therefore be estimated from soil physical, chemical or biological parameters. To account for the fact that soil management affects ES at multiple scales and that those services extend beyond the soil surface, this paper refers to *ecosystem services affected by agricultural soil management*. These services need to be considered when assessing the sustainability of agricultural management.

Research on ES is as diverse as ecosystems themselves. Different definitions and categorizations impede a direct comparison between studies. This lack of standardization also limits upscaling of case study results to global assessments and the potential of text mining approaches. Global assessments become increasingly important to support governance and policy in decision making on complex socioecological processes. Examples are assessments related to climate change (IPCC, 2019), biodiversity (IPBES, 2019), or the environment in general (UN Environment, 2019), all of which also prominently address soils. These assessments have to synthesize across thematic domains and local contexts, which is only possible with standardized metrics and indicators (Magliocca et al., 2018; Minx, Callaghan, Lamb, Garard, & Edenhofer, 2017). The magnitude and rapid expansion of the literature in this field make it necessary to apply automated data mining and text analysis techniques (Minx et al., 2017) for which standardized terminologies and indicators are a prerequisite (Höfing et al., 2019). For ES, these methods facilitate quantitative reviews, the construction of large data repositories, and finally the

compilation of global evidence on the supply of ES to increase policy relevance. In this regard, the Common International Classification of Ecosystem Services (CICES) (Haines-Young & Potschin, 2018) developed on behalf of the European Environment Agency (EEA) constitutes an important step forward (Schwilch et al., 2016). It builds on earlier classifications provided by the Millennium Ecosystem Assessment (MEA, 2005) and the Economics of Ecosystems and Biodiversity (TEEB, 2010). The latest CICES version (V5.1) was launched in January 2018 and distinguishes 83 classes of ES.

Although the high number of service classes in the CICES allows the detailed analysis of very different ecosystems, it is also impractical for most research contexts. Not all of the service classes are relevant for each research question and ecosystem. The definition of subsets relevant for specific assessments is a critical step to increase the applicability of the CICES. Identifying soil-related ES will help to better integrate soil research into the wider context of ES and socioecological systems research. Identifying the ES affected by agricultural soil management provides a necessary tool for the sustainability assessment of agricultural management options (Helming et al., 2018). In this regard, a complete picture is indispensable because consideration of only a selection of the relevant ES may create biased assessment results (Paul & Helming, 2019). Until now, a clear categorization of the CICES classes relevant for soils and their agricultural management is lacking. Although multiple authors list soil-related ES (Adhikari & Hartemink, 2016; Keesstra et al., 2016) or ES affected by agricultural soil management (Stavi, Bel, & Zaady, 2016), none of them lists soil-related ES at the level of CICES classes. Furthermore, whether the sets of ES compiled by these authors are identical or whether they differ has not yet been investigated.

With regard to soils and the CICES classification, the objectives of this paper are to:

- A. develop a subset of *soil-related ecosystem services* in the CICES and compare it to the soil-related ecosystem services identified in the literature;
- B. create a subset of *ecosystem services affected by agricultural soil management* to facilitate sustainability assessments of soil management options and to integrate them with assessments of soil-related ecosystem services; and
- C. assess the suitability of the CICES to reflect soil-related ecosystem services and ecosystem services affected by agricultural soil management, and formulate recommendations for future updates of the CICES to better integrate the role of soils and their management.

2 | MATERIALS AND METHODS

2.1 | Description of the CICES classification

CICES has been designed to help measure, account for and assess ES in a standardized way. Standardization is key to compile larger environmental databases with the potential to derive more meaningful conclusions for a good management of ecosystems. In this regard, CICES is one of several internationally utilized typologies of ES. It is the most detailed classification with a linguistic taxonomy that follows a strict nested hierarchical structure and is very influential in the European Union (Czucz et al., 2018). Compared to other international ES typologies, CICES is more universal (i.e., less specific to particular environments and particular beneficiaries) (La Notte & Rhodes, 2020). Therefore, CICES promises to avoid gaps and overlaps in the definition of ES and to work towards a global standard of ES classification.

CICES has been developed on behalf of the European Environment Agency (EEA), contributing to the revision of the international System of Economic and Environmental Accounting (SEEA) (Haines-Young & Potschin, 2012). In the context of environmental economic accounting, ES derive from stocks of natural capital in combination with manufactured capital and human capital to produce human welfare (Costanza et al., 1997). Thus, the definition of ES as the contributions of ecosystem structure and function in combination with other inputs to human well-being (Burkhard et al., 2012) is the basis for CICES.

The latest version of CICES (V5.1) was released in January 2018 and is referred to throughout this manuscript. The update includes more systematic approaches to naming and describing ES, as well as examples for measurable goods and benefits suitable as indicators. In former versions, CICES focused on ES that depend on living systems (i.e., on biodiversity in its broadest sense). Version 5.1 also includes services arising from abiotic ecosystem structures and processes (Haines-Young & Potschin, 2018).

CICES follows a strict hierarchical structure. At the highest or most general level the services are divided into those provided by biotic ecosystem components (“living systems”) and services arising from abiotic components, each subdivided into the three sections “provisioning services”, “regulation & maintenance services” and “cultural services”. These are further subdivided into “divisions”, “groups” and “classes” (Haines-Young & Potschin, 2018). Other classifications, such as the Millennium Ecosystem Assessment (MEA, 2005) or the Economics of Ecosystem Services and Biodiversity (TEEB, 2010), also include so-

called “supporting services”. These are considered to be services that mainly support other ES and that impact humans only indirectly or over very long timespans (MEA, 2005). In CICES, supporting services are not recognized because the concept is considered to conflict with the anthropocentric definition of ES (Haines-Young & Potschin, 2018; Potschin-Young et al., 2017). Several services grouped into the respective categories by the MEA or TEEB frameworks are, however, included in the CICES as “regulation and maintenance services”, such as the supply of nursery populations and habitats (2.2.2.3) or the regulation of the hydrological cycle and flood control (2.2.1.3).

For this work, we focus on the class level, which is the level typically used for ES assessments (Paul & Helming, 2019). CICES defines 83 specific classes representing 56 biotic and 27 abiotic services. Each class is identified by a four-digit code, whereby the first digit identifies the “section”, the second the “division” within this “section”, the third the “group” within this “division” and the last the “class” within this “group”. Throughout this manuscript, we use the letter “X” to refer to all elements of a specific hierarchical level. For example, 2.X.X.X stands for all classes belonging to Section 2: “Regulation & Maintenance (Biotic)”. CICES also encourages users to define additional classes as required and provides codes for these generic classes.

Unfortunately, the original names assigned to the classes are sometimes lengthy or require additional information to be understood. Throughout this manuscript, we therefore use simplified class names of no more than 50 characters. To aid intuitive understanding, names were derived by combining elements of the original name with information from higher hierarchical levels. Additionally, the class code is always provided to allow for exact identification.

2.2 | Selecting soil-related ecosystem services

The supply of a wide range of ES depends on soil properties, processes and functions. The definition of the so-called *soil-related ecosystem services* refers to the frameworks by Dominati et al. (2010) and Adhikari and Hartemink (2016), emphasizing the link between soil properties and related ES. The correlation between the service supply and specific soil properties enables the assessment of soil-related ES based on these measurable soil properties and their dynamics. Accordingly, ES are soil related if their supply is directly and quantifiably controlled by soils and their properties, processes and functions. For example, the filtration of water is regulated

by soil properties such as pore size or bulk density. Methods and proxies to quantify the supply of these services can therefore be supported by the assessment of soil parameters. In order to enable comparable assessments of soil-related ES, a predefined subset of soil-related ES is needed. We checked the 83 CICES classes to develop such a subset. The expert-based decision to include a service was dependent on its direct and quantifiable control through soil properties.

2.3 | Selecting ecosystem services affected by agricultural soil management

Agriculture is the main human activity causing changes to soil properties and their ability to deliver ES. The assessment of agricultural soil management on the supply of ES is therefore paramount in socioecological systems. To allow for this, we created a second CICES subset of ES that are affected by agricultural soil management. Although this list largely overlaps with the list of soil-related ES described above, there are also fundamental differences. Firstly, the supply of some services may be affected by soil properties, but not by soil management, such as service 2.2.4.1 *Soil quality by weathering processes*. Secondly, the supply of a service may not be related to an agricultural context, such as service 1.1.5.1 *Wild plants (terrestrial and aquatic) for nutrition* or service 4.3.1.2 *Mineral substances for materials*. Thirdly, agricultural soil management may also affect the supply of ES that are not determined by soil properties and their functions. Examples are effects of land cover on *Pollination* (2.2.2.1) or on the *Aesthetics from interactions with nature* (3.1.2.4).

Starting with the full set of ES classes in the CICES, we used a process of systematic elimination to derive a list of services affected by agricultural soil management. From the biotic ES, those provided by animals or aquacultures were removed for lacking a direct connection to soils. Provisioning services by organisms in the wild, noise attenuation and smell reduction were removed because they are mostly irrelevant in the context of agricultural management. The same criteria were applied to the abiotic ES, resulting in a removal of most services, with the exception of services related to water provision (4.2.1.1, 4.2.1.2, 4.2.2.1, 4.2.2.2), the *Control of liquid flows* (5.2.1.2) and the *Abiotic filtration, sequestration and storage of wastes* (5.1.1.3).

In a second step, we divided the remaining services into those relevant for the assessment of agricultural soil management practices in most intensively managed agricultural systems, and those relevant only under specific territorial or soil management circumstances (e.g., protection from landslides, fire protection, and religious meaning).

TABLE 1 Soil-related ecosystem services. Common International Classification of Ecosystem Services (CICES) class names were simplified to aid intuitive understanding [Color table can be viewed at wileyonlinelibrary.com]

CICES code	Biotic provisioning services	CICES code	Biotic regulation & maintenance services
1.1.1.1	Cultivated terrestrial plants for nutrition	2.1.1.1	Biotic remediation of waste
1.1.1.2	Cultivated terrestrial plants for materials	2.1.1.2	Biotic filtration, sequestration and storage of waste
1.1.1.3	Cultivated terrestrial plants for energy	2.2.1.1	Erosion control
1.1.5.1	Wild plants (terrestrial and aquatic) for nutrition	2.2.1.3	Hydrological cycle and flood control
1.1.5.2	Wild plants (terrestrial and aquatic) for materials	2.2.2.3	Nursery populations and habitats
1.1.5.3	Wild plants (terrestrial and aquatic) for energy	2.2.3.1	Pest control (including invasive species)
1.2.1.1	Genetic material from plants to maintain populations	2.2.3.2	Disease control
1.2.1.2	Genetic material from plants for breeding	2.2.4.1	Soil quality by weathering processes
	Abiotic provisioning services	2.2.4.2	Soil quality by decomposition and fixing processes
4.2.1.1	Surface water for drinking	2.2.5.1	Chemical condition of freshwaters
4.2.1.2	Surface water for non-drinking purposes	2.2.5.2	Chemical condition of salt waters
4.2.2.1	Groundwater for drinking	2.2.6.1	Chemical composition of atmosphere and oceans
4.2.2.2	Groundwater for non-drinking purposes	2.2.6.2	Local regulation of air temperature and humidity
4.3.1.1	Mineral substances for nutrition		Abiotic regulation & maintenance services
4.3.1.2	Mineral substances for materials	5.1.1.3	Abiotic filtration, sequestration and storage of waste
		5.2.1.2	Control of liquid flows

Note: Original compilation.

2.4 | Reviewing published lists of soil-related ecosystem services in the literature

We carried out a literature review to collate lists of soil-related ES published by other authors. We searched for evidence in the Web of Science Core Collection in November 2019 under a basic search string containing different synonyms for the term “soil-related ecosystem services”: (“soil-related ecosystem service*”) OR (“soil ecosystem service*”) OR (“soil service*”) OR (“soil ES”) in title, abstract, keywords and *Keywords Plus*. No restrictions were applied concerning the publication year. Only peer-reviewed publications originally published in English were considered for the screening phase. Screening was carried out on full texts. Papers were considered relevant for data extraction if they contained lists or overviews of soil-related ES with a claim for completeness, either in text, graphs or tables. Where we encountered relevant lists cited from publications not identified through our search, we added the respective papers. Publications that only contained cited lists of soil-related ES were excluded, whereas for lists by the same first author that only differ in minor aspects, only the latest publication was considered.

Lists of soil-related ES of relevant publications were extracted and reassigned to the ES classes provided by CICES. Matching the labels individually assigned by various authors to the strictly defined classes required

interpretation. The main difficulty was that CICES distinguishes between services provided by biotic and abiotic ecosystem components. As soils are by definition systems of interrelated biotic and abiotic components, we had to match many soil-related service classes mentioned in the literature to more than one CICES class, resulting in a higher number of services in the reassigned list.

3 | RESULTS

3.1 | Soil-related ecosystem services

Of the 83 classes defined in the CICES, we identified 29 classes that we consider soil related, comprising 14 provisioning services and 15 regulation and maintenance services (Table 1). The set does not include any of the cultural services listed in CICES, because cultural ES are not directly and quantifiably determined by soil properties, processes or functions. Nevertheless, soils have great cultural importance, mainly interrelated with other landscape compartments. For example, in Germany, specific soils altered by historical management practices, such as pluggen soils created in the Middle ages (Blume & Leinweber, 2004), are protected as cultural heritage. Furthermore, many religious beliefs refer specifically to the earth (Dominati et al., 2010).

3.2 | Ecosystem services affected by agricultural soil management

Of the identified 40 classes that were affected by agricultural soil management, nine were provisioning services, 20 were regulation and maintenance services, and 11 were cultural services (Table 2). Twenty-five of these services comprise a shortlist that we suggest should be considered in any impact assessment of agricultural soil management, as these ES are typically affected by intensive soil management. Whether the other 15 classes need to be considered in an assessment of soil management depends on the context and should be evaluated on a case-by-case basis.

3.3 | Reviewed soil-related ES lists

The need for a better characterization of ES supplied by soils and the call for a better understanding of soil-related ES bundles was addressed by Daily, Matson, and Vitousek (1997) more than two decades ago. Here we provide an overview of soil-related ES compilations that have been published since then. Our search of the Web of Science Core Collection identified a total of 201 results on the general topic of soil-related ES. The number of publications on the topic per year grew constantly after 2010, reaching 41 papers in 2019. We added another two papers that were mentioned in the identified literature as being relevant and another three papers that included previous and later versions of a list detected in the initial search.

We found 11 lists of soil-related ES that claimed completeness (Table 3). Of these, five were developed for specific circumstances such as urban soils (Teixeira da Silva et al., 2018) or specific territories (Bennett et al., 2010; Haygarth & Ritz, 2009; Prado et al., 2016), or had a focus on soil threats (Schwilch et al., 2016).

Most authors did not provide details on their selection criteria or an explanation for their choice of services. Exceptions are Rinot et al. (2019), who require that services must be quantifiable, and Adhikari and Hartemink (2016), who list the linkages between each of their ES and a set of “key soil properties”.

The median number of services defined in the published lists is 18, ranging from 11 (Bennett et al., 2010) to 27 (Robinson et al., 2014). Bennett et al. (2010) also defined four disservices. As outlined in Section 2.4, reassigning the services listed in the reviewed literature to CICES classes resulted in a higher number of services than originally published: a median of 18 services were reassigned to 32 classes (Table 3). The set provided by Pavan and Ometto (2018) contained the most classes (45) that were relevant with regard to soils. Focusing on

mitigating soil threats, Schwilch et al. (2016) listed only 20 services.

Due to the detailed classification in CICES, on average (median), only 11 out of 39 provisioning services are judged to be soil related. In relation to the number of services defined in CICES, cultural services are most often included in the reviewed lists, with a median of eight (out of 15). Although Pavan and Ometto (2018) include all cultural services, three lists do not consider cultural services at all (Bennett et al., 2010; Rinot et al., 2019; Schwilch et al., 2016). Six reviewed lists include services that cannot be matched to any CICES class. Most often (five times) this referred to soils as a *physical base* (also labelled “platform” or “physical support”), a service closely related to the soil function “physical and cultural basis for humans and their activities” defined in the European Soil Thematic Strategy (European Commission, 2006). Another item was the service *primary production*, recognized in MEA (2005) as a supporting service. Neither service has an equivalent in CICES.

Depending on their occurrence in the reviewed literature, we grouped the CICES classes into four categories:

- A. Classes with a consolidated direct soil relation, included in 9–11 of the analysed lists (upper quartile).
- B. Classes with a direct relationship with soil under discussion, included in three to eight of the analysed lists (interquartile).
- C. Classes without a direct relationship to soil, included in one or two of the analysed lists.
- D. Classes without a direct relationship to soil and not included in any of the analysed lists.

Category A: seven provisioning and five regulation and maintenance services add up to 12 classes with high agreement on their relevance for soil-related ES (see Table 4). Of these, four regulating services are included in all 11 lists, namely: *Hydrological cycle and flood control* (2.2.1.3), *Chemical composition of atmosphere and oceans* (2.2.6.1), *Abiotic filtration, sequestration and storage of waste* (5.1.1.3) and *Control of liquid flows* (5.2.1.2). In addition, the three provisioning services from cultivated terrestrial plants (1.1.1.X) are considered in all lists. Classes of category A seem to be most relevant and should be included in any assessment of soil-related ES.

Category B: a large number of 36 classes is marked relatively often as being soil related; 14 of these are cultural services, 11 provisioning services, and 11 regulation and maintenance services (details in Table 4). The services covered here may have great value in ES assessments and seem worth considering on a case-by-case basis.

TABLE 2 Soil management-related ecosystem services. Twenty-five services are typically affected by agricultural soil management (white background) and comprise a short list that should be considered in any impact assessment of soil management. Fifteen services (grey background) are only relevant within specific contexts (e.g., geographic peculiarities or special land uses). Common International Classification of Ecosystem Services (CICES) class names were simplified to aid intuitive understanding [Color table can be viewed at wileyonlinelibrary.com]

CICES code	Biotic provisioning services	CICES code	Biotic regulation & maintenance services
1.1.1.1	Cultivated terrestrial plants for nutrition	2.1.1.1	Biotic remediation of waste
1.1.1.2	Cultivated terrestrial plants for materials	2.1.1.2	Biotic filtration, sequestration and storage of waste
1.1.1.3	Cultivated terrestrial plants for energy	2.2.1.1	Erosion control
1.2.1.1	Genetic material from plants to maintain populations	2.2.1.3	Hydrological cycle and flood control
1.2.1.2	Genetic material from plants for breeding	2.2.2.1	Pollination
	Abiotic provisioning services	2.2.2.3	Nursery populations and habitats
4.2.1.1	Surface water for drinking	2.2.3.1	Pest control (including invasive species)
4.2.1.2	Surface water for non-drinking purposes	2.2.3.2	Disease control
4.2.2.1	Groundwater for drinking	2.2.4.2	Soil quality by decomposition and fixing processes
4.2.2.2	Groundwater for non-drinking purposes	2.2.5.1	Chemical condition of freshwaters
		2.2.6.1	Chemical composition of atmosphere and oceans
		2.2.6.2	Local regulation of air temperature and humidity
CICES code	Biotic cultural services		
3.1.1.1	Recreation through activities in nature	2.1.2.3	Visual screening
3.1.1.2	Recreation through observation of nature	2.2.1.2	Mass movement control
3.1.2.3	Culture or heritage from interactions with nature	2.2.1.4	Wind protection
3.1.2.4	Aesthetics from interactions with nature	2.2.1.5	Fire protection
3.1.2.1	Scientific interactions with nature	2.2.2.2	Seed dispersal
3.1.2.2	Education and training interactions with nature	2.2.5.2	Chemical condition of salt waters
3.2.1.1	Symbolic meaning of nature		Abiotic regulation & maintenance services
3.2.1.2	Spiritual meaning of nature	5.1.1.3	Abiotic filtration, sequestration and storage of waste
3.2.1.3	Entertainment value of nature	5.2.1.2	Control of liquid flows
3.2.2.1	Existence value of nature		
3.2.2.2	Option or bequest value of nature		

Note: Original compilation.

Categories C and D: 17 classes were included in only one or two lists identified by our review and another 18 classes were not mentioned at all and thus might be considered unusual for soil-related ES, or perhaps overlooked. Details on these classes without a direct soil-relation can be viewed in our complete overview of all CICES classes in Appendix S1.

3.4 | Comparison of our lists of soil-related ES and soil management-related ES with the soil-related ES lists from the literature

The 12 classes of category A showing high agreement on ES with a direct relation to soils have also been included in our list of soil-related ES. However, regarding our list

of soil management-related ES there were slight differences. The provisioning ES classes dependent on wild plants (1.1.5.X) were not considered relevant for agricultural ecosystems. The same applies to class 4.3.1.2 *Mineral substances for materials* (cf. Table 4). Still, most of the classes of category A were considered relevant also for agricultural soil management.

Regarding the classes of category B, which were included less often in the lists of soil-related ES identified in our review, the picture is far more diverse (cf. Table 4). Our own list of soil-related ES matched with 17 out of the 36 classes with a soil-relation under discussion. Matching classes include 10 services from the biotic regulation and maintenance ES (2.X.X.X), as well as five classes from the abiotic provisioning ES (4.X.X.X), the latter referring to surface water, groundwater and minerals for nutrition. The final two matches were the biotic

TABLE 3 Publications with a list of soil-related ecosystem services claiming completeness

#	Short reference (specific focus)	Number of services in published list	Number of reassigned CICES classes				Number of services not included in CICES
			total	provisioning	regulating	cultural	
1	Adhikari and Hartemink (2016)	18	40	17	11	12	0
2	Dominati et al. (2010); (2014)	12	23	7	8	8	1
3	Jónsson and Davíðsdóttir (2016)	16	26	11	9	6	0
4	Robinson et al. (2012); (2013a; 2013b; 2014)	27	32	11	13	8	4
5	Rinot, Levy, Steinberger, Svoray, and Eshel (2019)	13	26	13	13	0	0
6	Pavan and Ometto (2018)	22	45	14	16	15	0
7	Bennett, Mele, Annett, and Kasel (2010) (Australia)	11	24	11	13	0	1 (+ 4 disservices)
8	Prado et al. (2016) (Brazil)	18	43	18	14	11	2
9	Haygarth and Ritz (2009) (UK)	18	33	11	11	11	2
10	Schwilch et al. (2016) (Mitigating soil threats)	18	20	6	14	0	0
11	Teixeira da Silva, Fleskens, van Delden, and van der Ploeg (2018) (Urban soils)	17	33	10	16	7	1
MEDIAN		18	32	11	13	8	1

Abbreviation: CICES, Common International Classification of Ecosystem Services.

provisioning ES *Genetic material from plants for breeding* and *Genetic material from plants to maintain populations* (1.2.1.2 and 1.2.1.1), relating to the soil seed bank. The remarkable difference of 19 classes is largely due to cultural ES (14 classes), which were not included at all in our list (cf. Methods section). Further differences concern all *Genetic material from animals* (1.2.2.X) and *Genetic material from plants for designing organism* (1.2.1.3) in particular, as well as *Control of gaseous flows* (5.2.1.3), which is considered an abiotic regulation and maintenance ES in CICES. Regarding our list of soil management-related ES, the agreement was higher. Of the 36 classes for which a soil-relation is under discussion in the literature, 25 classes matched with our list, whereas 11 did not. As before, the classes belonging to the section 'biotic regulation & maintenance ES' matched (2.X.X.X), except for *Soil quality by weathering processes* (2.2.4.1), which is obviously soil related but not directly related to soil management. Interestingly, by taking the management into account, all biotic cultural ES (3.X.X.X) became relevant for soils. Additional matches between the soil-related ES lists from the literature and our list of soil management-related ES were the services *Genetic material from plants to maintain populations* and *Genetic*

material from plants for breeding (1.2.1.1 and 1.2.1.2). On the other hand, *Genetic material from plants for designing organisms* (1.2.1.3) and generally all classes referring to *Genetic material from animals* (1.2.2.X) were not included in our list. Differences also exist for four abiotic cultural ES (6.X.X.X). Likewise, the ES *Mineral substances for nutrition* (4.3.1.1) is discussed in the literature as being soil related, but not included in our list of agricultural soil management-related ES.

Of the 17 classes of category C, only *Non-mineral substances for materials* (4.3.2.2) was included in our subset of soil-related ES, indicating broad accordance. In contrast, five regulating services and one cultural service were included in our subset of soil management-related ES. We argue that although the supply of these services is not determined by soil properties, it is strongly influenced by soil management. For example, *Pollination* (2.2.2.1) was included because soils and vegetation in agricultural fields function as pollinator habitats and the quality of these habitats is determined by agricultural management (Kremen, Williams, & Thorp, 2002; Lentini, Martin, Gibbons, Fischer, & Cunningham, 2012).

The comparison of our list of soil-related ES with the 18 classes of category D revealed full concordance.

TABLE 4 CICES classes with direct soil-relation based on our literature review

CICES code	Class	Number of references	Soil-related ES	Soil management-related ES
Category A classes (9–11 references)				
1.1.1.1	Cultivated terrestrial plants for nutrition ^{1–11}	11	x	x
1.1.1.2	Cultivated terrestrial plants for materials ^{1–11}	11	x	x
1.1.1.3	Cultivated terrestrial plants for energy ^{1–11}	11	x	x
1.1.5.1	Wild plants (terrestrial and aquatic) for nutrition ^{1–5,11}	10	x	
1.1.5.2	Wild plants (terrestrial and aquatic) for materials ^{1–5,11}	10	x	
1.1.5.3	Wild plants (terrestrial and aquatic) for energy ^{1–5,11}	10	x	
2.2.1.3	Hydrological cycle and flood control ^{1–11}	11	x	x
2.2.2.3	Nursery populations and habitats ^{1,3,5–11}	9	x	x
2.2.6.1	Chemical composition of atmosphere and oceans ^{1–11}	11	x	x
4.3.1.2	Mineral substances for materials ^{1–9}	9	x	
5.1.1.3	Abiotic filtration, sequestration and storage of waste ^{1–11}	11	x	x
5.2.1.2	Control of liquid flows ^{1–11}	11	x	x
Category B classes (3–8 references)				
1.2.1.1	Genetic material from plants to maintain populations ^{1,5,8}	3	x	x
1.2.1.2	Genetic material from plants for breeding ^{1,5,8}	3	x	x
1.2.1.3	Genetic material from plants for designing organism ^{1,5,8}	3		
1.2.2.1	Genetic material from animals to maintain populations ^{1,5,8}	3		
1.2.2.2	Genetic material from animals for breeding ^{1,5,8}	3		
1.2.2.3	Genetic material from animals for designing organism ^{1,5,8}	3		
2.1.1.1	Biotic remediation of waste ^{2–4,6–8,10,11}	8	x	x
2.1.1.2	Biotic filtration, sequestration and storage of waste ^{2–4,6–8,10,11}	8	x	x
2.2.1.1	Erosion control ^{1,5,6,8–11}	7	x	x
2.2.3.1	Pest control (including invasive species) ^{2–5,7,8,10,11}	8	x	x
2.2.3.2	Disease control ^{2–5,7,8,10,11}	8	x	x
2.2.4.1	Soil quality by weathering processes ^{1,5,6,8–11}	7	x	
2.2.4.2	Soil quality by decomposition and fixing processes ^{1,4–6,8–11}	8	x	x
2.2.5.1	Chemical condition of freshwaters ^{1,4–9}	7	x	x
2.2.5.2	Chemical condition of salt waters ^{1,4–9}	7	x	x
2.2.6.2	Local regulation of air temperature and humidity ^{4,7,10,11}	4	x	x
3.1.1.1	Recreation through activities in nature ^{1–4,6,8,9}	7		x
3.1.1.2	Recreation through observation of nature ^{1–4,6,8,9}	7		x
3.1.2.1	Scientific interactions with nature ^{1,3,4,6,8,9,11}	7		x
3.1.2.2	Education and training interactions with nature ^{1,6,8,9,11}	5		x
3.1.2.3	Culture or heritage from interactions with nature ^{1–4,6,8,9,11}	8		x
3.1.2.4	Aesthetics from interactions with nature ^{1,2,4,6,8,9,11}	7		x
3.2.1.1	Symbolic meaning of nature ^{4,6,8}	3		x
3.2.1.2	Spiritual meaning of nature ^{6,8,11}	3		x
3.2.2.1	Existence value of nature ^{1,2,6}	3		x
3.2.2.2	Option or bequest value of nature ^{1,2,6}	3		x
4.2.1.1	Surface water for drinking ^{1,3,7–9,11}	6	x	x
4.2.1.2	Surface water for non-drinking purposes ^{1,3,7–9,11}	6	x	x

(Continues)

TABLE 4 (Continued)

CICES code	Class	Number of references	Soil-related ES	Soil management-related ES
4.2.2.1	Groundwater for drinking ^{1,3,7–9,11}	6	x	x
4.2.2.2	Groundwater for non-drinking purposes ^{1,3,7–9,11}	6	x	x
4.3.1.1	Mineral substances for nutrition ^{4,6,8}	3	x	
5.2.1.3	Control of gaseous flows ^{1,5,7,9,11}	5		
6.1.1.1	Recreational interactions with abiotic nature ^{1–4,6,8,9}	7		
6.1.2.1	Intellectual interactions with abiotic nature ^{1,3,6,8,9,11}	6		
6.2.1.1	Symbolic and spiritual meaning of abiotic nature ^{1,2,4,6,8,9,11}	7		
6.2.2.1	Non-use value of abiotic nature ^{1,6,9}	3		

Note: Those classes that have been included in most comprehensive lists of soil-related ES (Category A) are distinguished from those with less agreement in the literature (Category B). Further, a comparison is shown with our subsets of soil-related and soil-management related ES.

Abbreviation: CICES, Common International Classification of Ecosystem Services; ES, ecosystem services.

¹Adhikari and Hartemink (2016).

²Dominati et al. (2010)³ Dominati, Mackay, Green, and Patterson (2014).

³Jónsson and Davíðsdóttir (2016).

⁴Robinson et al. (2012, 2013a, 2013b, 2014).

⁵Rinot et al. (2019).

⁶Pavan and Ometto (2018).

⁷Bennett et al. (2010).

⁸Prado et al. (2016).

⁹Haygarth and Ritz (2009).

¹⁰Schwilch et al. (2016).

¹¹Teixeira da Silva et al. (2018).

Services not included in any of the 11 lists identified in the review were also not included by us. Regarding our list of soil management-related ES, we included *Wind protection* (2.2.1.4) from category D.

4 | DISCUSSION

4.1 | The ES concept and agricultural ecosystems

The concept of ES was originally created to highlight the value of natural ecosystems for human societies (Costanza et al., 1997). These ecosystems are characterized by very limited human interventions so that the supply of all services can be considered to originate from the ecosystems themselves. However, with the publication of the Millennium Ecosystem Assessment (MEA, 2005), it became common for ES assessments to also include managed ecosystems, such as agricultural systems. For services supplied by these systems, such as the provision of food, it is very difficult to separate the influence of human intervention from the supply by the ecosystem. Although some authors have attempted to distinguish between natural and anthropogenic contributions

(Bengtsson, 2015; Jones et al., 2016; Wiggering, Weißhuhn, & Burkhard, 2016), most authors choose to consider human management as an integral part of these systems. Thus, in agricultural ecosystems the management shapes the ecosystem and controls the set of ES provided (Swinton, Lupi, Robertson, & Hamilton, 2007). For developing our lists of soil-related and agricultural soil management-related ES classes, we build on the concept that agricultural soils exhibit natural properties, which are inextricably intertwined with anthropogenic alterations, such as ploughing or irrigation. However, we acknowledge that this view reduces the relative importance of soil properties for ES supply: identical soils may provide very different service levels, depending on the type of management, such as producing different amounts of food crops due to different levels of fertilization.

4.2 | Integration of CICES and the need for standardization

The 11 reviewed lists of soil-related ES exhibit a wide diversity of ES-class definitions and nomenclatures. Although for all 11 lists of soil-related ES, the MEA (2005)

is cited as a foundation for ES definition, selection and categorization, the CICES classification system was considered less often. Only Pavan and Ometto (2018) adopt CICES V5.1 and also use its nomenclature. Schwilch et al. (2016) state that they considered CICES in their creation of a framework for assessing soil threats. Adhikari and Hartemink (2016) consider a former version of CICES (V3) in their review on soils and ES. Robinson, Hockley, et al. (2013a) and Teixeira da Silva et al. (2018) cite CICES without integrating or adopting the classification scheme. Dominati et al. (2010) provided a highly influential framework for the provision of ES from soil natural capital. It is based on the MEA typology, including supporting services that are explicitly avoided in the logic of CICES. The concept of soil as natural capital providing flows of ES and the assessment of economic value is also prominent in Robinson et al. (2012, 2014); Robinson, Hockley, et al. (2013a); Robinson, Jackson, et al. (2013b) and Jónsson and Davíðsdóttir (2016). Overall, CICES seems far from being established in soil-related ES assessments.

Nevertheless, promoting the application of the CICES classification to contribute to the standardization of ES assessments and thereby improve their relevance for policy is one central aim of this paper. For 10 of the 11 comprehensive lists of soil-related ES from the literature, the reassigning to CICES classes was subject to interpretation. For example, we assigned the ES *water flow regulation* to the classes 2.2.1.3 (*Hydrological cycle and flood control*) and 5.2.1.2 (*Control of liquid flows*). The need for interpretation due to different terminologies made it difficult to combine the findings of our review into a comprehensive list and limits the reproducibility. However, this difficulty also highlights the need for a standardized classification of ES in the context of soils and soil management.

We advocate for the definition of CICES subsets compiling ES classes relevant for assessments with specific focus or framework conditions. We present two ES lists here in the context of soils (Tables 1 and 2).

4.3 | Classification problems in CICES with regard to soils

Our analysis of the CICES classification revealed several problems when applied to soils and agricultural soil management. One of the most prominent ones is the CICES distinction between services provided by living elements of the ecosystem and services provided by abiotic ecosystem components. Because soils exist by definition at the intersection between the pedosphere, atmosphere, hydrosphere and biosphere, this distinction is problematic. Most

services would have to be allocated both to a biotic and a matching abiotic service. However, this is technically difficult because the number of abiotic services in CICES V5.1 is much lower and they are often more generic than their biotic counterparts. For example, CICES contains a biotic service *hydrological cycle and water flow regulation* (2.2.1.3), whereas the closest abiotic service only refers to *physical barriers to liquid flows* (5.2.1.2).

The remaining problems can be categorized as overlaps/redundancies, gaps/missing classes, and classes where the definition is either very narrow or very wide. Overlaps in CICES emerge from competing service definitions. Good examples of such overlaps are services based on the capabilities of soils to filter and transform organic wastes and thereby protect water bodies. This soil function could be allocated to three services focused on the underlying processes: *Biotic remediation of waste* (2.1.1.1), *Biotic filtration, sequestration and storage of waste* (2.1.1.2) and *Abiotic filtration, sequestration and storage of waste* (5.1.1.3). Additionally, it could be allocated to two services focusing on the result of these processes: *Chemical condition of freshwaters* (2.2.5.1) and *Chemical condition of salt waters* (2.2.5.2).

Two examples of missing classes are the control of soil compaction and of soil salinization. As *Erosion control* (2.2.1.1) is considered, other soil degradation issues could also be addressed.

Examples of definitions that are very specific and could be combined from a soils' perspective include those that refer to a landscape's potential to offer recreation. Here, CICES differentiates between *Recreation through activities in nature* (3.1.1.1), such as hiking, and *Recreation through observation of nature* (3.1.1.2), such as birdwatching. Likewise, it is often very difficult with regard to agricultural landscapes to differentiate between their importance for local culture and heritage (3.1.2.3) on the one hand and their aesthetic value (3.1.2.4) on the other.

Finally, there are also some examples where it might be advisable to further distinguish classes. The ES *Erosion control* (2.2.1.1.) could be split at least into the prevention of wind erosion and the prevention of water erosion, and the ES *Soil quality by decomposition and fixing processes* (2.2.4.2) could be addressed in singular classes for macronutrients, micronutrients and soil carbon.

4.4 | Conceptual differences between soil-related ES and soil management-related ES

Ecosystem services with relevance for soils while at the same time affecting and being affected by agricultural soil management were numerous. Twenty-three CICES

classes were included in both subsets, reflecting this overlap in scope. However, the number of ES relevant for soil management assessments (40) clearly exceeded those with a direct relation to soils (29). This is largely due to the 11 cultural ES, which are affected by agricultural soil management, but are not quantifiable by soil properties and thus were excluded by our rather narrow definition of soil-related ES. The same approach was taken by three published lists of soil-related ES which also exclude cultural services. On the other hand, cultural ES occur more frequently on the 11 lists we reviewed than provisioning services or regulation and maintenance services. However, cultural benefits of soils usually require interrelation with other natural compartments. For example, most cultural and religious concepts related to *nature* involve more than just one part of complex ecosystems. Accordingly, Schaich, Bieling, and Plieninger (2010) argue that most cultural ES only emerge at the landscape scale. Agriculture strongly influences landscapes and, in combination with other land uses, forms the often valued cultural landscapes, including rural viewsapes and the cultural heritage of rural lifestyles (Swinton et al., 2007). The recognition of agriculture as a cultural phenomenon explains why the provisioning ES supplied by wild plants (1.1.5.X, in contrast to those supplied by cultivated plants) are not on the list of soil management-related ES but are listed as soil-related ES. Differences with regard to regulating ES are due to the effects of specific soil-management procedures. Examples such as *Pollination* (2.2.2.1) or *Seed dispersal* (2.2.2.2), which are heavily influenced by soil-management operations such as tillage or the use of herbicides, show that the set of soil management-related ES is broader in certain cases. As an exception, the service *Soil quality by weathering processes* (2.2.4.1) shows that in rare cases the influence of soil management is limited, although a clear ES relation to soils exists.

4.5 | Assessment of soil-related and soil management-related ES

A prerequisite for operationalizing the assessment of soil-related and soil management-related ES identified in this paper is the availability of suitable methods and data. Appropriate methods have to incorporate the regulation of the ES supply by soils; in maps, the spatial variation in soil properties has to be reflected in the ES supply. The soil science community developed the concept of soil functions (Blum, 2005) and related concepts such as soil quality (e.g., Doran & Parkin, 1994), emphasizing the contribution of soils to human well-being. In these concepts, the soil functions and the status of soils depend

directly on soil properties and their dynamics, contingent on external factors such as climate and management. Haygarth and Ritz (2009), Bouma (2014) and Keesstra et al. (2016) link the soil function concept to the ES approach by defining the contribution of specific soil functions to the supply of soil-related ES. Accordingly, Dominati et al. (2010) and Adhikari and Hartemink (2016) emphasize the dependence of the supply of soil-related ES on (dynamic) soil properties and provide appropriate conceptual frameworks. Dominati et al. (2014) provide corresponding methods for quantifying a set of soil-related ES. As there is no widely accepted compilation of methods suitable for the assessment of specific soil-related ES, further research is needed.

Greiner, Keller, Gret-Regamey, and Papritz (2017) reviewed studies quantifying and mapping soil-related ES with regard to the utilized methods. According to them, three categories of methods can be distinguished: (a) indicator approaches utilizing simplified proxies based on key soil properties as indicators, (b) static approaches applying empirical relationships to link soil properties with soil functions (soil function assessment [SFA] methods), and (c) dynamic approaches applying biophysical methods integrating soil, climate and environmental factors to model soil processes in time. All reviewed methods utilize soil properties either obtained in fieldwork, extracted from soil survey data or indirectly acquired by applying regional-scaled pedotransfer functions. We agree with Greiner et al. (2017) that SFA methods are suitable to assess the supply of soil-related ES, and they can contribute to the assessment of soil management-related ES. SFA methods were developed by the applied soil science community to generate spatial explicit data based on soil survey data. For example, the soil survey authorities of the German federal states developed guidelines providing a wide range of SFA methods for assessing the supply of soil functions, which are used in planning processes (e.g., AG Boden, 2007; Müller & Waldeck, 2011 for Lower Saxony). SFA methods are scaled to defined input data (usually strictly defined soil survey data: soil properties for whole soil profiles, specifically formatted and corresponding maps) and restricted to specific regions. Therefore, identifying appropriate SFA methods and acquiring suitable soil data are critical to assess soil-related and soil management-related ES.

4.6 | CICES subsets for sustainability assessments

Both subsets of identified CICES classes prominently showcase and characterize the paramount role that soils

and their management play in key societal challenges. Taking the UN Sustainable Development Goals (UN General Assembly, 2015) as a globally accepted reference for societal challenges, the identified classes refer to five out of the 17 goals. These are the provision of biomass for food, feed, fibre and bioenergy (SDGs 2, 7); provision of clean water (SDG 6); mitigation of and adaptation to climate change (SDG13); and conservation of biodiversity and environmental integrity as well as disaster control (SDG15). The role of soil in achieving SDGs has been outlined by Keesstra et al. (2016) and the ES approach is useful to conceptualize the link between soils and SDGs (Helming et al., 2018).

More specifically, society in general and policymakers in particular are increasingly demanding scientific evidence to support their decision making in favour of sustainable development in complex socio-ecological systems. Impact assessments are means to synthesize scientific information in support of policy (Carpenter et al., 2009). Such assessments are increasingly based on simulation modelling and employ scenarios of future management options to conduct a comparative assessment of future management implications. To be comparable and to enable the upscaling from case studies to global implications, standardized metrics, indicators and ontologies are required (Minx et al., 2017). This is particularly relevant for soils because of their very high spatial heterogeneity, their diverse management, and the multiple ES they supply. The two CICES subsets derived in this study are meant to facilitate this standardization.

5 | CONCLUSIONS

Although the concept of soil functions is well suited to highlight the importance of soils in communications with stakeholders and policymakers, the concept of ES facilitates their integration into the wider context of ecosystem assessments. However, the widely varying definitions of specific ES make it difficult to combine the findings of different studies. This also became apparent when we compared published lists of soil-related or soil management-related ES to derive the state of knowledge. For example, it was difficult to assess in how far a service named “water storage” by Haygarth and Ritz (2009) is identical to a service referred to as “freshwater/water retention” by Adhikari & Hartemink, 2016. The CICES classification offers an option for standardization, although not all classes are relevant in the contexts of soils. Out of the 83 service classes, we identified those

where the supply of the service is directly influenced by soil properties and processes (soil-related) and those where the supply is influenced by agricultural soil management (soil management-related). The CICES classification was designed to represent all ES and it is not yet well tailored to the needs of soil research. Our study highlights a number of shortcomings and lists potential improvements. We hope that these findings will contribute to a better integration of the soil's perspective in future versions of CICES. For the soil-related services, soil function assessment methods may be used to map levels of potential service supply. The list of soil management-related services is designed as a checklist to support the assessment of agricultural management options and their effects on the supply of ES. The approach specifies the interrelation between natural properties and processes of soils and their alterations through land use and management, thereby facilitating sustainability assessment of land management. The standardization made possible by this study is important for improving the policy and management relevance of soil-related assessments and to facilitate meta-analyses across geographic, climatic or management ranges. It also improves the consideration of the important role of soils in global assessments, for example regarding the topics of climate change and biodiversity loss.

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CONFLICT OF INTEREST

There were no conflicts of interest.

AUTHOR CONTRIBUTIONS

C. Paul developed the original idea, B. Steinhoff-Knopp and K. Kuhn conducted the literature review, B. Steinhoff-Knopp, K. Kuhn and C. Paul developed the lists of CICES classes, and all authors discussed the data and wrote the manuscript.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

ORCID

Carsten Paul  <https://orcid.org/0000-0002-6936-8415>

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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