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Soil function assessment: review of methods for quantifying the contributions of soils to ecosystem services

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ABSTRACT

Soils and their functions are critical to ensure the provision of various ecosystem services (ES). Many authors nevertheless argue that there are a lack of satisfactory operational methods for quantifying the contributions of soils to the supply of ES. In this study, we review ES mapping studies that have taken the roles of soils in ES supply into account, and propose soil function assessment (SFA) methods approved by German Federal States in spatial planning procedures to use in assessments of ES supply. We found 181 ES mapping studies in which the roles of soils in ES supply were considered. At least one soil property was used as an indicator of soil-related ES in 60% of the publications, and 13% of the publications were mainly focused on the roles of soils in supplying ES. More than two soil functions were considered in a minority of cases, indicating that the multi-functionality of soils has barely been taken into account in previous ES studies. Several decades ago, the soil science community has adopted the concept of soil functions to bring different aspects of soil to the fore and to emphasize the multi-functionalities of soils and their vastly different chemical, physical, and biological properties. We provide a set of approved SFA methods that cover the multi-functionalities of soils and are applicable to ES supply assessments. We propose that this set of operational SFA methods is a starting point for quantifying how soil systems underpin the supply of a wide range of ES. The minimal soil dataset required for these SFA methods is relatively small, and much progress has been made nationally and globally over the last decade in improving soil data infrastructure and online access for end users. These improvements will facilitate the incorporation of SFA into ES studies and thereby improve information for land use decisions. We recommend that ES assessments include the essential and multifunctional roles of soils to promote sustainable land use.

Introduction

The ecosystem Service (ES) approach is increasingly used to incorporate ecological sustainability into political decision-making (Grêt-Regamey et al., 2015). In particular, land use policies should foster spatial planning procedures that drive not only new urban areas and transport infrastructure but also take into account ecological aspects such as the provision of essential ES. In this context, quantifications and maps of ES must be transparent and accurate if they are to be accepted and applied with confidence by policy makers. The body of literature dealing with and illustrating the importance of the ES concept is growing, but relatively few data-driven ES studies and ES assessments using appropriate quantification methods have been published (Baveye, 2017; Liekens et al., 2013; Seppelt et al., 2011). Several publications proposed that more effort should be made to develop accurate and practical methods for quantifying ES (Boyanova et al., 2014; Crossman et al., 2013; Daily et al., 2009). There are two noteworthy models including multiple ES – also soil-based ES – that are increasingly used in ES assessment studies: The Integrated Valuation of Ecosystem Services and Tradeoffs model (InVEST) (Sharp et al., 2014) and the Artificial Intelligence for Ecosystem Services model (ARIES) (Villa et al., 2014). ES are increasingly incorporated into political instruments (Bouwma et al. 2017) and there is a particular need for spatially explicit ES quantifications for use in land-use planning to support the sustainable use of also soil resources (van der Biest et al., 2013; van Wijnen et al., 2012).

1.1. *Soil is important for ES supply*

Soils are critical to various ecosystem goods and services and underpin the delivery of a wide range of ES, including food production, water and climate regulation, energy provision and biodiversity

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(Haygarth and Ritz, 2009; Grêt-Regamey et al., 2016a; McBratney et al., 2014; Volchko et al., 2013). Soil is the skin of the earth and the central interface between atmosphere, hydrosphere, lithosphere and biosphere.. Therefore, soil contributes to many ES (Bouma, 2010; Dominati et al., 2014), and several publications stress that human wellbeing relies greatly on soil resources (Amundson et al., 2015; Banwart, 2011). Huber and Kurzweil (2012) and Dominati et al. (2010) suggested that soil needs to be integral to ES assessments, and soils importance in this regard has been highlighted in several studies (Adhikari and Hartemink, 2016; Bouma, 2014; Bouma et al., 2012; Haygarth and Ritz, 2009; Hewitt et al., 2015; Robinson et al., 2013). Bouma et al (2015) demonstrated the importance of soil and the use of soil information for six case studies clearly showing the necessity to include soil in ES assessments.

1.2. Integration of soil in assessments of ES supply

Soil has hardly been considered or has not been well represented in previous ES studies (Breure et al., 2012; Dominati et al., 2010). Although "soil formation" or "soil fertility" were explicitly mentioned as services in publications by MEA (2005), CICES (2013), Crossman et al. (2013), de Groot (2011) and Haines-Young and Potschin (2008), operational tools for quantifying soil-related ES were not provided in these studies. A number of recently published literature reviews have focused on evaluating ES mapping tools (Bagstad et al., 2013; Crossman et al., 2013; Grêt-Regamey et al., 2016a; Grêt-Regamey et al., 2016b Nelson and Daily, 2010; Vigerstol and Aukema, 2011; Waage et al., 2011) or on providing overviews of ES mapping case studies (Egoh et al., 2012; Layke et al., 2012; Martínez-Harms and Balvanera, 2012; Pagella and Sinclair, 2014; Sch & gner et al., 2013; van den Belt and Blake, 2014). The question of whether and how soil is incorporated into ES studies was not addressed in these reviews. Adhikari and Hartemink (2016) recently reviewed the literature on the relationships between soils and ES and compiled the key soil properties related to individual ES. However, these authors did neither provide operational methods for quantifying the contributions of soils to ES and linking soil properties to ES.

1.3. Soil functions

In the ES community, soils are often called 'natural capital stocks' to value and quantify their contributions to ES (e.g., Hewitt et al., 2015; Robinson et al., 2009, 2013). In the last two decades the soil science community has adopted the concept of soil functions to place value on the roles soils play in sustaining the wellbeing of humans and of society in general (Bouma, 2014; FAO and ITPS, 2015; Haygarth and Ritz, 2009). Soil functions are closely related to soil quality, which was defined by an American Soil Science Society working group in 1995 as "the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries…" (Karlen et al., 1997), emphasising the multi-functionality of soils and their chemical, physical and biological properties. The capacity of soils to deliver ES is largely determined by its functions, and each individual soil function can be seen as providing a soil-related contribution to ES (Bouma, 2014). The soil science community has been developing an understanding of soil systems for more than 100 years (Hartemink, 2015), and closely related concepts, such as soil quality indicators, soil health and soil protection,were developed some decades ago (Doran, 2002; Karlen et al., 2003; Wienhold et al., 2004).

The European Commission's soil protection strategy (EC, 2006) was an important initiative that brought the concept of soil functions to the attention of the wider public and placed the concept on the political agenda, even though the strategy was not later adopted. Seven soil functions were defined in the strategy (EC, 2006): (i) production of food and biomass, (ii) storage, filtering and transformation of compounds, (iii) habitats for living creatures and gene pools, (iv) the physical and cultural environment, (v) source of raw materials, (vi) carbon pool, and (vii) archive of geological and archaeological heritage.

Koch et al. (2013) and McBratney et al. (2014) recently proposed an integrative framework termed 'soil security', aimed at maintaining and optimising soil functionality to value the contributions of soils to environmental and social benefits. The authors defined soil security as "… the maintenance and improvement of the global soil resource to produce food, fibre and freshwater, contribute to energy and climate sustainability, and to maintain the biodiversity and the overall protection of the ecosystem". The soil security framework can therefore be seen as one soil-related component in the overall ES approach defined by MEA (2005). The roles of soils in ES were highlighted in the United Nations sustainable development goals for 2015–2030 in goal 15, "….to protect, restore and promote sustainable use of terrestrial ecosystems…" (United Nations, 2015). Nevertheless, it is still challenging to move from these general, theoretical frameworks to specific operational approaches that can be applied in practice.

1.4. Outline and objectives

In the following, we review ES mapping studies that take into account the roles of soils in delivering ES, compile how soil functions were linked to ES in the studies, and identify the main gaps concerning the assessment methods. The aim of this review is to support the quantification and mapping of soil-related ES. To address the main gaps in the assessment methods, we gathered soil function assessment (SFA) methods from the applied soil science community in selected European countries, and provide a selection of assessment methods that are applicable to ES assessment studies. Finally, we discuss what soil data is required by the assessment methods and the sources of available data from global to local scale.

2. Definitions and methods

2.1. Search of the literature published by the ecosystem service community

We combined several information sources for our search of ES studies that consider soil-related issues. We first screened literature reviews of ES mapping and quantification provided by the Ecosystem

Table 1
Reviews of ecosystem services (ES) assessment and mapping (n = 15).

Review type	Authors
ES mapping studies	Crossman et al. (2013), Egoh et al. (2012), Martínez-Harms and Balvanera (2012), Pagella and Sinclair (2014), Sch & gner et al. (2013) and van den Belt and Blake (2014)
ES assessment tools	Bagstad et al. (2013), Nelson and Daily (2010), Vigerstol and Aukema (2011) and Waage et al. (2011)
ES indicators	Layke et al. (2012)
Framework for mapping and assessing ES (not focused on soil)	Maes et al. (2012)
Framework for mapping and assessing ES (focused on soil)	Adhikari and Hartemink (2016), Jónsson and DavíÐsdóttir (2016) and Schwilch et al. (2016)

Service Partnership Thematic Working Group for Ecosystem Service Mapping platform (ESP, 2015). We found a total of 15 reviews focusing on the assessment, quantification and/or mapping of ES were found (Table 1). Three reviews focusing directly on soil-related issues were published recently (Adhikari and Hartemink, 2016; Jónsson and DavíÐsdóttir, 2016; Schwilch et al., 2016) but do not provide operational tools how to take into account the role of soils in ES mapping studies. In this review we go one step further and focus on SFA methods that can link soil functions to ES..

All the studies potentially quantifying the supply of soil-based ES found (264) and tools mentioned (4) in the 15 reviews were included in our literature review.

We also compiled publications and tools available through the IPBES Catalogue of Assessments on Biodiversity and Ecosystem Services platform (IPBES, 2015) and used ScienceDirect® to search for the terms “ecosystem service” AND “mapping” AND “soil” in titles or abstracts of publications. The studies described in the publications were extensively screened. Then, we updated the reference list at the end of 2016, searching ScienceDirect® again using the same key terms. Given the large number of hits, we limited the search to publications in which at least one of the top ten most cited soil-related ES studies found in the first step of our review were cited. This yielded more than 400 publications in which the roles of soils in ES were at least mentioned. We screened these publications and selected those mentioning at least one soil-related ecosystem service. We narrowed the search by excluding publications potentially using dynamic modelling or focusing on specific soils, such as flooded soils in wetlands and on the coast, or forest soils. It became clear that issues related to soil biodiversity and ES (a relatively new discipline in soil science) have been investigated in numerous studies. Most of these studies involved basic research on soil biota, but the development of meaningful and widely applicable soil biological indicators is still ongoing (Lavorel et al., 2017; Pulleman et al., 2012; Rutgers et al., 2012; Thomsen et al., 2012). We therefore decided to exclude these studies. More information on soil biodiversity and its role in ES for different soils, climate types and land uses are available through the European Union Ecological Function and Biodiversity Indicators in European Soils project (EcoFinders, 2017). A list of soil biological indicators for soil biodiversity and ES was recently suggested and evaluated as part of the EcoFinders project (Griffiths et al., 2016).

We classified the ES studies using the domains (1) mapping, (2) conceptual, (3) reviews and (4) combinations of the first three categories. We also classified them based on the level of detail with which soil was considered. In level 1, soil was the main focus of the study and soil-related ES assessments were provided. In level 2, soil was not the focus of the study, but soil was at least considered with one indicator or method when ES were assessed or mapped. In level 3, soil was mentioned but not taken into account when ES were assessed or mapped.

2.2. Search of the literature published by the applied soil science community

We used the cascade model developed by Haines-Young and Potschin (2008) to develop an understanding of how soil functions can contribute to ES. This model is often used as a general framework in ES studies (e.g., Schwilch et al., 2016). The steps required to link key soil properties and soil processes to soil functions and to link soil functions to ES and related benefits and values are shown in Fig. 1. The baseline of the data processing chain is usually given by soil mapping surveys in which the spatial distributions of soils are investigated, involving, amongst other things, field observations (soil profile descriptions), chemical analyses of soil properties and the generation of soil maps. Soil properties can be quite static (e.g., texture, stone content and soil depth) or dynamic (e.g., soil pH, organic matter content, water content and nutrient content). Temporal changes in the dynamic soil properties in agricultural soils partly depend on land management practices. Numerous studies have been conducted in which the multivariate and complex relationships between land management practices and changes in soil properties have been investigated with the aim of allowing the soil functions of arable soils to be maintained or improved (e.g., Schulte et al., 2014, 2015; Valujeva et al., 2016). Soil processes such as sorption, degradation, heat and gas exchange, nutrient leaching and water flow have been determined in conjunction with changes in the soil properties and the capacity of the soil to fulfil its functions. As suggested by Bouma (2014), we avoid using the term “soil services” because it suggests that soils can act independently. Using food production (one of the most frequently considered services) as an example: the yield depends strongly on the soil conditions, but other factors such as the climate, crop and pest management, fertilisation, machinery infrastructure, and the socio-economic boundary conditions of the agricultural land, also affect the yield.

In line with the soil function classification described by EC (2006) and further studies in which soil functions were taken into account (Calzolari et al., 2016; Dominati et al., 2014; Haygarth and Ritz, 2009), we used the main soil functions and sub-functions shown in Table 2 to cover the multi-functionality of soils.

In addition to these soil functions, soils can also represent cultural archives of geological and archaeological heritage, supporting cultural services which have quite a potential “to motivate and sustain public support for ecosystem protection” (Daniel et al. 2012) . The archive function is not considered here because it can be mostly assessed independently of the soil itself. The same is true for soil functions, such as the extraction of raw materials and the role of soil in the human physical and cultural environment. These soil functions are not considered here as well.

We classified each soil assessment method into one of three approaches.

2.2.1. Indicator approaches

This class of approaches defined soil indicators derived from key chemical, physical and biological soil properties serving as simplified and one-dimensional proxies for soil functions or soil quality (e.g., Karlen et al., 2003; Obade and Lal 2016; Wienhold et al., 2004).

2.2.2. Static approaches

The second class of approaches were static approaches using simplified empirical rules to quantify soil functions (e.g. Lehman et al., 2013; Calzolari et al., 2016). Static approaches assess the general capacity of a soil to fulfil a specific function, but the impacts of land use and land management practices are not taken into account. Static approaches are particularly suitable in land-use planning to support the sustainable use of soil resources (Lehmann and Stahr, 2010; Mueller et al., 2007).

2.2.3. Dynamic approaches

The third class of approaches comprised semi-dynamic or dynamic approaches including soil processes, climate and other site-specific environmental factors as well as temporal and spatial variations in land use and land management practices. This class includes soil and environmental modelling studies, as well as biophysical models developed in different sub-disciplines (e.g., nutrient cycling, water cycling, and soil degradation), taking into account physical, chemical and biological soil processes. Vereecken et al. (2016) recently highlighted the role of soil process modelling in relation to ES and proposed that an international soil modelling consortium should be established to foster communication between workers in different disciplines. A collection of soil biophysical models can be found through a web-based soil modelling platform (ISMC, 2017). Using biophysical soil models is by far the most data-demanding and time-consuming approach, because gathering and processing data, calibrating model parameters, mapping, and validation all require great effort for each case study. However, once a model is appropriately calibrated for a region of interest, this is the most powerful approach for modelling the impacts of past and future land use

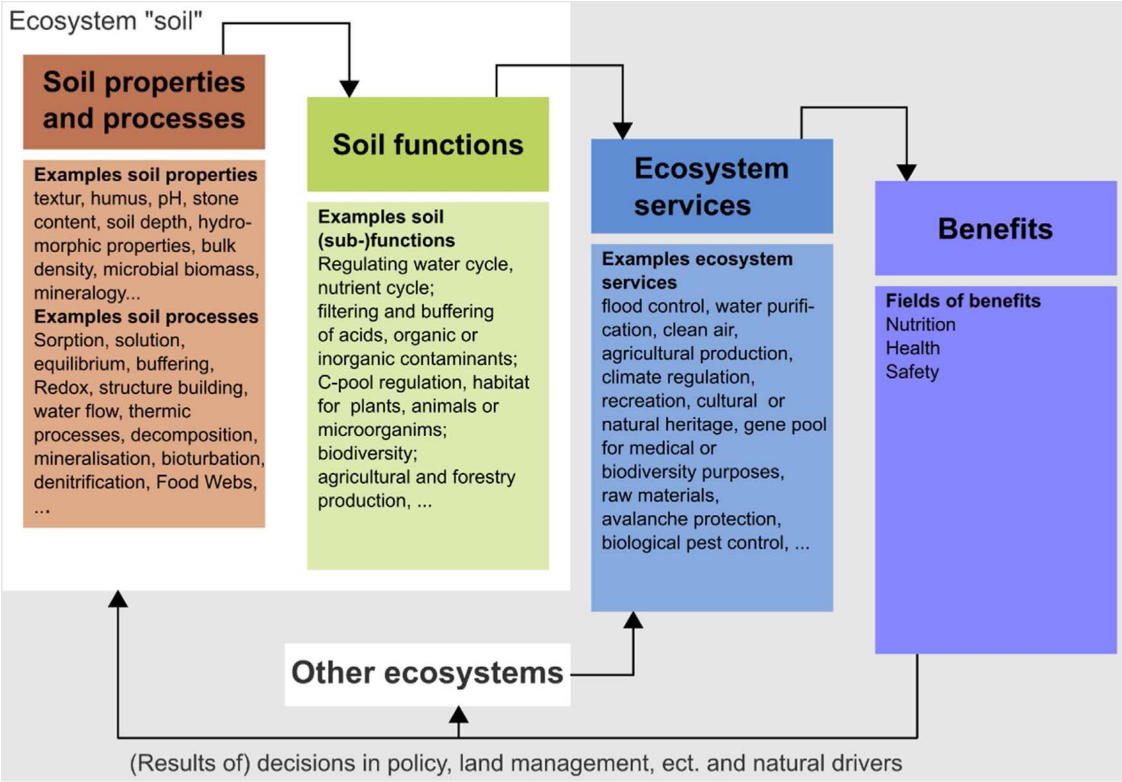

Fig. 1. Assessment of the contributions of soil functions to ecosystem services using the cascading framework developed by Haines-Young and Potschin (2008).

Table 2
Selected soil functions and sub-functions used to characterise the multi-functionality of soils. *[in brackets:terminology according to EC 2006]*.

Soil function	
Soil sub-function	Examples of assessment criteria
Regulation function [storage, filtering and transformation of compounds; carbon pool]	
Water cycling	Water purification, plant available water, water infiltration,
Nutrient cycling	Nutrient storage capacity, prevention of nitrate leaching or gas exchange, nutrients in soil available to plants
Filtering and buffering of organic compounds	Filtering of, for example, persistent organic pollutants, antibiotics or pesticides, degradation of soil pollutants
Filtering and buffering of inorganic compounds	Filtering of trace elements
Acidity buffering	Buffering of nitrogen oxides
Soil carbon storage	Soil carbon pool
Habitat function [habitats for living creatures and gene pools]	
For natural plant populations	Support for vegetation, soil types providing niches for plant species
Production function [production of food and biomass]	
Agricultural production	Crop yield, forage, bioenergy

and land management practices on soil functions.

Overall, soil indicators and the static approach focus on the status of soils, and the dynamic approach is suitable for assessing trends. Policy-making related to ES requires both soil status and any trends to be assessed in spatially explicit ways (Maes et al., 2012).

Both status and trend approaches can be used if sufficient data are available for a study region, but only the indicator and the static approach are applicable if data are limited. Such a tiered procedure was also recommended by Tallis and Polasky (2011) and Nelson et al. (2011) and shown on an example for ES by Grêt-Regamey et al. (2015).

Simple, static and low-data models provide results that are easier to communicate and are better suited to planning and scoping activities than those provided by dynamic models. A static assessment of soil functions is more meaningful – from a soil science point of view – and more helpful for further ES assessment than the even more simplifying indicator approach. Further, it is more easily performed than a dynamic assessment and we think, it should be carried out first before a dynamic soil model is used. We therefore focused our review of the literature published by the soil science community on static approaches.

In European countries, static methods for assessing soil functions have commonly been developed by geological or soil survey institutions that are responsible for soil mapping surveys in the countries in which they are based. These institutions are mostly affiliated to government organisations rather than universities, so the documents containing the methods developed to assess soil functions are sometimes written in languages other than English and hardly any documents about methods for assessing soil functions have been published in international scientific journals.

We concentrated our search on soil mapping and geological institutions at the national and federal level in selected European countries, including Austria, France, Germany, the Netherlands, Switzerland, and the UK, and we contacted the responsible people or working groups if published documents were not comprehensive. Similar to the review of the literature published by the ES community, we excluded soil functions and sub-functions related to soil biodiversity, forest soils and wetlands.

3. Soil functions and ecosystem services

3.1. *Overview of literature published by the ES community*

3.1.1. *Reviews*

In most of the 15 reviews (see Table 1), emphasis was placed on mapping and assessing ES, partly including soil-related provisioning, regulation and supporting services (Crossman et al., 2013; Egoh et al., 2012; Layke et al., 2012). In some of the reviews, the recent literature was summarised with the aim of outlining general concepts for assessing and mapping ES (e.g., Maes et al., 2012; Pagella and Sinclair, 2014). Other reviews focused on economic methods of valuing ES (Jónsson and DavíÐsdóttir, 2016; Schägner et al., 2013). The main characteristics of the 15 reviews are listed in Section 3 in the SI.

Schwilch et al. (2016) recently proposed a soil-focused ES framework taking threats to soil as the starting point. The aim was to promote sustainable soil management and to develop operational tools to mitigate threats to soil and negative impacts on soil-related ES. The framework was developed as part of the European Union FP7 project RECARE. Implementing this framework at various sites across Europe could provide operational tools for quantifying the roles of soils in ES provision in the near future. Jónsson and DavíÐsdóttir (2016) screened the literature to identify the many contributions soils make to ES and to illustrate the importance of soil-related ES by demonstrating that economic approaches can be used for that purpose. In contrast, Adhikari and Hartemink (2016) focused on studies that relate soil properties to ES and summarised the inter-relations between soil properties and ES. Soil properties were considered by all reviews mentioned, and the relevance to provisioning, regulation and supporting services was indicated. However, operational tools for quantifying the contributions of soils to ES were hardly provided in the reviews mentioned above. Only Adhikari and Hartemink (2016) and Egoh et al. (2012) cited some references to case studies in which soil properties were linked quantitatively to ES.

3.1.2. ES literature

In our literature search we found a total of 181 publications in which the roles of soils in ES supply were considered. About half of these publications were about ES mapping, 22% mainly addressed conceptual issues and 10% considered both topics (Fig. 2). In 60% of the publications at least one soil property was used as an indicator of soil-related ES or at least one method was used to quantify the contributions of soils to ES. In about 27% of the ES mapping studies soil was mentioned in the approach but was not then included in the ES assessment. Notably, 13% of the publications were mainly focused on the roles of soils in ES provision. In some of these studies, the emphasis was on single soil functions, such as nutrient filtering and storage (e.g., Hewitt et al., 2015; Van Wijnen et al., 2012; Wang et al., 2015). Attempts were made in only a few studies to characterize the multifunctionality of soils outlined in Table 2 (e.g., Calzolari et al., 2016; Dominati and Mackay, 2013; Dominati et al., 2014; Robinson et al., 2013; Rutgers et al., 2012; Schulte et al., 2014). The full list of the publications found is provided in the supplemental information (SI 1), and more information on the key foci of the studies and the soil properties and soil-related ES considered is provided in the supplemental information as well (SI 2).

At least one method of quantifying soil-related ES or a proxy indicator derived from soil properties was documented in 83 of the 181 publications. A soil-related ecosystem service was quantified 220 times in total in these 83 studies (Fig. 3). The most prominent soil functions assessed in the studies were contributing ones to regulation services, such as the soil organic carbon pool (C-pool) and the water storage capacity. The soil C-pool is probably the most often used soil-related indicator because organic carbon in soil is one of the key basic soil properties, is easy to understand, and calculating the soil C-pool is simple and requires only a few soil properties. The plant-available water capacity has been used as a proxy to characterise the soil–water cycle in many studies. Such information is often provided in national soil databases and is often derived from pedotransfer functions (see below). Agricultural production, the key provisioning service related to soils, has also been considered in many ES studies. While crop yields, forage production or biomass production have been used as proxies in many studies, the suitability of soils have been assessed and classified based on soil type information, soil properties or soil taxonomic units (e.g., Mueller et al., 2007; Mueller et al., 2007; Toth et al., 2013). Other essential soil functions, such as nutrient cycling and the filtering and buffering of chemical compounds, have been incorporated in only a few ES studies (e.g., Calzolari et al., 2016; Dominati et al., 2014; Rutgers et al., 2012). A full list of the soil properties used and the soil-related ES quantified in each of the 83 ES studies is given in Section 4 of the SI.

The frequency with which soil-related ES were considered in the ES mapping studies compared well with frequencies reported by Adhikari and Hartemink (2016), who found that 41% of the ES studies between 1974 and 2014 (n = 935) were related to regulation services (mainly climate regulating factors such as the C-pool, water regulation and purification), while 34% were related to provisioning services such as food production. Crossman et al. (2013) published a review of ES mapping and modelling in which they found that the most commonly mapped ES associated with soil were soil carbon storage as a proxy for climate regulation, food provision, water supply and the regulation of

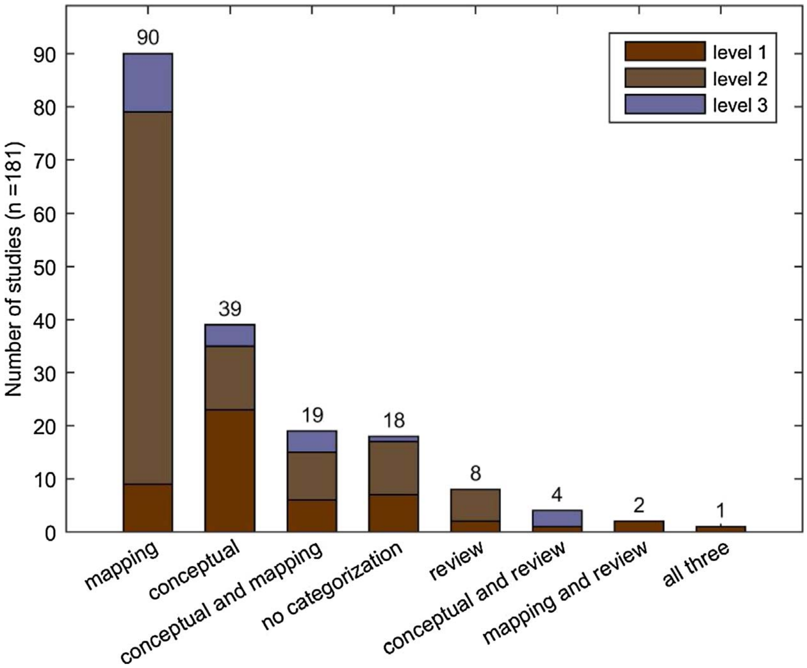

Fig. 2. Frequency of ES studies in the categories ‘mapping’, “conceptual”, “review” and combinations of the three first categories including level of soil focus (level 1: soil was the main focus of the study; level 2: soil was at least considered using one indicator or method; level 3: soil was only mentioned.) The studies not categorised were mainly focused on the demand for ecosystem services.

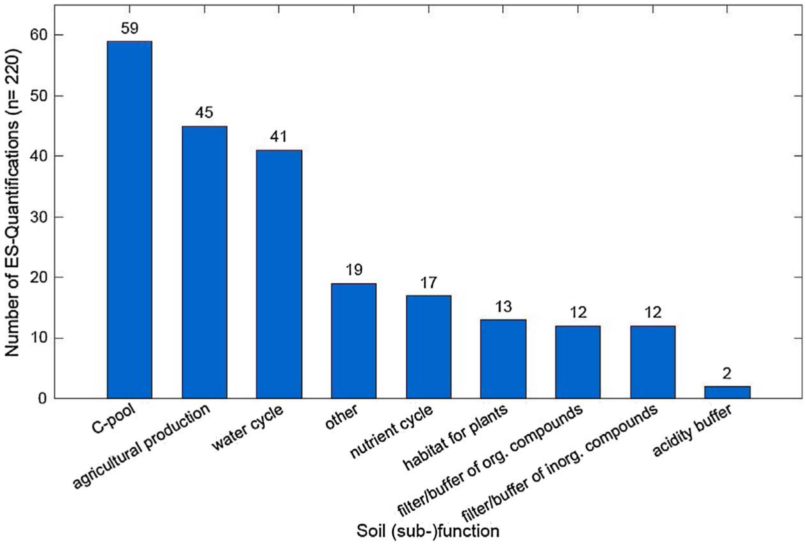

Fig. 3. Frequency of soil-related ecosystem services (ES) considered in ES mapping studies (the figure is based on 83 ES studies).

water flows.

The multi-functionality of soils has hardly been taken into account in ES mapping studies (Fig. 4). A complete list of the soil properties used and the soil-related ES assessed in the 83 ES mapping studies found is given in Section 4 of the SI. About half of the publications described studies in which only one or two soil functions were included, 22% were studies in which three soil functions were considered, and 24% studies used four or more soil functions. We found that most ES mapping studies took into account one of the three most commonly considered soil functions (soil carbon pool, agricultural production and water cycle), but often ignored the remaining capacities of soil to deliver ES as outlined in Table 1. Notable exceptions to this are the studies by Dominati and Mackay (2013), Dominati et al. (2014), Rutgers et al., (2012) and Schulte et al. (2014) and in particular by Calzolari et al. (2016) who comprehensively assessed soil-related ES for a catchment in northern Italy. The authors used available regional soil profile data and soil maps and other environmental GIS maps to quantify and map the spatial variability of eight soil functions as indicators of soil-related ES. Bouma (2014) and Haygarth and Ritz (2009) also found that the multi-functional role of soils in ES is generally not well assessed. They proposed that a unified ES framework for soil systems should be developed.

3.2. ES mapping studies

3.2.1. Soil properties used for mapping

In conjunction with the top three soil-related ES mentioned above (Fig. 3), the most frequent soil properties used in ES mapping studies are the soil organic carbon content, the available water capacity, the clay and silt contents (texture), the soil type, the soil depth and the bulk density (Fig. 5). The category “other soil data” in Fig. 5 includes various soil parameters, such as the C:N ratio, the P and N contents, and physical soil properties such as macro-aggregates. Hydromorphic features of soils, such as waterlogging, the grey colours of bleached soil horizons and water conductivity, have also been used to describe water cycle in soil (e.g., Hewitt et al., 2015; Landuyt et al., 2015). Haygarth and Ritz (2009), Adhikari and Hartemink (2016), Robinson et al. (2013) and Dominati et al. (2014) described similar typical soil properties relevant

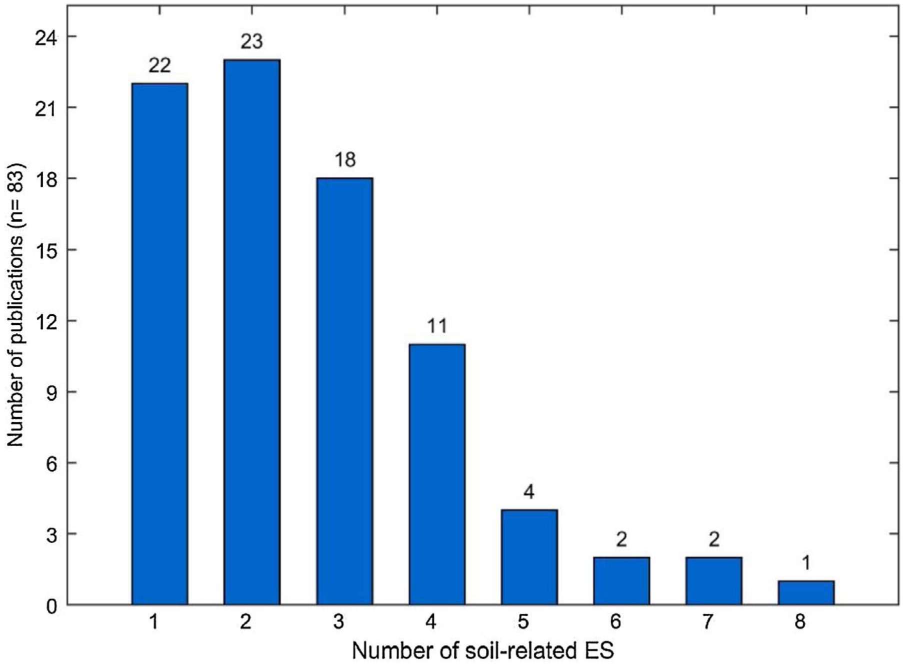

Fig. 4. Number of soil-related ecosystem services (ES) considered per ES mapping study.

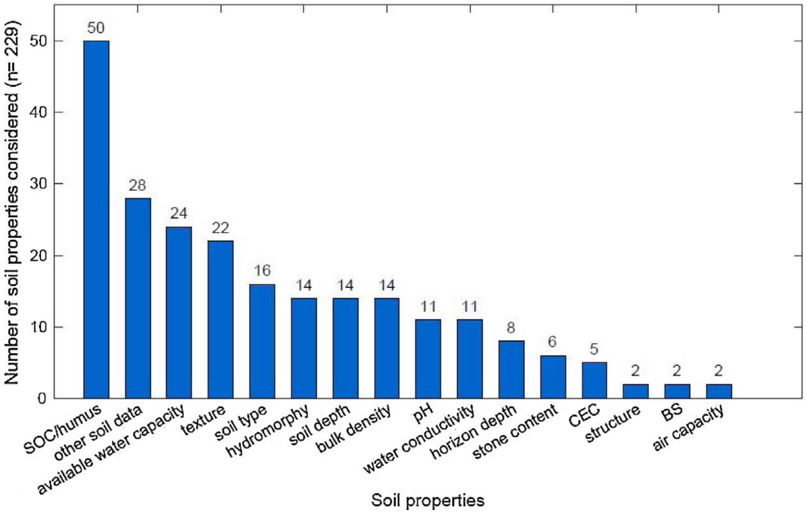

Fig. 5. Frequencies with which soil properties have been considered in ecosystem service mapping studies (n = 83 studies).

for ES assessment.

3.2.2. Scale

In most (60%) of the 83 studies, ES were quantified on a local or regional scale, i.e., from several fields or a small catchment to a larger region of several hundred square kilometres. In a few ES studies (15%), soil-related ES were also quantified at a national level (e.g., Anderson et al., 2009; Bateman et al., 2013; Egoh et al., 2008; Turner et al., 2014), and in some studies, ES were even quantified at a continental scale (Tóth et al., 2013). Where soil property data were applied, they were usually gathered from available soil databases. At a local or regional scale, these were often soil maps (1:5′000 to 1:50′000) and soil profile datasets. In particular, local and regional scales are the scales, where land use policies are defined and implemented.

3.2.3. Soil data sources

In some countries government institutions provide national scale soil databases and soil maps with medium resolutions (1:50′000 or lower). However, many authors emphasise the lack of soil data required to assess soil-related ES (e.g. Adhikari and Hartemink, 2016; Liekens et al., 2013; Maes et al., 2012) and other available environmental information such as land use or land cover maps are used as substitutes for missing soil data. This may lead many authors to criticize the ES approach, when applied to soils. (Baveye et al., 2016) Clearly, the availability of soil databases is key to allowing soil functions to be assessed. In a few cases, the authors performed their own soil surveys (Lavelle et al., 2014; Le Clec'h et al., 2016; Yao et al., 2016) or used soil data from the European Soil Data Centre (Panagos et al., 2012; Schröter et al., 2005) or the Harmonized World Soil Database (FAO, 2012) (Maes et al., 2011). The soil data sources used in the ES studies we identified are listed in Section 5 of the SI.

3.2.4. Documentation

It is essential for transparency and reproducibility that the methods used to assess soil-related ES are documented properly. A good example of method documentation is the ecosystem service assessment tool InVEST (Sharp et al., 2014, http://www.naturalcapitalproject.org/invest/), which is relatively widely used (e.g., Fu et al., 2014; Harmáčková and Vačkář, 2015; Nelson et al., 2009; Terrado et al., 2014).

However, we found that most ES mapping studies applied methods that were incompletely documented. Only about a quarter of the studies provided fully documented methods, another quarter referred to methods used in other studies, and 43% of studies provided only partial information on the quantitative methods used or pointed only partially to other sources (Fig. 6).

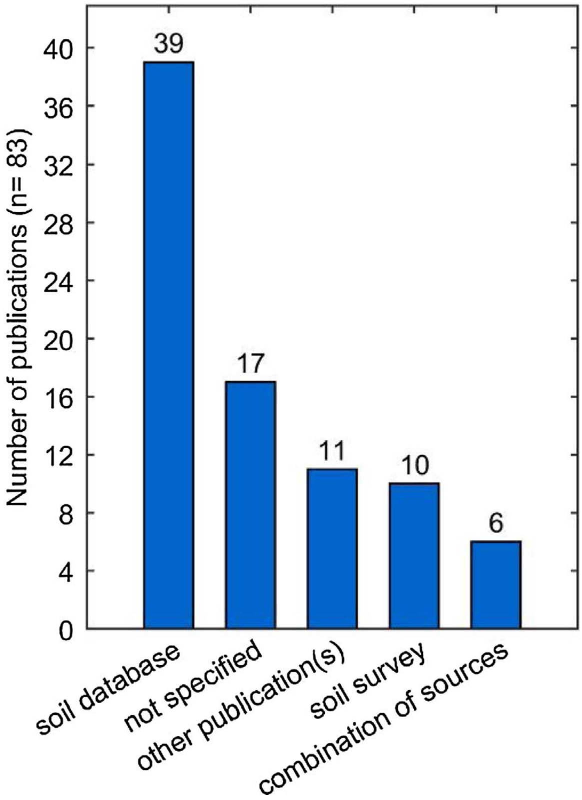

Fig. 6. Types of soil data sources used in studies quantifying soil-based ecosystem services.

4. Soil functions in the applied soil science community

4.1. Overview of soil functions (literature) in considered countries

In our SFA method review, we searched for static SFA methods in Austrian, Dutch, French, German, Swiss, and UK guidelines.

We found applicable SFA methods mostly in **German** guidelines. German federal states have had up to 20 years experience in SFA because the Federal Soil Protection Act, which was adopted in 1998, provides a legal basis for protecting soil functions. The main soil functions are explicitly defined in the act. Different federal states provide SFA guidelines (e.g., Lehle et al., 1995; Gröngröft et al., 2001; Hochfeld et al., 2003; Müller and Waldeck, 2011), and a national consortium (Ad-Hoc AG Boden 2007) even evaluated the available methods and offered meta-information and recommendations for users of SFA methods.

On an international level, the TUSEC project − inspired by German SFAs − proposed interesting and well documented SFA methods (Lehmann et al., 2013). In various case studies it has been demonstrated that SFA methods and the related soil function maps were successful in spatial planning procedures to foster the discussion about tradeoffs between the provision of ES and the development of new urban areas, for instance in the German federal state of North Rhine-Westphalia (Feldwisch et al., 2011), Bavaria (Danner et al., 2003) or Hamburg (Hochfeld et al., 2003).

Austria has had nationwide SFA guidelines since 2013 (ÖNORM, 2013), and these were mostly based on German methods. Several regional studies were recently conducted (Geitner et al., 2005; Knoll et al., 2010). Haslmayr and Gerzabek (2010) performed a case study in which they determined whether German SFA methods could be adopted in Austria. They concluded that this is possible in principle but requires German soil taxonomy to be translated into Austrian soil taxonomy. Legislation in **France** does not yet cover soil functions, but there have been attempts to include and protect soil functions in the “Code de l’Environnement” (Lambert and Schellenberger, 2013). The French Environment and Energy Management Agency (Agence de l'Environnement et de la Maîtrise de l'Energie) has been running a project entitled “Fonctions environnementales et gestion du patrimoine sol” (GESSOL, 2011) since 1998. Natural soil functions have been investigated in this project, but no static SFA methods have yet been published. Soil policy in **the Netherlands** has been developing for more than 30 years (NL, 2010), but the central concept is “soil quality” rather than soil functions, so no SFA methods have been developed. A soil strategy based on soil functions is currently being developed in **Switzerland** and a National Research Programme on “Sustainable Use of Soil as a Resource” (www.nrp68.ch) runs between 2013-2017. For example, assessment methods are available in Switzerland for determining the suitabilities of different soils for agricultural use (FAL, 1997; Jäggli et al., 1998), for assessing acidity buffering (Blaser et al., 2008; Zimmermann, 2011) and filtering and buffering of heavy metals (Keller and Desaules, 2001). The **UK** has had a soil strategy based on soil functions since 2009 (UK, 2009) and is working on implementing this strategy (Mayr et al., 2006). One SFA mentioned in Wadsworth and Hall (2005), provides an SFA for nutrient cycling.

We are aware that other methods suitable to assess soil functions not labelled as SFA, are available in Switzerland, and that this is probably also the case in the other countries.

4.2. Approaches to SFA methods and soil data for use in SFA methods

4.2.1. Suggested SFA methods

In this section, we present a catalogue of SFA methods that can be used in ES assessments to create maps of the soil-based supply of ecosystem services. We provide a list of SFA methods to assess regulation, habitat, and production functions via the eight soil sub-functions in Table 3. We selected SFA methods using criteria originally presented by Ad-hoc-AG-Boden (2007) and Hochfeld (2004) with slight adaptations. We determined that the methods should be 1) transferable to other regions, 2) well documented and therefore reproducible and transparent, 3) successfully applied and tested, and 4) simple and therefore easy to interpret. Most of the SFA methods listed in Table 3 were developed in the frame of the german Federal Soil Protection Act mentioned above, and rely on soil data collected with standard soil mapping surveys.

To assess soil functions, soil data, pedotranfer functions (PTFs) and sometimes other geoinformation is required, as shown in Fig. 7. The assessment itself involves deducing further data (e.g, saturated hydraulic conductivity for a certain depth) and then translating different data to an ordinal scale (e.g., a combination of high saturated hydraulic conductivity and high water storage capacity leads to high capacity in regulating the water cycle). The scale is defined by soil scientists and will probably be specific to the soils of a given region and specific to legislative goals. The scale can be adjusted if necessary. An overview of the available methods and the required soil data and PTFs are presented in Table 3, and further information on soil data and PTFs is presented in Section 4.2.2.

A static SFA is a good starting point for integrating spatial soil information to achieve sustainable land use and is suitable for general and long-term spatial planning. More dynamic approaches would, however, be helpful when, for example, decisions need to be made between different land management options.

4.2.2. Availability of soil data and PTFs

The applicability and reliability of an SFA method largely depends on the availability of soil data. Soil data are key to quantifying the contributions of soils to ecosystem services (Dominati et al., 2014; Robinson et al., 2009). As outlined above, the majority of studies that consider at least one soil related ES acquired the necessary soil data from publicly available soil databases. At regional and national level soil data are available in many countries (see below). The majority of soil data origin from soil mapping surveys performed by national institutions. The main aim of a soil mapping survey is to capture the spatial distributions of soils and their properties. The mapping procedure involves, among other things, recording soil profile descriptions, analysing soil properties in the laboratory, describing landscape characteristics, and spatially delineating soil units. The main products of soil mapping surveys are soil maps and soil databases containing the information described above and the results of laboratory analyses (“soil information”).

An advantage of performing a static SFA, as presented here, is that almost all the methods shown in Table 3 were developed in the context of soil mapping surveys and so rely only on soil data originating from soil mapping campaigns. The minimal basic soil dataset required to meet the data demands of a static SFA method is relatively small. The basic soil properties required for soil horizons up to a depth of at least 1 m (or – if the soil is more shallow than 1 m – up to soil depth) are the soil organic carbon content, texture (clay and silt contents), pH, stone content, bulk density (or pore volume), and soil hydromorphic properties (e.g., indications on stagnant soil horizons, drainage and water logging data). These soil properties can be regarded as the minimum dataset required to allow at least some basic regulation, habitat, and production sub-functions to be assessed (see Table 3). Assessing other soil sub-functions requires data for other soil properties, e.g., the carbonate content, soil aggregate classes (to allow the soil structure to be described), nutrient status, cation exchange capacity, and base saturation.

Most SFA methods also require PTFs. PTFs are indispensable for deriving soil properties (“secondary soil properties”) that are difficult to measure or costly to determine from basic soil properties (Bouma, 1989). PTFs are mostly used when estimating soil hydrological characteristics, such as the saturated hydraulic conductivity or the plant-available water capacity (Wösten et al., 2001; Vereecken et al., 2016). Tools have been developed to improve the applicability of PTFs for soil hydrological properties. Widely used tools include ROSETTA (Schaap et al., 2001), HYPRES (Wösten et al., 1999), and SOILPAR (Acutis and Donatelli, 2003). Each of these PTFs is only applicable to a specific geographical area and only for the ranges of soil property values with which the PTFs were developed, but efforts have recently been made to develop common PTFs for soil hydrological properties that are valid at the European scale (Tóth et al., 2015). In general, the PTF concept can be applied to any soil attribute, and numerous PTFs have been developed based on the national soil datasets of many countries for bulk density, cation exchange capacity and base saturation. Overviews of PTFs have been presented by McBratney et al. (2002) and Vereecken et al. (2016). McBratney et al. (2011) noted the importance of checking the validity of a PTF for the particular study region of interest and

Table 3
Static methods for assessing soil functions used by the applied soil science communities in some European countries.

Soil function assessment criteria	Soil property data required									Pedotransfer functions required[a]	Sources
	Texture	Soil organic carbon	pH	Bulk density	Hydromorphic prop.	Stone content	Soil depth	Horizon depth	Other soil properties		
Regulation function											
Water cycling											
Soil capacity for water infiltration and storage, to control flooding	x	x		x	x	x	x	x		AWC, AC, Wcond	Danner et al. (2003), Bechler and Toth (2010), Lehmann et al. (2013), Calzolari et al. (2016)
Water storage in topsoil available for plants	x	x		x		x	x	x	For peat soils: decomposition of organic material	Wcond	Gröngröft et al. (2001)
Groundwater recharge	x	x		x		x	x	x	For peat soils: decomposition of organic material	AWC, RD, Wcond	Müller and Waldeck (2011)
Nutrient cycling											
Nutrient availability to plants	x	x	x	x		x	x	x	Clay type	CEC	FAL (1997), J & ggli et al. (1998), Lehmann et al. (2013)
Soil capacity for retaining soluble substances (e.g., nitrate)	x	x	x	x	x	x	x	x	Horizon designation, carbonate content	AWC, PR, AC, RD, S-value, BS, ANS, SSAmin, SSAhum	Danner et al. (2003), Müller and Waldeck (2011), Makó et al. (2017)
Soil capacity for delivering nutrients to vegetation	x	x		x						Wcond, RD	Gröngröft et al. (2001)
Filter and buffer for organic pollutants											
Soil capacity for sorbing and degrading organic pollutants	x	x	x	x	x	x	x	x	For peat soils: decomposition of organic material, horizon designation, soil type, soil structure	CEC, AWC, S-value, AC	Litz (1998), Müller and Waldeck (2011)
Soil capacity for retaining organic pollutants	x	x	x	x	x	x	x	x	For peat soils: decomposition of organic material, horizon designation	Wcond, BS, ANS, SSAmin, SSAhum	Hochfeld et al. (2003), Makó et al. (2017)
Potential for microbiological decomposition of organic pollutants		x	x						Soil structure	–	Lehmann et al. (2013)
Filter and buffer for inorganic pollutants											
Sorption capacity for inorganic pollutants	x	x	x	x	x	x	x	x	For peat soils: decomposition of organic material, soil type	CEC, BS	DVWK (1988), Danner et al. (2003), Lehmann et al. (2013), Makó et al. (2017)
Buffer for acids											
Stocks of exchangeable bases and carbonates	x		x	x		x	x	x	Clay type, carbonate content	CEC, BS	Danner et al. (2003)
Resilience against acidification (forest soils)	x	x	x	x		x	x	x		CEC, BS	Müller and Waldeck (2011)
Buffering capacity	x				x				Soil type	Soil sulphate absorption capacity	Wadsworth and Hall (2005)
State and resilience of soil acidification, risk of aluminium toxicity in soil	x	x	x	x	x	x	x	x		CEC, BS, ratio BC: aluminium cations	Blaser et al., (2008), Zimmermann (2011)
Carbon pool											
Stock of soil organic carbon	x	x		x		x	x	x		–	Calzolari et al. (2016)
Habitat function (hosting biodiversity)											
Habitat for plants											
Range of soil properties that provide specific conditions for diverse plant species	x	x		x	x	x	x	x	Carbonate content, soil type	AWC, CEC	Danner et al. (2003), Siemer et al. (2014)

(continued on next page)

Table 3 (*continued*)

Soil function assessment criteria	Soil property data required									Pedotransfer functions required[a]	Sources
	Texture	Soil organic carbon	pH	Bulk density	Hydromorphic prop.	Stone content	Soil depth	Horizon depth	Other soil properties		
Natural soil fertility					×					AWC	Bechler and Toth (2010)
Soils providing niches for plant species	×	×		×		×	×	×		AWC	Lehmann et al. (2013)
Production function											
Agricultural production											
Long-term soil quality and crop yield potential (Münchenberg soil quality rating)	×	×		×	×	×	×	×	Soil structure	AWC, RD, PD, BA	Mueller et al. (2007)
Natural soil fertility	×	×		×		×	×	×	Decomposition of organic material	AWC, AC, RD, CEC	Lehmann et al. (2013)
Potential utilization and productivity capacity (adapted Storie Index)	×	×	×	×	×	×	×	×		AWC, SAR, EC	O'Geen et al. (2008)

[a] Required pedotransfer functions for deriving secondary soil properties (AWC = available water capacity, AC = air capacity, ANS = anion sorption factor, BA = biological activity, BC = sum of base cations, BS = base saturation, CEC = cation exchange capacity (potential or effective), EC = soil electrical conductivity, PD = packing density, PR = percolation rate, RD = rooting depth, SAR = sodium adsorption rate, SSAmin = specific surface area of mineral soil, SSAhum = specific surface area of humus, S-value = sum of exchangeable base cations, Wcond = saturated hydraulic conductivity).

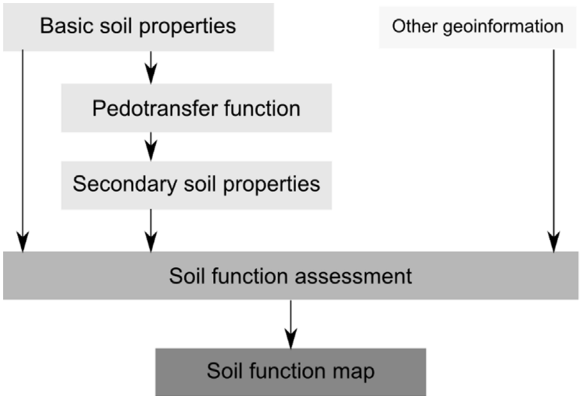

Fig. 7. Soil function assessment workflow.

identified selection criteria.

We anticipate that improved soil data availability will make incorporating soil functions in ES studies substantially easier in future. There is a trend at the international level towards harmonizing and coupling national soil datasets. In the past, many regional and national soil information sources were scattered, and the availability of soil data was often limited, but much progress has been made in the last decade in improving soil data infrastructure and online access for end users. Data infrastructure improvements, soil harmonization programmes, and online interface technologies for the end users of soil data will over the next few years dramatically improve the availability of soil datasets (Rossiter, 2016). The compilation of soil information sources maintained by Rossiter (2016) and a review published by Omuto et al. (2013) provide valuable overviews of soil information sources available worldwide. In many countries, soil data required for local ES assessment studies can be acquired from national soil databases that have fine spatial resolutions. For instance, as well as the overview provided by Rossiter (2016), the European Soil Data Centre (http://esdac.jrc.ec.europa.eu) maintains web directories of sources of regional and national soil information. Several international programmes (e.g., activities initiated by the Global Soil Partnership, the Harmonized World Soil Database, ISRIC World Soil Information, and the GlobalSoilMap consortium) aimed at increasing the availability of harmonized soil datasets at the continental and global level are currently underway.

The Global Soil Partnership is a consortium coordinated by the Food and Agriculture Organization that was established in 2012 to improve "governance of the limited soil resources of the planet…". The Global Soil Partnership addresses five "pillars of action", Pillar 4 being to improve the quantity and quality of soil data. A review of the status of global soil information (Omuto et al., 2013) led to the development of a plan to implement a global soil information system. The backbone of Pillar 4 is a network of international soil information institutions.

The most widely used soil dataset at the global scale is the Harmonized World Soil Database (FAO, 2012), which contains soil property data and soil units for fixed soil depths in a raster format (at a spatial resolution of approximately 1 km × 1 km). The International Soil Reference and Information Center (www.isric.org) has made further contributions to addressing increasing demand for soil information. The center has developed spatial data infrastructure and harmonized soil property data further than previously achieved, and has established a World Soil Information Service (Ribeiro et al., 2015). The SoilGrids platform hosted by the center (http://soilgrids.org) is an important tool that provides basic soil property and soil unit data for fixed soil depths at a resolution of 1 km × 1 km using digital soil mapping methodologies (Hengl et al., 2014). An end user can easily access soil data from the SoilGrids platform using a web interface, tablet, or smartphone (using the "Soil-Info" app). The automatic mapping procedure recently added to the SoilGrids platform has been successfully used to map the soil properties of African soils at a spatial resolution of 250 m × 250 m (Hengl et al., 2015).

Another initiative is the GlobalSoilMap project, the aim of which is to build a free downloadable database of key soil properties at multiple depths (Sanchez et al., 2009). Global mapping specifications for this project have been defined, and the ambitious goal is to produce maps of basic soil properties using digital soil mapping techniques at a spatial resolution of 100 m × 100 m (Arrouays et al., 2014).

At the continental level, the European Soil Data Centre has produced a web-based soil portal that provides access to the European Soil Database and related products at http://eusoils.jrc.ec.europa.eu (Panagos et al., 2012). This soil portal is the focal point for soil data and information in the European Union. The European Soil Database contains four well documented databases of soil geographical units, PTFs, soil profile analysis results, and soil hydraulic properties. Notably, the European Soil Database also contains measurements of the basic soil properties of topsoil at approximately 22000 sites across Europe from the Land Use/Land Cover Area Frame Survey (Tóth et al., 2013). The Land Use/Land Cover Area Frame Survey topsoil database can easily be used to assess soil functions of topsoils or to map soil properties over the whole geographical extent of Europe (Ballabio et al., 2016).

The efforts described above to improve the distribution of soil information between disciplines therefore make the information available for use in interdisciplinary ES mapping studies. It should be noted, that in such interdisciplinary studies, soil scientist may offer valuable expertise and knowledge about the soil system and soil processes, interpretation of soil data sets and practice in soil management. Such soil expertise goes far beyond the application of simplified SFA methods and advances the discussions with stakeholders (Bouma et al. 2012).

5. Conclusions

Human well-being relies strongly on soil resources, so soil should be better integrated into ES assessments. ES studies should address, in addition to other environmental issues, the crucial roles soils make in supplying ES and allow decisions to be made to support the sustainable use of soils. However, soil has multiple functions and has many functions and sub-functions in terms of regulation, habitat, and production, so multiple soil functions (rather than one general soil function) must be taken into account. Our literature review clearly indicates that the multi-functionalities of soils have barely been taken into account in ES assessment studies to date. The aim of this study was to help people involved in quantifying and mapping ES to better account for the important roles of soils. We linked the ES concept with approved assessment methods developed in recent decades by the applied soil science community. If an ES study is intended to include the multi-functionality of soil, the list of simplified SFA methods presented here could be a useful starting point. The simple static assessment methods described here can easily be applied using available soil databases and are particularly suitable for ES studies in the context of land-use planning. There are approved SFA methods for characterizing various regulation and production functions of soils, but further efforts to establish applicable methods that link soil biology and soil biodiversity to ES are required.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.landusepol.2017.06.025.

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