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Linking soils to ecosystem services — A global review

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ABSTRACT

Soil plays a crucial role in ecosystem functioning. In the 1990s ecosystem services (ES) research focused on developing the concept and framework and only a few studies linked soil properties to ecosystem services. This study reviews the literature on the relationship between soils and ecosystem services and aims to contribute to the scientific understanding on soil and ecosystem services and their interrelations. Most studies have focused on provisioning and regulating ES relating to soil physico-chemical properties. Cultural services had only a few studies, and supporting services were mostly related to soil physico-chemical and biological properties. The number of ES papers increased rapidly after 2000 and in the past 5 years, regulating services such as carbon sequestration, climate and gas regulations, were commonly studied. Once the concept was established in the 1990s, studies focusing on the assessment, valuation, and payments of services became more prominent. Most soil-ES research is published in *Geoderma*. Soil scientists seems to be hesitant to use the term 'ecosystem services' even if their research is devoted to linking soils to ecosystem services. We suggest that future ES research should focus on exploring soil functional diversity of soil biota and the spatial aspects of soil properties to lower level ecosystem services (e.g., water purification, gene pool, and climate regulation). Soil scientists should engage professionals from other disciplines to further promote the contribution of soils to ecosystem services delivery and human well-being. ES soil studies could be used in local and national policy development and program on natural resource use and management.

Contents

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1. Introduction

Ecosystem provides a wide range of goods and services to the benefits of human-kind (Costanza et al., 1997; MEA, 2005). There is now broad agreement how these services are to be grouped. The 2005 Millennium Ecosystem Assessment grouped ecosystem services into four categories: (i) provisioning services (direct or indirect food for humans, fresh water, wood, fiber, and fuel); (ii) regulating services (regulation of gas and water, climate, floods, erosion, biological processes such as pollination and diseases); (iii) cultural services (esthetic, spiritual, educational and recreational); and (iv) supporting services (nutrient cycling, production, habitat, biodiversity).

Soils of natural and managed ecosystem are a critical and a dynamic three-dimensional regulatory system that generates a multitude of functions, also called soil functions (Blum, 2005; CEC, 2006). These functions support the delivery of ecosystem services (Hannam and Boer, 2004). Soil is one of the most complex biomaterials on earth (Young and Crawford, 2004), and a key component of the terrestrial ecosystem operating at the interface of the lithosphere, biosphere, hydrosphere, and atmosphere (Szabolcs, 1994). In spite of its importance, most studies (Costanza et al., 1997; de Groot et al., 2002; MEA, 2005) have described ecosystem focusing on the services only (i.e., provisioning, supporting, regulating, and cultural services) with little emphasis on soil. We have considerable knowledge about soils, its formation and distribution, but our understanding on its functions and soil ecosystem services is incomplete (Daily et al., 1997; Swinton et al., 2006). Hewitt et al. (2015) mentioned that soil is as an overlooked component in ecosystem services studies and policy level decisions. Daily et al. (1997) suggested that soils are one of the important determinants of a nation's economic status, and that the inclusion of soils in ecosystem services frameworks and policy and decision-making is essential. The need for soil ecosystem services assessment and promoting soil–ecosystem linkage in the development of land resource policy and management was emphasized by McBratney et al. (2014) and Robinson et al. (2012). Using the UN-Sustainable Development Goals (SDGs), Bouma et al. (2015) emphasized soil science contribution to ecosystem services in the Netherlands and Italy.

Soil has been termed as a natural capital or stock yielding a sustainable flow of useful goods and services (Dominati et al., 2010; Palm et al., 2007; Robinson et al., 2009). Dominati et al. (2010) suggested a framework to quantify soil natural capital in which soil properties, soil processes, and drivers were linked. Most studies on the valuation of ecosystem services lack a soil component or the soil component is poorly defined or too generalized (e.g., Liu et al., 2010; Winkler, 2006).

Only a few studies have linked soil properties to ecosystem services. The majority of these studies were relating soils to the defined soil functions that ultimately determined the delivery of ecosystem services. The relationship between soil carbon, soil biota, soil nutrient cycling, and moisture retention to ecosystem services has been well documented (e.g., Barrios, 2007; Ghaley et al., 2014; Khanna et al., 2010; Krishnaswamy et al., 2013; Marks et al., 2009; van Eekeren et al., 2010; Williams and Hedlund, 2013). Similarly, the spatial aspects and dynamics of soil properties to ecosystem services have been studied through mapping or scenario modeling of future changes. Instead of using soil information directly, some of the mapping and modeling exercises used environmental variables as a proxy to soil information (Deng et al., 2011; Egoh et al., 2008; Guerra et al., 2014; Sumarga and Hein, 2014; e.g., Trabucchi et al., 2014). The most commonly used proxy is the land use and land cover (LULC) data (Plieninger et al., 2013; Schägner et al., 2013; Seppelt et al., 2011) which have been found useful in regions where data are scarce (Vrebos et al., 2015). LULC data are often favored to produce spatially distributed biophysical parameter values needed for production function models, e.g., many of the InVEST models (Kareiva et al., 2011). In other studies, the use of soil

Table 1
Ecosystem services as categorized by the Millennium Ecosystem Assessment (MEA, 2005), the Economics and Ecosystems and Biodiversity (TEEB, 2010), and the Common International Classification Services (CICES, 2011).

Ecosystem services	MEA categories	TEEB categories	CICES categories
Provisional services	Food, fodder	Food	Biomass (nutrition, animal and plant materials for agriculture use)
	Fresh water	Water	Water (nutrition, drinking, and non-drinking purposes)
	Fiber, timber	Raw materials	Biomass (materials from plants and animals for direct use and processing)
	Biochemical	Medicinal resources	Biomass (materials from plants and animals for direct use and processing)
	Genetic resources	Genetic resources	Biomass (genetic materials from all biota)
	Ornamental resources	Ornamental resources	Biomass (materials from plants and animals for direct use and processing)
			Biomass based energy sources
			Mechanical energy (animal based)
Regulating and supporting services (MA)	Air quality and gas regulation	Air quality and gas regulation	Mediation of gas and air flows
Regulating services (TEEB)	Water purification and treatment	Waste treatment (water purification)	Mediation of waste, toxics, and other nuisances by biota, and by ecosystem
Regulating and maintenance services (CICES)	Water regulation	Regulation of water flows	Mediation of liquid flows
	Erosion regulation	Moderation of extreme events	Mediation of mass flows
	Climate regulation	Erosion prevention	Atmospheric composition and climate regulation
	Pollination	Climate regulation	Life cycle maintenance, habitat and gene pool protection
	Pest and disease regulation	Pollination	Pest and disease control
	Primary production	Biological control	Life cycle maintenance, habitat and gene pool protection
	Nutrient Cycling	Life cycle maintenance (migratory species)	Soil formation and composition, maintenance of water condition
		Genetic diversity maintenance	
Cultural services (MA)	Spiritual and religious values	Spiritual experience	Spiritual and/or emblematic
Cultural and amenity services (TEEB)	Esthetic values	Esthetic information	Intellectual and representational interactions
	Cultural diversity	Inspiration for culture, art and design	Intellectual and representational interactions
	Recreation and ecotourism	Recreation and tourism	Spiritual and/or emblematic
	Knowledge system and educational values	Information for cognitive development	Physical and experimental interactions
			Intellectual and representational interactions
			Other cultural outputs (existence, bequest)

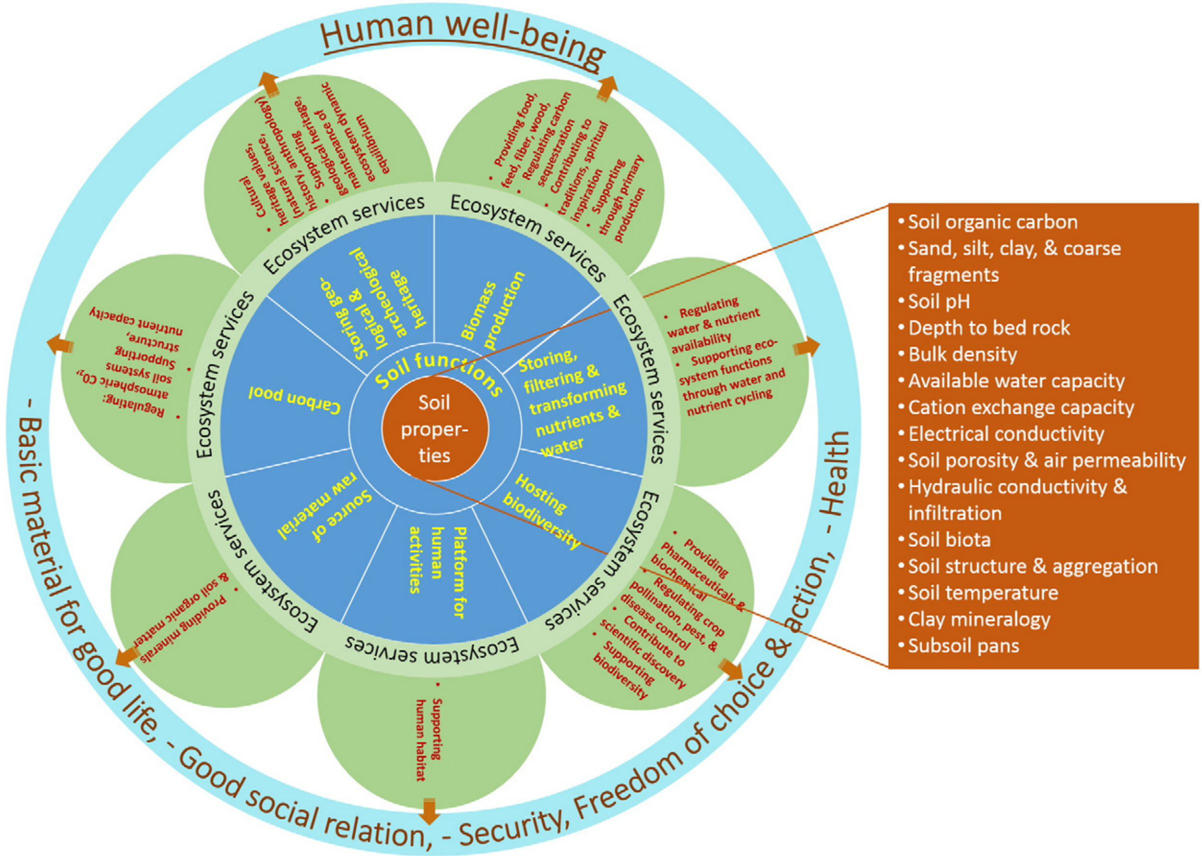

Fig. 1. A conceptual diagram linking key soil properties to ecosystem services through soil functions for the well-being of humans.

data is minimal (Kandziora et al., 2013; Maes et al., 2012), although inclusion of soil variables in ecosystem services assessment and mapping increased model reliability and map precision (Guo et al., 2001; Schägner et al., 2013). In the spatial context, ecosystem services assessment can benefit from pedometrics research for the dynamic spatio-temporal modeling of soil properties and processes (Adhikari et al., 2014; Minasny et al., 2013).

Soil ecosystem services depend on soil properties and their interaction, and are mostly influenced by its use and management. Landslides, erosion, decline in soil carbon and biodiversity lead to soil degradation which is a serious global challenge for food security and ecosystem sustainability (Godfray et al., 2010; Montgomery, 2010; Oldeman, 1998). The contribution of soils to human welfare beyond food production requires appreciation (McBratney et al., 2014) and this can be addressed by incorporating soils to ecosystem services framework and linking it to the multitude of functions it provides (Daily et al., 1997; Dominati et al., 2010, 2014). Here we present a review of the relationship between soils and ecosystem services. The overall objectives of this review are (i) to contribute to the scientific understanding on soil and ecosystem services and their interrelations, (ii) to highlight the contribution of soils for a range of ecosystem services, and (iii) to support a framework for ecosystem research focusing on soils.

2. Materials and methods

2.1. Data compilation

Ecosystem services are defined and classified differently and they are often context specific (Fisher et al., 2009). In this study, we considered the three main international classification systems (Table 1) that are widely used in the literature. In all three systems, four major groups of services are distinguished: provisional, regulating, cultural, and supporting services. They were divided into lower level services such as food, fiber, water supply, and esthetic values. In order to compile and review literature on the linkages of soils to the ecosystem services, a search was conducted using the Web of Science (Thomson Reuters), and Google Scholar. Two approaches were used. Firstly, all the articles with 'ecosystem services' in the title were compiled, and later the search was refined with 'soil' in title, abstract or keywords. Keyword specific search was applied in which the links between 'soil' and lower level 'ecosystem services' were investigated. The main question was how lower level services (e.g., food production, moisture retention, and gas emissions) were linked to soils.

2.2. Data analysis

An analysis on the temporal and geographical dimension of the published papers was performed. The papers were plotted against published years grouped into four periods: up to 1990, 1991–2000, 2001–2010, and 2010–2015. Papers in each period were divided considering the four major ecosystem services categories. A map was made for the total number of papers for each continent.

Linkages between soil and ecosystem services were investigated through a diagram (Fig. 1) that conceptualizes the connection of key soil attributes to ecosystem services through soil functions. A table linking given ecosystem services to the specific soil attributes was generated (Table 2). This table provided insight into the soil properties and their connection to the defined ecosystem services. Soil properties governing services were grouped into four major classes: soil carbon, physico-chemical properties, hydrological properties, and biological properties. The frequency of journal to which the papers were published was also analyzed setting a threshold frequency of 5 to give priority to commonly used journals.

Table 2
List of key soil properties related to ecosystem services.

Key soil properties	Provisioning services				Regulating services							Cultural services				Supporting services		
	Food, fuel, & fiber	Raw materials	Gene pool	Fresh water/ water retention	Climate & gas regulation	Water regulation	Erosion & flood control	Pollination/ seed dispersal	Pest & disease regulation	Carbon sequestration	Water purification	Recreation/ ecotourism	Esthetic/sense of place	Knowledge/ education/ inspiration	Cultural heritage	Weathering/soil formation	Nutrient cycling	Provisioning of habitat
Soil organic carbon	x	x		x	x	x	x		x	x		x	x			x	x	x
Sand, silt, clay, & coarse fragments	x	x		x	x	x	x			x	x				x	x	x	
pH	x								x		x					x	x	
Depth to bed rock				x		x	x				x							
Bulk density	x				x							x	x					
Available water capacity	x			x	x	x	x				x							
Cation exchange capacity	x										x						x	
Electrical conductivity	x																x	
Soil porosity & air permeability	x			x	x								x					
Hydraulic conductivity & infiltration	x			x	x	x	x				x							
Soil biota	x		x		x			x	x	x	x	x				x	x	x
Soil structure & aggregation	x			x	x	x	x									x		x
Soil temperature	x								x							x	x	
Clay mineralogy		x														x	x	
Subsoil pans	x			x		x	x											

3. Results

3.1. Temporal and geographical distribution

Total number of ecosystem services papers published between 1990 and 2015 is shown in Fig. 2. Until the year 2000, there were only a few papers published but this changed with the papers by Costanza et al. (1997) and Daily et al. (1997). Costanza et al. (1997) categorized ecosystem services into 17 classes and mapped the value of ecosystem services at a global scale. Daily et al. (1997) provided a detail description and a valuation method for the six categories of ecosystem services supplied by soils. A large number of papers were published thereafter describing economic as well as ecological aspects of ecosystem services. Another increase in papers was found after the United Nations published the Millennium Ecosystems Assessment (MEA) report (MEA, 2005). MEA provided a framework of ecosystem services and its categorization into the four major services discussed previously.

The number of papers of Fig. 2 was categorized into four ES classes (Fig. 3). In the 1990s only a few papers were published but in the following two decades, there were many studies on provisioning and regulating services compared to cultural and supporting services. Between 2011 and 2014, studies on regulating and cultural services exceeded the number of studies on provisioning and supporting. Moreover, the number of studies on regulating services outperformed all other services in the last five years.

The largest number of papers on ES is from Europe (38%) followed by North America (28%), and Asia (15%). Africa, South America and Australia/Oceania have about 6 to 7% of the total number of papers on ES (Fig. 4).

3.2. Ecosystem services and soil properties

Of all papers published between 1975 and 2014 showing a direct link of soil properties to lower level ecosystem services as listed in Fig. 5, about 41% were related to regulating services and 34% to the provisioning services. Cultural and supporting services were the focus of 8 and 13% of the papers. For the regulating services, the largest number of papers focused on climate and gas exchange while a limited number of papers dealt with pollination or seed dispersal function. The largest number of papers in the provisioning services was related to the production of food, fiber, or biomass. Few studies have linked raw materials and cultural heritage to soil properties.

In the supporting services, various studies focused on provisioning of habitat followed by nutrient cycling (Fig. 5). Examples of such studies are Derzhavin et al. (1975), Juma (1993), Römkens (1980), Rahimi et al. (2010), Kobal et al. (2015), Cox et al. (2005), and Zhao et al. (1997). These researchers studied the influence of soil variability on the provisioning of food, fiber, timber and soil water retention and supply. The effect of soil attributes in regulating water flow and erosion, carbon sequestration, gas regulation and emissions has also been investigated (e.g., Burke et al., 1989; Dilustro et al., 2005; Juarez et al., 2013; Keesstra et al., 2012; Maljanen et al., 2004; Pepper and Morrissey, 1985; Wang and Shao, 2013). The effect of soil variation on cultural and supporting services has been reported by Charyulu and Rao (1980), Lee (1991), Marion and Cole (1996), and Paul and Clark (1996).

The largest number of ES studies was conducted on soil physicochemical properties in relation to regulating and provisioning services and soil carbon was mostly studied in relation to regulating services. There were only a few studies on cultural services in relation to biological properties, whereas there were very few studies on hydrological properties and supporting services (Fig. 6).

3.3. Soil science journals

In total 33 journals have published at least 5 papers that linked soil properties to ecosystem services. Most ES soil research is published in *Geoderma* followed by *Soil and Tillage Research* and *Soil Biology and Biochemistry* which had about 10% of the total published papers. The journals *Soil Science* and the *European Journal of Soil Science* had the lowest number of papers on ES whereas the *Soil Science Society of America Journal* had about 4% of the papers on ES.

4. Discussion

4.1. Use of soil information in the valuation and mapping of ecosystem services

Most of the early ES publications were devoted to defining and developing the ES concept and framework and linking it to human welfare. Once the concept was established in the 1990s, studies focusing on the assessment, valuation, and payments of services became more dominant. The valuation of ES as conducted by Costanza et al. (1997) stimulated much debate. It also received criticism and, for example, Brown et al. (2007) claimed that the distinction between 'ecosystem services' and 'ecosystem goods' was obscured by Costanza et al. (1997). Nonetheless the Costanza paper inspired the scientific community and continues to do so.

Attributing soil value with respect to ecosystem goods and services delivery is difficult (McBratney et al., 2012), and has been considered incalculable (Daily et al., 1997). The inclusion of soil information in the process is crucial (Daily et al., 1997; Dominati et al., 2014; Robinson et al., 2009) and there have been several attempts to quantify the contribution of soils to ecosystem services. Most valuation attempts demonstrated how soils affect the flow of ecosystem services, e.g., soil erosion, water retention, carbon sequestration, or climate regulations. A valuation example is the productivity chain approach (PCA) which values the change in soil productivity as expressed through changes in crop yield considering production cost and market price. Sparling et al. (2006) valued food provisioning (dairy production) and regulating services (carbon sequestration) generated through soil organic matter recovery in New Zealand. Hewitt et al. (2015) reported a stock adequacy method for assessment and quantification of soil natural capital highlighting the role of soil information obtained from soil survey.

Mapping and modeling of ecosystem services are emerging fields of ES research. Table 3 lists examples of ES mapping and modeling studies with model type, input data, scale of mapping, and the services that were mapped. Several of these studies used soil survey information but often the soil data are too generalized in the model. Exclusion or limited use of soil information in ES models could be caused by inadequate availability of soil data (Sanchez et al., 2009) or low quality of the data and limited spatial coverage (Rossiter, 2004).

Biophysical and empirical models for ecosystem assessment and mapping require soil data to be included within the model environment. The studies of Guo et al. (2000) and Nelson et al. (2009) have recognized the importance of soil survey and used soil property data to parameterize models on erosion control and for the mapping of hydrological services. Similarly, parent material is a relevant input variable in ecosystem services assessment and modeling (Dymond et al., 2012; Reyers et al., 2009). Realizing the role of soil variability in ES mapping, Schägner et al. (2013) suggested that inclusion of soil variables in ES mapping increases map precision and product reliability. Andrew et al. (2015) pointed out that the users should be cautious in the use of soil information while developing ES models that require a detailed soil data so that the influence of soil attributes in ecosystem functions and services delivery could be assessed enhancing the quality and reliability of the model output.

4.2. Temporal and geographical distribution of ES papers

During the past five years regulating services was the primary focus of the research. In particular, climate change, carbon sequestration, and water management were prioritized research areas. Other studied

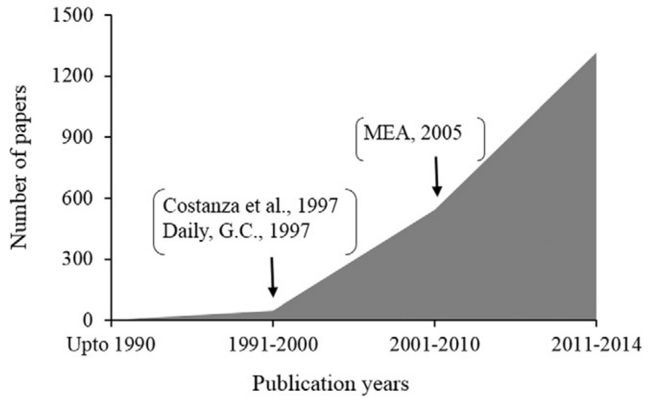

Fig. 2. Number of papers published between 1990 and 2014 with 'Ecosystem Services' in the title. Arrows indicate the seminal papers of Costanza et al. (1997), (Daily et al., 1997) and the publishing of the Millennium Ecosystems Assessment report of 2005.

focused on resource management and sustainability for development planning and policy regulations.

Most studies on ES and soils were conducted in Europe. The EU Thematic Strategy on Soil protection (CEC, 2006), the EU Biodiversity Strategy (European Commission, 2011), and the Common Agricultural Policy have recognized the importance of ecosystem services. Such policies and strategies may have played a crucial role in the awareness and research development that led to an increased publication on ES research.

4.3. The soil science journals

Soil science papers highlighting the role of soils to one or several of the ecosystem services seemed hesitant to use the term 'ecosystem services'. Most research focus has been on particular soil properties or related services so that the use of 'ecosystem services' in the title may have been less appropriate. There is a gap in highlighting the role of soils in ecosystem services studies. A good example in this regard is the research by Winowiecki et al. 2015 who mapped soil carbon stocks in Tanzania and linked the SOC stocks to soil erosion and land cover changes with ecosystem services.

4.4. Soil contribution to ecosystem services and global issues

Soil is a key component to global environmental sustainability issues like climate change, biodiversity decline, water and energy security, hunger eradication and food security, and soil receives increasing attention at global policy levels (Bouma and McBratney, 2013; Hartemink and McBratney, 2008). However, the Sustainable Development Goals (SDGs) formulated by the United Nations (UN) for the period

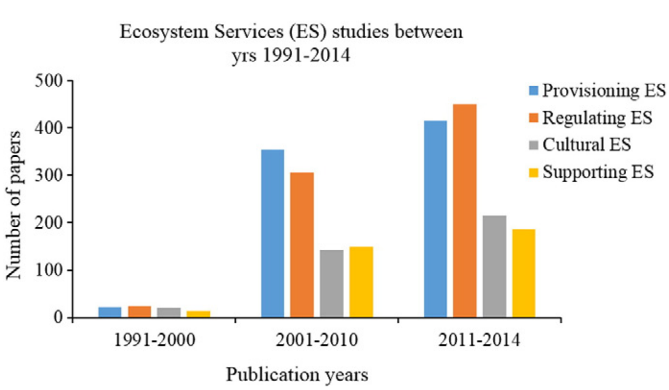

Fig. 3. Variation of four major ecosystem services studies between 1991 and 2014. Note that, x-axis does not have equal class interval due to a lower number of papers between 1991 and 2000.

2015–2030 that replace the Millennium Development Goals by 2015, have paid insufficient attention to the importance of soils (Table 4). There is a whole range of global initiatives on soils (Hartemink, 2015). For example, recognizing the contribution of soils to ecosystem services, Food and Agriculture Organization of the UN (UN-FAO) has established the Global Soil Partnership (GSP) that advocates and coordinates initiatives to ensure that soils are represented in global change dialogues and policy decisions. Valuing soil involvement in global arena can be strengthened by the concept of 'soil security' that connects various environmental issues (Bouma and McBratney, 2013). The theme of soil security that plays a role among food and energy security to climate change and biodiversity, is the protection and sustainability of ecosystem through maintenance and improvement of global soil resources (McBratney et al., 2014). Knowledge on soil diversity and its function as a system is a key to soil security and the links among soil and ecosystem services must be recognized for sustainable development, human well-being (Bouma, 2014), and economic development (Bouma, 2014; Daily et al., 1997). Several ES studies emphasized the role of soils in sequestering atmospheric carbon (Buckingham, 2014; Franzluebbers, 2005; Lal, 2004), food security (Lal, 2009), and biodiversity conservation (Decaens and Lavelle, 2011; Pulleman et al., 2012). While increased atmospheric temperature globally has been reported to increase loss of soil carbon, soil carbon pools in agroecosystems can be enhanced through restorative measures like no-till farming, maintaining good soil structure and tilth, and by improving soil quality. Lal (2011) estimated that improving soil quality with an increase of 1 t SOC/ha/year in the root zone can increase annual food production in developing countries by 24–32 million tons of food grains that could assist in achieving food security (Lal, 2004). Furthermore, soil conservation measures and best management practices (Fedoroff et al., 2010) could enhance yield maximization thereby ensuring food security (Godfray et al., 2010).

Soil also provides a habitat for soil biota preserving soil biodiversity and soil biota are essential for soil processes and functions like nutrient cycling, decomposition, and bioturbation (Brussaard, 1997) thereby maintaining a flow of ecosystem services. Degraded soils suffer from reduced biodiversity where soil functions are deteriorated and ecosystem services delivery is affected. Due to the effects of reduced soil biodiversity on soil functioning, CEC (2006) has identified biodiversity decline as a major threats to soils in Europe.

4.5. Spatial aspects of soil role in ecosystem services delivery

Several studies explored the spatial aspects of ecosystem services at varying levels of detail (e.g., Grêt-Regamey et al., 2007; Kandziora et al., 2013; Nahuelhual et al., 2014; Nelson et al., 2009) (Table 3). The maps have been used at different levels of decision making and policy support (Burkhard et al., 2013; Hauck et al., 2013; Maes et al., 2012). A tiered approach of mapping is more flexible in selecting variables, and ensures relevant information to the decision makers and supporting towards a standardized ES assessment and monitoring at different scales. Mapping of lower level ecosystem service classes such as crop yield, water purification, and retention shows the impact of soil information to the services. For example, instead of assessing the impacts of soils in regulating services, it would be more relevant to investigate how soil properties (e.g., soil porosity) affect gas exchange. This could give more insight into the spatial links of soils to ecosystem services. Some examples where the impacts of soil properties to lower level ecosystem services were studied are listed in Table 5.

In the study of spatial dynamics and aspects of ES, the quality of the output and its relevance are determined by the data availability, its quality and selection of mapping and modeling procedures. Most common input data correspond to LULC data which include maps of habitat, vegetation types, and biomes. These data have been used as indicators of ES (Metzger et al., 2006), of ecosystem properties (Nelson et al., 2009) or for a spatial estimates of ES or its valuation (Sutton and

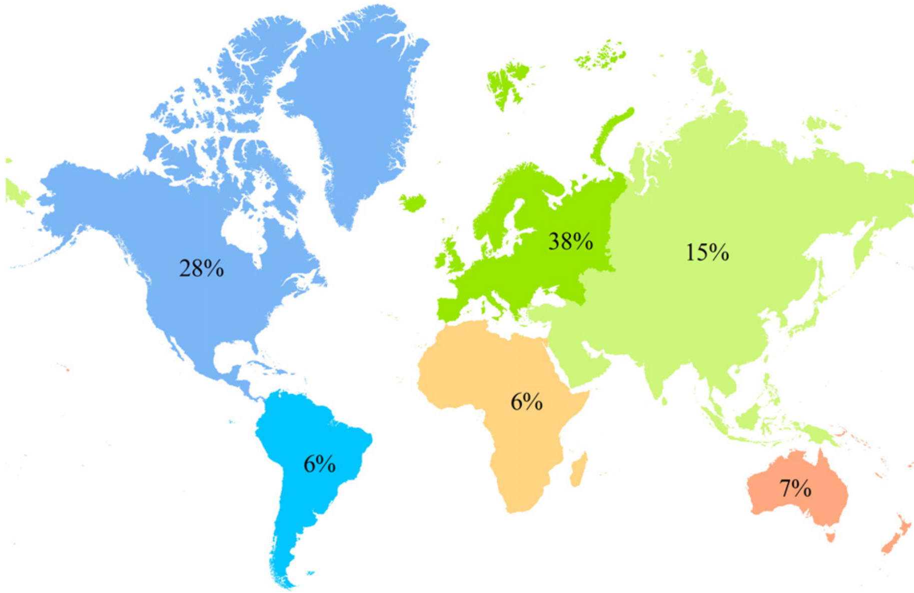

Fig. 4. Studies on ecosystem services by continents (based on papers published from 1990 to 2014).

Costanza, 2002). Sources of data widely used in the spatial modeling of ecosystem services include: climate data such as precipitation to indicate model water availability (Mendoza et al., 2011) or for erosion control services (Nelson et al., 2009), digital elevation models for hydrologic (Nelson et al., 2009) and esthetic services (Grêt-Regamey et al., 2007), and census data (Bateman et al., 1999).

There are tools and models for spatial assessments of ES and two common models are InVEST models (Integrated Valuation of Ecosystem Services and Tradeoffs) (Sharp et al., 2014), and ARIES (ARtificial Intelligence for Ecosystem Services) (Villa et al., 2014). Both models have been used in the quantification of ecosystem services and in spatial planning. They have a suite of modeling tools for biodiversity assessment, carbon storage and sequestration, coastal protection and fisheries, erosion control and water purification, sediment regulation, fresh water supply, assessment of recreation services and so on. For example, Nelson et al. (2009) give an example of modeling multiple ecosystem services including biodiversity conservation, soil erosion and water quality assessment, and carbon sequestration using InVEST model.

4.6. Soil and ecosystem services in environmental policy

Information from soil and ES assessments, for e.g., ecosystem services maps, has been given priority by government and non-governmental organizations for spatial planning and decision making (e.g., Egoh et al., 2008; Maes et al., 2012). In Europe, “EU biodiversity strategy to 2020” recognizes ES mapping as an action to be included in

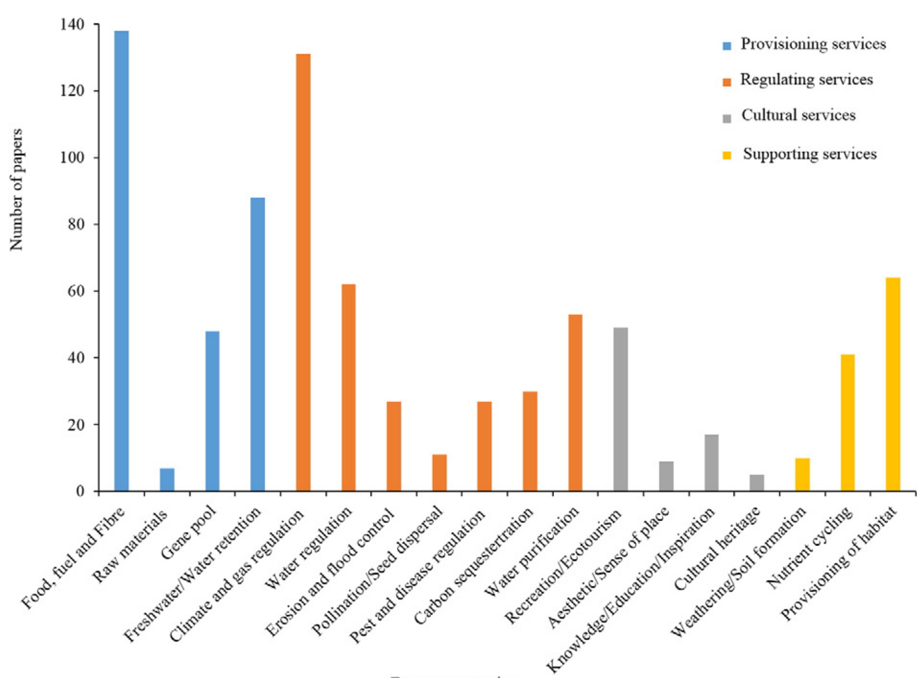

Fig. 5. Number of papers citing the direct linkage of soil attributes to lower level ecosystem services over the period 1975–2014; graph based on 935 papers.

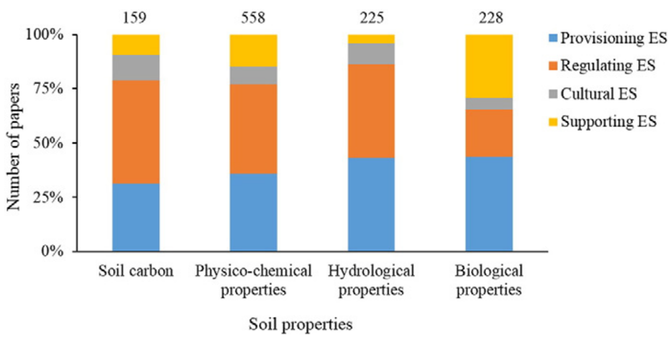

Fig. 6. Number of papers linking soil properties to ecosystem services. Indexed based on 935 papers between years 1975 and 2014. Value on the top of each bar represents the number of studies.

the strategic document and the member states are being assisted to map and assess the state of ecosystems and their services (Hauck et al., 2013; European Commission, 2011). Globally, the UN Sustainable Development Goals and UN-FAO Global Soil Partnership are initiatives that value soil contribution to ES for environmental sustainability and human welfare. Adopting the concept of soil ecosystem services in policy making can be a powerful tool to evaluate a range of natural resources and environmental management strategies. Decision makers could evaluate the impact on the environment and on human well-being and could develop or update policies and programs that would benefit society and environment. Bouma (2014), Daily et al. (1997), Dominati et al. (2014), and Robinson et al. (2009) have highlighted the need of soil inclusion in environmental policy and planning for societal benefits and environmental sustainability.

Table 4
Sustainable Development Goals (SDGs) formulated by the United Nations for the period 2015–2030.

S. no.	Goals
1.	End poverty in all its forms everywhere.
2.	End hunger, achieve food security and improved nutrition, and promote sustainable agriculture.
3.	Ensure healthy lives and promote well-being for all at all ages.
4.	Ensure inclusive and equitable quality education and promote life-long learning opportunities for all.
5.	Achieve gender equality and empower all women and girls.
6.	Ensure availability and sustainable management of water and sanitation for all.
7.	Ensure access to affordable, reliable, sustainable and modern energy for all.
8.	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.
9.	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.
10.	Reduce inequality within and among countries.
11.	Make cities and human settlements inclusive, safe, resilient and sustainable.
12.	Ensure sustainable consumption and production patterns.
13.	Take urgent action to combat climate change and its impacts.
14.	Conserve and sustainably use the oceans, seas and marine resources for sustainable development.
15.	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.
16.	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.
17	Strengthen the means of implementation and revitalize the global partnership for sustainable development.

4.7. On unknown ecosystem services

Due to the dynamic nature of ecosystems, the services that we enjoy from the ecosystem might not be there forever. Also, not all the ecosystem services to humans are known. With the advancement in scientific knowledge, novel functionalities and services might be discovered. The dynamic nature of ecosystem is primarily due to a key ecosystem component, the soil, which harbors a range of biota and their diversified roles in soil is a key to many processes and functional variations. Furthermore, the impact of human activities and the role of changing

Table 3
Examples of ecosystem services (ES) mapping and modeling studies at different spatial resolutions using a range of different input data.

Ecosystem service model	Input data	Mapping or modeling scale	Services mapped	References
A Kernel density based GIS approach considering the theory of social network	– No. of farmers – Socio-demography – Agriculture practices and crop yield – Institutional and social network	– Study area: 172,400 ha – Spatial resolution: 100 × 100 m	Cultural ES (e.g., agricultural heritage, social relation, system of knowledge)	Nahuelhual et al. (2014)
GIS based classification and mapping	– Land use and land cover data – Topographic and administrative information – Agricultural data and yield	– Study area: 60 km^2 – Temporal resolution (years 1990, 2000, 2006) – Spatial resolution: variable	Provisioning ES (e.g., crop and fodder production)	Kandziora et al. (2013)
GIS based mapping	– Land cover and land use and urban atlas – Population	– 3 spatial extents (city-wide, nation--wide, and region-wide scale) in Europe – Spatial resolution: 2.5 × 2.5 m	Regulating services (e.g., surface emissivity, f-evapotranspiration, carbon storage)	Larondelle et al. (2014)
Tiered approach using GIS	– Land use and land cover – Digital elevation model – Population density – Water quality	– Three different levels (EU level; national level—Switzerland; city level—Zurich) – Spatial resolution: not mentioned	Cultural services (e.g., recreation)	Grêt-Regamey et al. (2015)
Empirical model assisted with GIS and simulation	– Vegetation types – Soil types – Slope angle	– Study area: 2316 km^2 – Spatial resolution not mentioned	Regulating services (e.g., water flow regulation)	Guo et al. (2000)
InVEST model	– Land use land cover data – Slope, soil depth, surface permeability – Rainfall, soil type,	– 30 × 30 m	Water quality, soil erosion, carbon sequestration, biodiversity conservation	Nelson et al. (2009)

Table 5
Example of ecosystem services (ES) studies linking soil properties to lower level ecosystem services.

Ecosystem services	Lower level ES	Paper title	References
Regulating services	Water purification	Soil as a filter for ground water quality	Keesstra et al. (2012)
Provisioning services	Yield of rice	Soil quality and constraints in global rice production	Haefele et al. (2014)
Provisioning services	Yield of cotton fiber	Selected soil property variability and their relationships with cotton yield	Cox et al. (2005)
Supporting services	Nutrient cycling	Copper, zinc, lead and cadmium bioavailability and retention in vineyard soils (Rouffach, France): The impact of cultural practices	Duplay et al. (2014)
Provisioning/Supporting services	Gene pool, nutrient cycling, and provisioning of habitat	Effect of soil texture on the size of the microbial biomass and on the amount of C and N mineralized per unit of microbial biomass in Dutch grassland soils	Hassink (1994)
Cultural services	Esthetic/Sense of place	Spatial and temporal variation in soil and vegetation impacts on campsites	Marion and Cole (1996)

climate and land use on soils coupled with changing demands over time changes soil physio-chemical processes and lead to a different set of functions or services. Information on hidden biota and their functional behavior could be assessed through cloning of soil metagenome and their correlations could possibly help to identify novel functions or services. Metagenomic libraries can be a powerful tool for the identification of soil microbial diversity and provide access to genetic information of the uncultured soil biota (Rondon et al., 2000).

4.8. The way forward to soil and ecosystem services research

There have been many studies defining the linkage of soil properties to ecosystem functionalities or to ecosystem services, but the number of studies that directly linked soil properties to the services is limited. Most studies focus on economic assessments and valuation but ES valuation approaches are not able to capture the complexity of the nature and the services it provides (Layke, 2009). Nonetheless, approaches to provide understanding on the ecosystem functionalities and the services it provides are evolving (Viglizzo et al., 2012). In the past 10 years, there have been a number of papers in which the potential role of soils in a holistic ecosystem analysis has been analyzed (Hewitt et al., 2015).

Mapping the spatial aspects of soil ecosystem services has been effective for sustainable environmental management but there are several knowledge gaps to verify whether the outputs are understandable and satisfy user needs or the feedback mechanism is operative (Burkhard et al., 2013). The quality data is a bottleneck and reliability of the map product is a concern which could be addressed using model uncertainty and accuracy assessment. New insights into soil microbial diversity and their role in soil functional variability should receive more attention. Studies on soil carbon and sequestration should receive a higher priority in soil ecosystem services research but also other services like water supply and retention should receive more attention (Hartemink et al., 2014; Perrings et al., 2010).

Future soil ES studies should rely on the requirement of inter- and transdisciplinary research approaches of soil functions in relation to the sustainable development goals of the UN (Bouma, 2015). An example of interdisciplinarity approach is the study of Bonfante and Bouma (2015) in which soil scientists pro-actively engaged with crop breeders, agronomists and irrigation engineers and illustrated the value of soil information in yield performance of maize in a climate change scenarios. In addition, it is important to reframe soil realization and communicate in a way that policy makers understand the value of soils to environmental sustainability and human well-being (Bouma and McBratney, 2013). Advocating soil security (Bouma and McBratney, 2013; McBratney et al., 2014) which connects several global issues, is an approach to value the contribution of soils to environmental and societal benefits. However, the concept needs to be further developed, recognized and be made operational from the local to the global policy level.

We should be cautious on the use of the term 'soil contribution' to ecosystem services because the current knowledgebase may be limited. A weak and incomplete understanding might lead to a poor decision influencing the ecological and socio-economical aspects of ecosystem services and its delivery in a proper way. So, future soil and ecosystem service research may demand some efficient tools and techniques to gather soil information in-situ or in the lab and its processing. Digital soil morphometrics could be of great help in this regard (Hartemink and Minasny, 2014). We recommend that tools for soil ecosystem services evaluation should include the essential role of soils. Future studies should focus on decision support tools for assessment and monitoring of soil resources in an ecosystem services context.

5. Conclusions

This paper reviewed links between soil and ecosystem services and identified the current status of soil–ES studies. It identified niches in which future soil ES research could focus on. From this review, the following can be concluded:

- There are many studies on soil and ecosystem services but not all studies explored the direct relation with soil properties.
- Most studies focused on provisioning and regulating ES and most research has been conducted in Europe.
- Mapping of ecosystem services should be at the lower level ES classes to which the impact of soil properties can directly be incorporated. Use of soil information in all ES modeling studies should be emphasized.
- Soil scientists should engage professionals from other disciplines to further promote the role of soils in ecosystem services delivery.
- Future soil and ecosystem services research should focus on soil functions considering the sustainable development goals of the UN. It should highlight the multi-dimensional role of soil security in sustainable environmental policy and management.
- Finally, soils are a complex system and are so intimately incorporated into the ecosystem processes that separating out the soil portion in the ES studies might be incomplete. It needs a holistic approach to understand the ecosystem process and the services it offers to the society.

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