SOIL SCIENCE ANNUAL
2025, 76(1), 203722

https://doi.org/10.37501/soilsa/203722

Soil ecosystem services: trends, challenges, and opportunities for Colombia

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Received: 2024-09-06
Accepted: 2025-04-04
Published online: 2025-04-04
Associated editor: Stephan Glatzel

Keywords:

Environmental services
Land use
Soil management
Valuation
Decision-making
Territorial planning

Abstract

As a fundamental ecosystem component, soil houses incredible biodiversity in terms of richness and functionality, so inter and transdisciplinary approaches are needed to understand its dynamics. On a global scale, the suitability of soils and their Ecosystem Services (ES) are decreasing due to the increase in inadequate production or use practices, which reduces the capacity to regulate these essential services for sustainability. It is widely recognized that soil is also a determining factor in achieving the Sustainable Development Goals (SDGs) due to its role in generating healthy food, water regulation, carbon capture, and prevention of biodiversity loss. However, in the case of Colombia, the zoning that has been implemented is mainly due to the supply of land for production and its relationship with food security, without considering the different ES, which generates an incomplete interpretation of its potential and benefits, which leads to the degradation and deterioration of this resource. This review describes general aspects of ES, such as its definition, history, background, and classifications and tools to measure, assess, and model them. Subsequently, the ES are addressed exclusively from soils, and a review of the studies done in Colombia is presented. It concludes by mentioning some challenges and research opportunities regarding the topic and other considerations, which can lead environmental and territorial planning and management decision-makers to address the consideration of ES when planning the use and management of this resource. This study highlights that the study of soil and its ES has taken on greater relevance at a global level due to its role in addressing problems such as climate change, the decrease in biodiversity, water and energy security, and the eradication of hunger or food safety.

1. Introduction

The concept of land is more comprehensive than that of soil because it encompasses other terrain characteristics desirable for production and political domination. It implies, for example, proximity to markets, access roads, and availability of water sources. However, for the sake of facilitating the concepts of soil and land will be used interchangeably. In the Neolithic period, probably around 12.000 B.C., the soil began to be considered a productive resource. Its value as the basis or support or fundamental component of any natural ecosystems was added to the value and foundation of agricultural production. Since ancient times, it has been valued for its edaphic and ecosystem characteristics, as well as for the value of use, exchange, and social hierarchy. Its destination, which was basically agricultural, began to compete with other increasingly complex uses, considering the advance of social demands and technological developments. In a contemporary way, there are new demands: mining, urban, tourist uses, sinks of solid waste, or those of a speculative or rentier type, turning the land into a source of domination and political power regulated by an imperfect market that does not differentiate the concepts of value and cost, to its access and loss as a consequence of negative environmental impacts, in many cases irreversible. Therefore, soil is a permanent source of conflicts arising from its ownership and use, being one of the main factors of production, a provider of income, and a means of obtaining other social gratifications of private or public access.

Soil, as a fundamental component of any ecosystem, houses great biodiversity both in terms of richness and functionality (Comerford et al., 2013; Jeffery et al., 2010) therefore, inter- and transdisciplinary approaches are needed to understand its dynamics (Morel et al., 2015; Pereira et al., 2018; Van Oudenhoven et al., 2012). Although they provide a wide range of vital services for ecosystems, on a global scale, they are threatened by the development of intensive practices, which decrease their biomass, biota, carbon, and increases their compaction, acidification, erosion, and salinization (Drobnik et al., 2018; Pereira et al., 2018).

Since economic growth and development are prerequisites for the demand for environmental goods and services, Natural Capital (NC) has long been excluded from development policies (Dasgupta, 2012; Greenstone and Kelsey, 2015). As a result, it is frequently claimed that if a nation is impoverished, its citizens do not appreciate the environment. Accordingly, the depletion of NC stocks is justified if it promotes economic expansion and reduces poverty. Nonetheless, it is thought that as a nation grows, its citizens start to demand better environmental conditions, which should increase its NC reserves (Dasgupta, 2012).

In Colombia, the Natural Resources and Environmental Protection Code, established by Decree-Law 2811 of 1974 (República de Colombia, 1974), establishes the factors that deteriorate the soil and land resources, such as pollution, degradation, and erosion. It points out that the use of soils must be carried out, considering their conditions and constituent factors, and that it is necessary to determine the potential use and classification according to the ecological, physical and socioeconomic factors of each region. Law 99 of 1993 (República de Colombia. Ministerio del Medio Ambiente, 1993), defines within the functions of the Ministry of the Environment and Sustainable Development (Ministerio de Ambiente y Desarrollo Sostenible, MADS for its acronym in Spanish) to issue and update national regulations on land use, regulate the use of chemical and biological substances in agricultural activities, and make recommendations to reduce geospheric and landscape pollution.

Colombia has a great diversity of productive systems linked to different types of soil and varied ecosystem conditions, where this resource presents different levels of degradation, especially due to its fragility. Therefore, in 2016, MADS promulgated the "Policy for Sustainable Land Management" aiming to promote the responsible use of land within a framework that integrates biodiversity, water and air conservation, land use planning, and risk management, thereby fostering sustainable development and the well-being of Colombians. This policy indicates that among the causes of degradation, we can mention "the growing demand for goods and services, the lack of knowledge of its functions and importance and of alternatives for its recovery restoration and rehabilitation, the planning and territorial ordering processes that do not take into account their characteristics, the weakness in the quality monitoring processes, institutional dismantling, and the lack of standards and instruments for sustainable management" (MADS, 2016, p7). According to the Geographical Institute Agustín Codazzi (For its acronym in Spanish IGAC, 2012), Colombia has 11 of the 12 existing soil orders in the world. There are three primary properties that determine the provision of ES: (*i*) texture; (*ii*) mineralogy and (*iii*) the organic matter, determined in part by texture and mineralogy, modified by the use and management of the soil, by climate change, erosion, sealing, pollution, loss of organic matter, salinization and desertification, which in Colombia greatly affect the Andean, Amazon, Caribbean, Orinoquia and Pacific coast regions (IGAC, 2012). Considering the known effects on ecosystem complexity and individual ES components, changes in these areas are also likely to alter the relationship between multiple services and biodiversity (Cordingley et al., 2016). Although land use and changes associated with different productive activities affect both the diversity of biotic communities and the provision of ES (Tscharntke et al., 2005), studies that relate biodiversity and multifunctionality in a land use context are scarce (Lefcheck et al., 2015). For this matter, this paper identifies the need to redesign areas of knowledge and research that promote the obtaining of information about ecosystems and their services (Landis, 2017).

Colombia is facing regulatory and conceptual changes that lead to multiple uncertainties, lack of legal clarity and consequently practical problems, which is the case, for example, with soil. The IGAC (2012) when studying the conflict of uses in the territory, accepted the concept of areas of conservation and environmental protection in order to produce a cartography that would account for this issue. And to this end, it went to establish priority areas for conservation that did not have any legal protection figure that conserved and protected them from human intervention, from extractive activities of renewable and non-renewable natural resources (for example, areas of paramo that are not in the category of National Natural Parks) and areas with high and very high susceptibility and threat due to volcanic risks, seismic, erosion and flooding.

Six levels of land use are defined by regulations which seem exclusive and exclusive of each other: level of environmental protection, agricultural use, cultural heritage, infrastructure, metropolitan development, and trade, industry and tourism. Apart from the conflict of competition with the CARs and with the municipalities in their Territorial Planning (POT for its acronym in Spanish), it is problematic to define exclusive and exclusive uses, since in practice there may be mixed uses that complement each other, hence the Rural Agricultural Planning Unit (Unidad de Planificación Rural Agropecuaria, UPRA for its acronym in Spanish) is now in place to achieve the adequate implementation of the vocation and use of the land. Hence, it is possible to differentiate between "soil conservation" and "land use class" (Fedesarrollo, 2024; IGAC, 2012).

On the other hand, of the 114 million hectares that Colombia has, approximately 22 million are suitable for agricultural activities, 15 million for livestock, 4 million for agroforestry systems (mainly agrosilvopastoral), 64 million for forestry, 6 million for soil conservation, among others (IGAC, 2012). However, livestock farming is present in more than 30% of the country when it could only be implemented in 13.3%, while the agricultural panorama is opposite: 4.7% has crops, when its potential area is 19.3%. Hence, there is a wide margin to make more appropriate use of the land in accordance with the productive, environmental and cultural vocations of their territories. The country can increase the use of land for agricultural purposes from the current 7 million hectares to 22 million suitable for this purpose, while at the same time it must reduce the uses associated with extensive livestock farming and expand the areas with forest coverage (Unidad de Planificación Rural Agropecuaria – UPRA, 2015). Likewise, soil erosion in the country's continental and insular areas (45.379.057 ha) occurs in 48% of the national territory, salinization in 5%, and lands susceptible to desertification occupy 24%. There, soil functions and services, such as fertility, water regulation and storage or biodiversity are deteriorated, making their restoration very difficult, expensive and time-consuming (Instituto de Hidrología, Meteorología y Estudios Ambientales – IDEAM, 2015; IDEAM et al., 2017; IDEAM, 2013; IGAC, 2012). Additionally, because its use does not correspond to the vocation, considering its services, potential, and opportunities, a series of conflicts have been generated in the country, where evidence of overuse and underuse of the land respectively stands out, of 16% and 13% (IGAC, 2012; UPRA, 2015).

The reality at the national level translates to the municipal level where limitations are evident for local development and its impact on agricultural activities. Especially, those linked to the deterioration of resources and, with low use of practices for the efficient use of land, where producers face limitations in that, to produce sustainably, they resort, for example, to overusing water resources. That means agriculture is faced with multiple challenges related to maintaining production for the growing population but in a sustainable manner. Challenges include reducing the deterioration of soil and water resources, limiting contamination due to the use of various agrochemical products such as pesticides, or the reduction of greenhouse gas emissions in order to face the phenomena of climate change in an intelligent and adaptive way. Panorama by which various commitments have been assumed worldwide in order to ensure the supply of food and fiber, reduce impacts and conserve NC (Ministerio de Agricultura y Desarrollo Rural de Colombia – MADR and UPRA, 2014). Understanding that ES are the opportunities and benefits that human beings obtain from the NC, the purpose of this review is to present a diagnosis about the way in which soils and their ES have been considered and valued in Colombia. Which can lead environmental and territorial planning and management decision makers to address the consideration of only some ES when planning the use and sustainability of this resource (Braat and de Groot, 2012; de Groot et al., 2012; Kenter et al., 2015; Millennium Ecosystem Assessment – MEA, 2005; Pandeya et al., 2016).

In this regard, the FAO (2017) has pointed out that the suitability of soils and their ES are decreasing as a consequence of the increase in inappropriate production or use practices, which reduces the capacity to regulate these essential services for the sustainability of ecosystems and the communities. Thus, the way in which its management is carried out has important implications on the quantity and quality of ES, especially in areas subject to disturbances, alterations or that present some degree of anthropogenic intervention (Morel et al., 2015; Jónsson and Davídsdóttir, 2016; Pereira et al., 2018; Van Oudenhoven et al., 2012). Additionally, Koch et al. (2013) indicate that soil is generally omitted from land use decisions and segregated as a two-dimensional surface, the multitude of functions of which is not explicitly recognized. On the other hand, Adhikari and Hartemink (2016) specify that soil is a key component in addressing global environmental sustainability problems such as climate change, the decrease in biodiversity, water and energy security, the eradication of hunger and food security, therefore which receives increasing attention at the global policy level, where defining, valuing and understanding ES will contribute to informed decision making (Comerford et al., 2013; Robinson et al., 2012a). In this context, the review of the studies carried out in Colombia regarding ES includes their definition, history, background, classifications, and items, all of which are used for their evaluation, measurement, and formulation of qualitative models. Subsequently, research exclusively carried out on soils is addressed, and finally, some challenges and opportunities are listed on the subject.

2. General aspects of ecosystem services

2.1. History, background, and definition of Ecosystem Services

The conceptualization of nature and its management is an old topic, to the point that Plato (426 and 347 BC) in his work "Critias" exposes the impacts of deforestation. In the same way, Aristotle (384 BC) did so in his "Philosophy of Nature" when exposing ideas about the creationist vision, which continues to our time with naturalistic studies and the distribution of species with Linnaeus (1707–1778), Humboldt (1769–1859), Darwin (1809–1882) and the appearance of the anthropocentric domain with the manifestation of reductionist-mechanistic science until the 19th century. At this time the Industrial Revolution took place from 1760 to 1840, and it was Malthus (1766–1834) who relaunched the importance of natural resources in 1830, exposing the idea that the accelerated growth of the population would not correspond to the rate at which they grow food, which would lead to large-scale poverty. Until then, natural resources were considered an inexhaustible source, but with population increase and environmental pollution processes occurring at a global level, everything is reconsidered in world and regional forums, but to date, there are no major results.

In 1914, the Spanish Institute of Oceanography established the concept of sustainable development, referring to marine resources (Instituto Espańol de Oceanografía, 2014). The concept of NC was addressed, a term used for the first time by Schumacher (1973) (as cited in Gómez-Baggethun and de Groot, 2007), which refers to natural reserves in materials or information that produce a sustainable flow of valuable goods and useful services or natural income over time. And establishes that no organized economic system can be maintained without taking into account the flow of renewable and non-renewable resources (Costanza and Daly, 1992; Prugh et al., 1999). It can be interpreted as "the components of the ecosystem -structure- and the processes and interactions between them -functioning- which determines its integrity and ecological resilience; capital that generates a constant flow over time of goods and services useful to humanity, which can be valued in economic, environmental and social terms, seeking the sustainability of natural resources" (Costanza and Daly, 1992; Gómez-Baggethun and de Groot, 2007).

At the end of the 20th century and the beginning of the 21st, the concept of ES was promoted and defined as a wide range of conditions and processes through which natural ecosystems and the species they are a part of help sustain human life and are applied in management and policy decisions (Ash et al., 2010;

Cork et al., 2006; Daily, 1997; MEA, 2005). Similarly, the concept of socio-ecological systems emerged in the 90s to refer to systems characterized by discontinuous changes close to their critical values at their thresholds and the effect of resilience on their organization and health, as well as for its interdisciplinary approach between natural sciences and social sciences (Epstein et al., 2013; Folke, 2016; Perrings, 1994). Convergently with the new paradigms described, the concept of biodiversity continues to be discussed in relation to the ES and the conflicts that may generate contrasts or incompatibilities between the ES, the trade-offs (MEA, 2005), and management decisions (Martínez-López et al., 2019; Rincón-Ruíz et al., 2014).

The idea of ES was originally coined to quantify the benefits that natural ecosystems generate for human society (Motiejűnaitë et al., 2019), where its objective was to increase public awareness about the value of biodiversity and ecosystem conservation. According to Balvanera and Cotler (2007), the terms "ecosystem services" and "environmental services" can be used interchangeably, although they differ in their context. In ecosystem services, emphasis is placed on the fact that the ecosystem as a set of organisms, abiotic conditions, and their interactions, is what contributes to the well-being of society at different spatial and temporal scales (Nelson et al., 2009). And environmental services, it has been used mainly among decision makers and gives more weight to the concept of "environment", in which the interactions necessary to provide said services are not explicitly established (Balvanera and Cotler, 2007). Establishing, evaluating and valuing the environmental, social and economic variables or dimensions around the ES immersed in a space, when organizing it, is an unfinished task, since on many occasions, what prevails on the part of the actors involved is the excessive use of them, before which the criteria of sustainability are in the background (MEA, 2005; Hattam et al., 2015; Maydana et al., 2020; Rincón-Ruíz et al., 2014; Bongaarts et al., 2019).

In the same way, different concepts about SE have been explored (Costanza et al., 1997, 2017; Daily, 1997; de Groot et al., 2002; Jax et al., 2013; MEA, 2005). The most well-known and widely accepted concepts are summarized in Fig. 1. The one proposed by Daily (1997), which is one of the most used, describes them as the conditions and processes through which natural ecosystems and the species that make them up sustain and nourish human life.

Adhikari and Hartemink (2016) indicate that until a few years ago there were few articles published in relation to SE, which changed with the publications of Costanza et al. (1997) and Daily (1997) who have been representative references on the subject. From that, a considerable increase in research that describes economic and ecological aspects of ES has been generated. An additional distinctive increase in knowledge generation in this area was identified after the publication of the MEA report, where ES were defined as the benefits that people obtain from ecosystems, including those that people perceive and those that are not perceived. This definition conceptualizes the ecosystem as the basic functional unit of nature where biotic and abiotic components interact (Adhikari and Hartemink, 2016; MEA, 2005). In this regard, Jax et al. (2013) highlight that the concept represents one of the most used concepts in biodiversity conser-

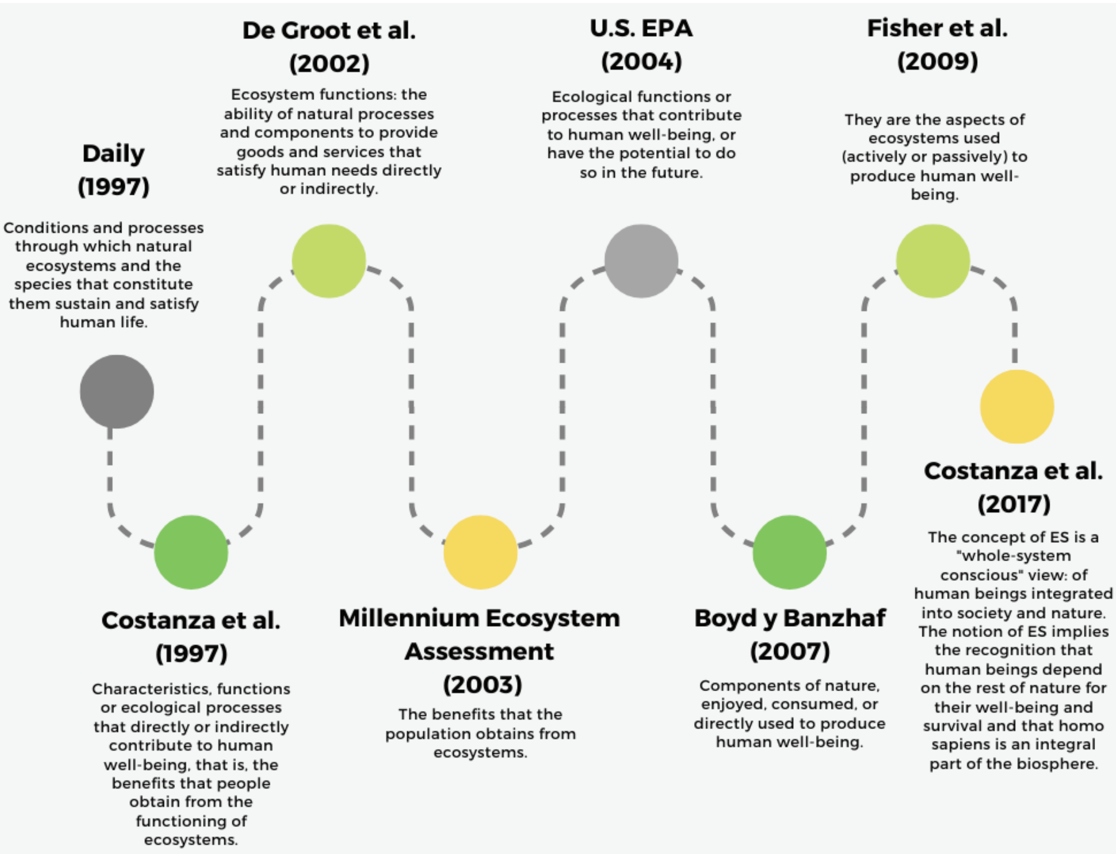

Fig. 1. Synthesis of the best-known and widely accepted concepts of ecosystem services
Source: Prepared by the authors with information from Boyd and Banzhaf (2007); Costanza et al. (1997); Costanza et al. (2017); Daily (1997); de Groot et al. (2002); MEA (2005)

vation, natural resource management, policy development, and environmental accounting, among others. For their part, Costanza et al. (2017) add that it is important to distinguish between ecosystem processes and functions on the one hand and ES on the other as processes contribute to ES but are not synonymous.

The ES and CN knowledge in Colombia are dispersed (Ruiz-Agudelo and Bello, 2014) and there are no homogeneous methodological frameworks that allow the use of information in decision-making (Crossman et al., 2013). In addition, their value is poorly understood and undervalued by markets and governments (Raudsepp-Hearne et al., 2010). Regarding publications from various sources on terrestrial ecosystems, including soils, 685 are registered in the Biodiversity Information System (198 national and 487 in international journals) (Fig. 2) with 12 universities and their research groups represented (Fig. 3) and nine environmental authorities (Fig. 4). Ruiz-Agudelo et al. (2022a) mention that the number of research on economic valuation has increased, considering that of the 154 studies they evaluated, the majority were recent: 76% were published between 2013 and 2020 and the remaining 24% between 1996 and 2009, highlight-

Fig. 2. The number of publications in various sources about terrestrial ecosystems in Colombia
Source: SiB Colombia (2024)

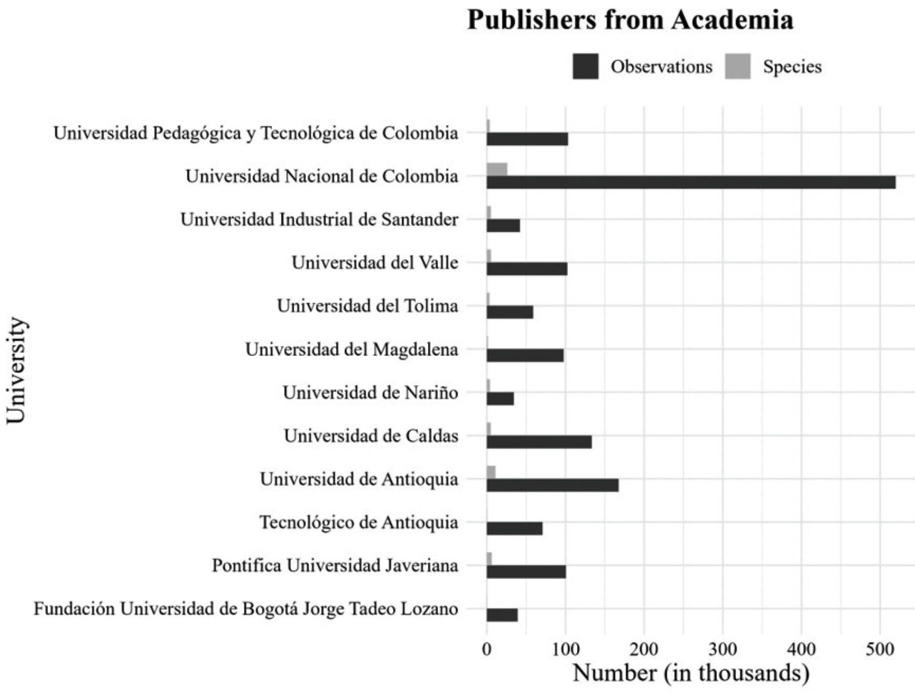

Fig. 3. The number of publications in various sources about terrestrial ecosystems in Colombia and their representation by universities.
Source: Prepared by the authors with information from SiB Colombia (2024)

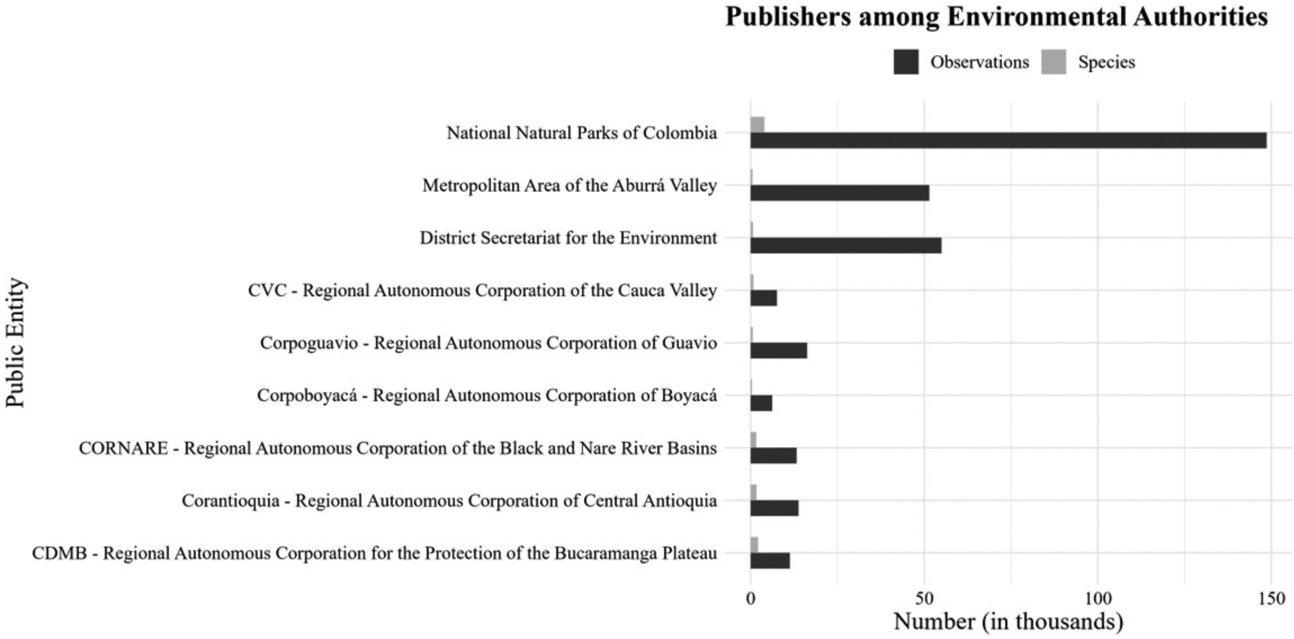

Fig. 4. The number of publications from various sources on terrestrial ecosystems in Colombia and their representation by environmental authorities. Source: Prepared by the authors with information from SiB Colombia (2024)

ing that the departments of Antioquia, Cundinamarca, Meta, Valle del Cauca and Bolívar, contributed 53% of the knowledge on the economic valuation of Economic Values of ES.

2.2. Classification of Ecosystem Services

To make the concept of SE more specific, classification systems were needed that would allow discussions, evaluations, model generation, and assessments. Costanza et al. (1997) presented a list of 17 services that include gas regulation, climate regulation, erosion control, soil formation, nutrient cycling and food and raw material production, among others, classifications that are still valid and widely used. However, time and divergence of opinion regarding the most appropriate categorization has led to the development of some revisions and several classifications scientific analysis, economic valuation, and policy formulation (Delibas et al., 2021). It is highlighted, MEA launched in 2001 as a predominantly ecological project of the United Nations Environment Program (UNEP), where consecutively the Economics of Ecosystems and Biodiversity (TEEB) project initiated by Germany and the European Commission and adopted by UNEP, added more economic aspects of ES (Brevik et al., 2018; Costanza et al., 1997, 2017; Ellili-Bargaoui et al., 2021; Jónsson and Davídsdóttir, 2016; Pereira et al., 2018; TEEB, 2018). Similarly, the Common International Classification of Ecosystem Services (CICES) was developed to provide a hierarchically consistent categorization based on science to be used for NC accounting purposes (CICES, 2024). The Final Ecosystem Goods and Services Classification System (FEGS) and the Ecosystem Services Classification System (NESCS) were developed by the United States Environmental Protection Agency to provide a system that generally is similar to CICES (Brevik et al., 2018; Costanza et al., 1997, 2017; Pereira et al., 2018).

Between the main ES classification systems used in the world, that there are differences and similarities. In this regard, it can be mentioned that all of these systems recognize that ecosystems provide multiple essential benefits for human well-being and aim to categorize these benefits to facilitate their study and management. The main differences lie in the terminology and in how services are grouped. For example, while the MEA distinguishes between supporting and regulating services, CICES combines them into a single category of “regulation and maintenance.” Other systems also emphasize cultural and spiritual interactions, placing greater importance on perceptions and social values. However, although there are similarities and differences in the classification and emphasis of ES depending on the system used, all agree on the importance of recognizing and valuing the multiple benefits that nature offers to humanity.

On the other hand, the largest number of articles on ES comes from Europe (38%), where the Operationalization of Natural Capital and Ecosystem Services (OpenNESS) project was developed, which translates the concepts of CN and SE into operational frameworks that provide proven, practical, and adaptable solutions for their integration in the management of territory, water, and urban areas, as well as in decision-making through an approach based in case studies at different scales (OpenNESS, 2017). The most commonly accepted and used classification of ES is the one proposed by the MEA (MEA, 2005) which divides them into four broad categories: (*i*) provision services; (*ii*) regulatory services; (*iii*) cultural services and (*iv*) support services. Each category has an interrelationship, and many services overlap or reinforce each other. This classification highlights the importance of conserving biodiversity and ecosystem integrity to maintain these benefits. In turn, various authors such as Ostrom (2000) include in their analysis variables which, being an application of the concept of common goods, do not fall into these categories and are aimed at knowing well the actions of States and communities, but their analysis is aimed at determining the way in which governance and governance over ecosystems and their benefits is developed. But what should never be ignored, whatever the classification proposal, is that everything must be based on the scientific knowledge of the established categories, in order to avoid subjectivity or political decisions contrary to sustainability.

2.3. Tools to measure, value, and model Ecosystem Services

According to different authors (Costanza et al., 1997; Daily, 1997; de Groot et al., 2002; Harrison et al., 2018; Neugarten et al., 2018; Peh et al., 2013) the measurement, assessment, and modeling of ES have been important instruments to convey to decision-makers the importance of ecosystems and the services they provide for their self-regulation. Information on ES provision can be useful as support to safeguard the multiple benefits provided by different areas, inform management decisions to ensure equity in the use of resources and distribution of benefits, or allow evaluation of the consequences of management or policy changes, among others. Therefore, the evaluations have led to the application of the ES concept to real-world situations to support sustainable management of the earth (Harrison et al., 2018; Neugarten et al., 2018).

The selection of the tool or method to apply in a specific case may depend on many factors, such as the purpose of the evaluation, pragmatic reasons (context), the related SE, the required outcomes (qualitative or quantitative, spatial or non-spatial, monetary or non-monetary), available resources (budget, time), the availability of data, or experience and practical considerations (strengths, limitations, feasibility) (Harrison et al., 2018; Neugarten et al., 2018). On this matter, Harrison et al. (2018) present an important review in relation to the different methods that could be applied in the evaluation of ES, proposing a decision tree methodology to guide evaluators in the selection of the tool, considering biophysical, sociocultural, and economic methods. Likewise, some of these and other tools have been reviewed by Neugarten et al. (2018). According to Harrison et al. (2018) perhaps the most complete is the inventory of ValuES methods. However, within the wide variety of tools, Neugarten et al. (2018) highlight alternatives frequently applied in new contexts and available on the web (Fig. 5).

In relation to the variability of methods, the importance of considering the participation of interested parties is highlighted. Key aspects in method selection include the inclusion of local knowledge, the ease of communication, the reasons oriented towards decision-making, the purpose of the case study and the ES at play (Harrison et al., 2018). Equally, it is important to mention that each tool has strengths, limitations, and provides different types of information. However, all tools provide key elements about the problems associated with ES and help support management and policy decisions (Neugarten et al., 2018).

3. Soil ecosystem services

Soil is a key component of the terrestrial ecosystem that operates at the interface of the lithosphere, biosphere, hydrosphere, and atmosphere (Adhikari and Hartemink, 2016; Ellili-Bargaoui et al., 2021). They are complex and dynamic ecosys-

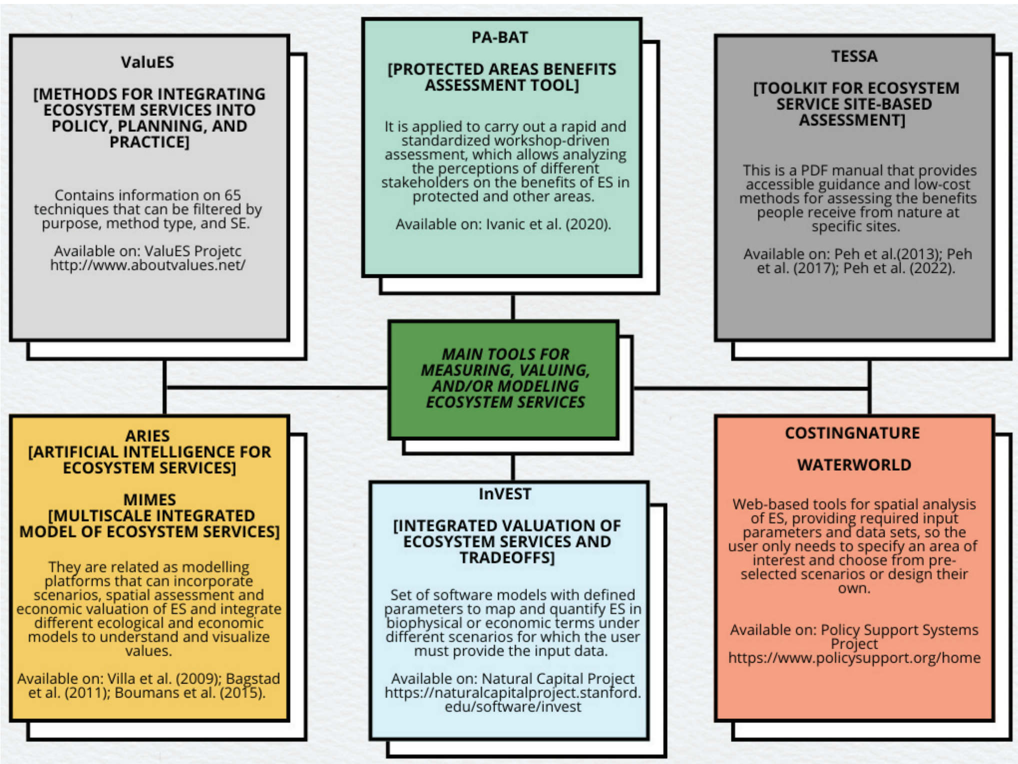

Fig. 5. Main tools for measuring, valuing, and/or modelling ecosystem services
Source: Prepared by the authors with information from Bagstad et al. (2011); Boumans et al. (2015); Harrison et al. (2018); Ivanic et al. (2020); Natural Capital Project InVEST (n.d.); Neugarten et al. (2018); Peh et al. (2013); Peh et al. (2017); Peh et al. (2022); Policy Support Systems (n.d.); ValuES Project (n.d.); Villa et al. (2009)

tems that sustain physical processes and chemical transformations fundamental to terrestrial life (Jónsson and Davídsdóttir, 2016). Soil is the main basis of biodiversity on earth and plays a crucial role in the functioning of ecosystems, in addition to being considered one of the richest habitats because it contains more species than all the other surface biota together. Because of this, the health and biodiversity of soil are of vital importance to human beings. Although their importance is often not recognized, soils and their biota provide a wide variety of ES (Fig. 6) (Adhikari and Hartemink, 2016; Comerford et al., 2013; Ellili-Bargaoui et al., 2021; Jónsson and Davídsdóttir, 2016) Pereira et al., 2018).

Fig. 6. Main Soil Ecosystem Services (SES)
Source: Prepared by the authors with information from: Comerford et al. (2013); Jónsson and Davídsdóttir (2016); Robinson et al. (2012a)

Soil is one of the most complex biomaterials on earth and, although there is representative knowledge about its formation and distribution, the understanding of its functions and ES is incomplete (Adhikari and Hartemink, 2016). On this matter Brevik et al. (2018) mention that studies on ES emerged in 1960 and, between 1970 and 1980, scientists classified these services by functions. However, the inclusion of soil evaluation in ES was rare until the 2000s, interest that increased after 2000 and, again after 2005, with an increasing focus on the contributions of soils to ES after approximately 2009, which coincides with the researchs reported for Colombia, where contributions to the study of ES were identified from 2010.

According to Bouma et al. (2022) soils play an important role in achieving at least seven of the Sustainable Development Goals (SDGs) (2: Zero hunger, 3: Health and well-being, 6: Clean water and sanitation, 7: Affordable and clean energy, 12: Responsible production and consumption, 13: Climate action, and 15: Life of terrestrial ecosystems), due to their role in the generation of healthy food, water regulation, carbon sequestration, prevention of soil degradation, and prevention of biodiversity loss. Likewise, these objectives include the need to protect, restore, and promote the sustainable use of terrestrial ecosystems, combat desertification, and halt and reverse land degradation, among other aspects, where clearly, soils and the ES they provide are fundamental for the achievement of these objectives.

Estimating the Colombian Remnant Natural Capital's ecological and economic value through human transformation indicators and economic valuation information in the Amazon, Orinoco, Caribbean, Pacific and Magdalena-Cauca basins, in current and future development scenarios, has an approach through the research of Ruíz-Agudelo (2023); Ruiz-Agudelo et al (2022a; 2022b; 2022c) and Ruiz-Agudelo and Bello (2014) provides a comprehensive assessment of the economic values for ES in Colombia (Fig. 7).

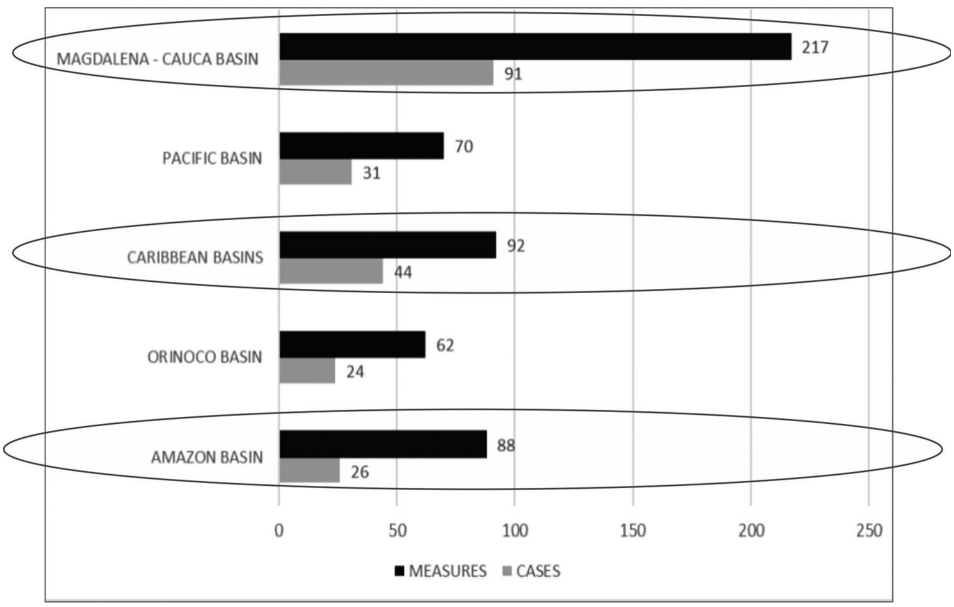

Fig. 7. Number of cases and measurements of ecosystem services economic values in the five Colombian basins
Source: Ruíz (2023)

4. Study of soil ecosystem services in Colombia

For the list of studies on Soil Ecosystem Services (SES) in Colombia, a systematic literature review was conducted in the following databases: Science Direct, SCOPUS, Web of Science, EBSCO, SCIELO, Redalyc, and Google Scholar, using the keywords: Soil Ecosystem Services, Assessment, Valuation, Colombia, Environmental Services, Soils, Land, Decision-making, Land Use, Land Management, Colombian Ecosystems, and Ecosystem Valuation. The search was carried out in Spanish and English and the Boolean operators AND, OR, and NOT were used in different combinations. The following criteria were considered in order to filter the information: 1) Select only studies conducted in Colombia. 2) That their main focus was on ES. Therefore, studies in which the primary objective was to study the role of biological communities, studies in which an integral valuation of ES (biophysical, sociocultural or economic) was carried out, and/or studies related to ES provided by other resources were excluded. 3) List only academic publications in peer-reviewed journals. Therefore, gray literature and graduate work were excluded. As a result of this review and cleaning, it was found that between 2010 and 2022 only 13 academic publications explicitly addressed the study of SES in Colombia, with an increasing trend.

Silva and Correa (2010) conducted an economic evaluation of goods and SES in floriculture companies as a basic criterion for strengthening corporate environmental management in Colombia, through an analytical literature review. Subsequently, it is observed that the first studies on SES in Colombia were applied in very different contexts, although with the same purpose of highlighting how land use can be a determining factor in the provision of ES. In this regard, Castro-Romero et al. (2014) analyzed the priorities for ecological restoration of soil and its ES in areas degraded by agricultural use in the Santa Helena microwatershed in the municipality of Suesca (Cundinamarca). They found that about 23% of the evaluated area presented deficient to very deficient conditions in the provision of ES, manifested by a strong deterioration of soil quality caused by erosion and mass removal processes. This study highlighted that intense agricultural use causes a decrease in SES, which endangers the economic stability and food security of the local communities that depend on them.

For their part, Lavelle et al. (2014) studied the change in SES and land use in the Orinoco River basin through the evaluation of macroinvertebrate communities and SES such as climate regulation, hydrological functions, soil stability, and nutrient supply potential in four of the main production systems of the region (improved pastures, annual crops, oil palm and rubber plantations), compared with original savannahs. They point out that the alternation of complementary systems in time through rotations, or in space through strategic spatial arrangement, would allow interactions and increase connection at the landscape scale, favoring different uses for the conservation of soil capital and its capacity in the provision of ES. In relation to other productive sectors in the Colombian economy, Rojas et al. (2014) presented a review on biodiversity and ES in soil-subsoil management focused on mining, where they highlight that the challenge for environmental and mining institutions is to achieve awareness and recognition of the importance of biodiversity and ES and their vulnerability to productive activities. The study was conducted, in the search for an environmental management of the territory based on its ecological structure, with the active participation of both the mining sector and the beneficiaries of the ES.

On the other hand, Giraldo et al. (2015) analyzed the problems associated with the occupation of suburban land in the municipality of Pereira (Risaralda) and the deterioration of ES leading to the loss of territorial capacities for the welfare of the population, in which, according to the comparative analysis of the extent of land cover between 2006 and 2011, they observed a 23.2% decrease in Forests and Semi-natural Areas over the total area studied. With the consequent loss of ES, the most significant reduction was in support services, where it went from 5,097.05 ha in 2006, to 535.3 ha in 2011 (a decrease of 89%), followed by a loss in provisioning (-2,247 ha) and regulating services (-2,103 ha). The study also indicates that these areas were replaced by agricultural lands, the latter showing an increase of about 490% in their extension. Therefore, they conclude that a sustainable occupation of suburban land should be sought through a set of guidelines, and regulatory proposals that direct the way of using and occupying these areas in search of sustainability, and where the planning, management, and financing instruments allow them to be operational. Finally, Ordońez et al. (2015) studied the effects of peasant and indigenous management practices on biogeochemical properties and carbon storage services in Andean soils in Popayan. Their main results suggest that traditional management strategies in this region, such as the use of natural pastures, forage crops and natural forest management, are successful in achieving food production using low levels of technology and limited resources. The study concludes that the food production management practices of these indigenous communities and farmers are compatible with maintaining the carbon storage service in these soils at a local scale. In relation to the most recent research, there is a tendency to evaluate alternatives that allow the integration of the SES study with land use and management planning. In this regard, Lozada et al. (2018) studied the provision of ES and land use from the perception of Afro-descendant communities in the Colombian Pacific, considering the three main economic activities of the population: agriculture, fishing, and tourism. Its main results show a detriment to the ES and changes in land use due to the loss of crops and traditional cultural and community activities, among other causes. For their part, Aldana-Domínguez et al. (2019) evaluated the effects of past and future changes in land cover and its relationship with ES, ecosystem damage, and biodiversity, to propose land use planning through a case study in the metropolitan area of Barranquilla. Here, they mention that natural areas have decreased in the last 30 years due to rapid urbanization, where the change in land use has driven the reduction of ES, especially supply and regulation. Likewise, they highlight the importance of incorporating the spatial analysis of SES and biodiversity in planning instruments, such as the Territorial Planning Plans in Colombia.

On the other hand, Clerici et al. (2019) studied the spatio-temporal and cumulative effects of land use and land cover and climate change on two ES (water production and carbon storage) in the Alto Bogotá and Alto Chicú river basins in the eastern Colombian Andes. They indicate that temporally and spatially explicit scenarios and maps where water supply areas and increased carbon offsets are identified can help direct land use decisions to maintain the supply of such services, such as climate change mitigation or other applications.

Recent studies also show a tendency to make valuations and propose indexes that generate information to identify how land use can affect the provision of ES, contribute to the integration of scientific knowledge with the practices carried out in the territories. In this regard, Machado et al. (2019) presented a proposal for the quantification and characterization of Natural Soil Capital (NSC) through an index of vulnerability to changes in vegetation cover and its influence on the provision of ES for erosion prevention in tropical soils, which was evaluated in the Riogrande watershed of the Andes of northern Colombia. They highlight that one way to evaluate the potential of the CNS to provide services is the construction of a vulnerability index that reports on its current state and the changes that land cover has faced in anthropogenic times. Similarly, Bedoya-Gómez et al. (2021) carried out an ecological assessment of the SES in coffee farms in Cuchilla de San Juan in the municipality of Belén de Umbría (Risaralda), where they point out that this assessment addresses the existing theoretical limitations in relation to the topic, such as supply for the definition of methodologies that articulate knowledge with practice and allow generating information on the state of the SES. Likewise, they highlight that anthropogenic dynamics have directly affected soil conditions and, therefore, property planning of the territories is substantial.

Rodriguez et al. (2021) evaluated the capacity of agroforestry and silvopastoral systems to sustain SES provision in the deforested Amazon, using a holistic ES evaluation framework in four municipalities in the department of Caquetá. They point out that to conserve the physically fragile and chemically poor soils of the Amazon region, continuous tree cover is required to allow their proper functioning. Likewise, they highlight that agroforestry could help mitigate soil degradation and the loss of its ES. Finally, Silva-Olaya et al. (2022) present a composite index to explore how land use change affects soil properties as indicators of its ability to provide five SES (plant growth support, C storage, nutrient cycling, control of erosion, and water regulation) in the department of Caquetá, northeast of the Colombian Amazon. They suggest that changes in land use, from forest to grassland, affect key ecological processes and, in particular, soil properties associated with ES provision. Therefore, they highlight the importance of readjusting management practices to mitigate the negative historical impacts of pasture conversion in the Colombian Amazon.

On the other hand, it is important to mention that the principal documents regarding the soils are: (i) National Study of Soil Degradation by Erosion; (ii) Carbon deposits in soils under forest remnants and grasslands of farms in the department of Caquetá; (iii) Protocol on Land and Land Degradation due to Desertification; (iv) Protocol on Soil and Land Degradation by Erosion, and (v) Protocol on Soil and Land Degradation by Salinization.

Finally, it is also highlighted that Colombia is a country with an oversized environmental policy, and at the international level, with bilateral or multilateral obligations arising from being a signatory to more than 120 bilateral Conventions, Protocols and Resolutions on natural resources. The MADS (Colombia. MADS, 2017) for the COP 16 on Biodiversity included among its goals for 2030 commitments on soil restoration, for which it has maps of degraded soils and portfolios of restoration priorities produced by the IGAC, the research institutes of the National Environmental System (SINA by its acronym in Spanish) and the MADS.

According to data from the UNDP BIOFIN Initiative on Biodiversity Finance, Colombia allocated approximately 1.6 trillion pesos annually (equivalent to about 522 million USD) from public budgets to biodiversity management between 2012 and 2021. In 2021, public spending on biodiversity accounted for 0.15% of Colombia's Gross Domestic Product (GDP), 0.34% of central government public spending, and 29.3% of national expenditure allocated to environmental purposes. On average, 62% of this public spending corresponds to investments in projects focused on areas such as strengthening environmental licensing processes, managing protected areas, and conserving ES, among others. The remaining 38% is classified as operating expenses, primarily related to payroll and general administrative costs in public entities within the environmental sector. Additionally, 43% of public spending on biodiversity is managed at the central level, while the remaining 57% is executed at the local level. Of this local spending, 37% is overseen by decentralized territorial entities, and 20% is managed by Regional Autonomous Corporations using their own resources (PNUD, 2022).

5. Challenges, opportunities, and other considerations

It is important to highlight that to avoid further degradation, soil science has been calling for a careful consideration of its quality in decision-making, taking into account that they are marginalized as a mere surface and their role in the provision of ES is not discussed (Doran, 2002; Doran and Parkin, 1994; Drobnik et al., 2018; Herrick, 2000; McBratney et al., 2014; Robinson et al. 2012a). Janzen et al. (2011) even mention that people who are not directly involved with the soil do not perceive it at all. This, coupled with the fact that SES are difficult to recognize for their supporting role in all ecosystems and, although their value exceeds that of other parts of the system, they remain under-recognized (Comerford et al., 2013; Robinson et al., 2012b). Additionally, Bouma (2014) mentions that the classification data, interpretation, and structure of the information available on soil are often complex and difficult to understand for anyone not belonging to the scientific community. This is a key aspect that should also be analyzed to promote its proper use and allow for the appropriation of knowledge.

Further research presents various challenges and continues to develop indicator frameworks, emphasizing the need to assess SES and promote soil-ecosystem linkages when developing land resource policies and management (Bouma et al., 2022; Ellili-Bargaoui et al., 2021; Robinson et al., 2012b). In this regard, several studies have attempted to describe these relationships as identifying and understanding these services is crucial for decision-makers and stakeholders (Ellili-Bargaoui et al., 2021; Hauck et al., 2016; Nelson et al., 2009; Robinson et al., 2012b; Wu et al., 2013). However, Adhikari and Hartemink (2016) found that the largest number of published articles on ES came from Europe (38 %) and North America (28 %). South America along with Africa and Oceania only generated about 6 to 7 %. Dominati et al. (2010) and Comerford et al. (2013) indicate that studies into SES, in particular, are limited. Therefore, one of the biggest challenges is the creation of a standard value system as there is no standard or widely recognized method that correctly defines and quantifies each service (Adhikari and Hartemink, 2016; Drobnik et al., 2018; Ellili-Bargaoui et al., 2021; Jónsson and Davídsdóttir, 2016). Likewise, there is no consensus on practical indicators that allow them to be evaluated (Ellili-Bargaoui et al., 2021).

In this context, it is important to mention that the National Biodiversity and SE Assessment (Chaves et al., 2021) highlights that Colombia's soil is diverse, fragile and requires attention and sustainable management for development to link its functions to the provision of SE. As a tool to value this resource and provide information for management and decision-making in the territory, where it is also important to identify local knowledge through community diagnoses, considering that such studies are often used to inform management decisions about resources natural, such as in the MEA (Chimello and Berkes, 2014). Likewise, the guidelines of the National Policy for the Sustainable Management of Biodiversity and ES (PNGIBSE for its acronym in Spanish) point out the importance of recognizing the value of the services that ecosystems provide for the benefit of people in addition to how these are integrated into decision-making. Talking about conservation and sustainable use of ES requires an adaptive approach based on social learning.

Land use planning processes, rather than technical exercises, must be considered and faced as deliberative processes that promote dialogue and reconciliation between different forms of assessment in which not only the individual ecological or social components are of interest, but also the interactions between these (Rincón-Ruíz et al., 2014). Under these considerations, the contribution of soil to human well-being goes beyond food production, so its evaluation must be addressed considering all its functions, which include: hosting nutrients, organisms and plants, accumulating water, regulating floods, and decomposing organic substances. All its ES are mediated for their conservation by their properties and the management and handling that is done of them (Robinson et al., 2012b; Adhikari and Hartemink, 2016; Ellili-Bargaoui et al., 2021). Daily (1997) suggested that soil is one of the most important determinants of the economic status of a nation and that their inclusion in ES frameworks and in decision and policy making is essential. Therefore, there is a critical need to promote soil-ecosystem linkage in policy development and resource management (Ellili-Bargaoui et al., 2021; McBratney et al., 2014; Robinson et al., 2012a).

According to Pereira et al. (2018), the value of SES depends on what they can provide and how they are managed. Therefore, the way we manage our earth can cause soil to provide only unsustainable short-term benefits, which leads to a devaluation and deterioration of services, while sustainable management can maintain or improve them. The approaches we follow to manage our lands can have critical effects on SES, which is directly related to sustainability. The damage or improvement induced by our activities will be reflected in our society and economy. Likewise, knowledge about soil diversity and its function as a system, and the identifying the links between this resource and ES, must be recognized for sustainable development and human well-being (Adhikari and Hartemink, 2016; Bouma, 2014; Bouma et al., 2022).

Similarly, the evaluation of practical ES indicators can contribute to identifying gaps that prevent policy-makers from adopting ES approaches more comprehensively. With the aim of understanding how to manage this resource to maximize the ES provided for the betterment of humanity and contribute to sustainable soil management (Comerford et al., 2013; Ellili-Bargaoui et al., 2021; Robinson et al., 2012b). Therefore, SES studies could be used in the development of local and national policies, as well as in programs on the use and management of natural resources (Adhikari and Hartemink, 2016; Ellili-Bargaoui et al., 2021; Jónsson and Davídsdóttir, 2016). They can potentially lead to establishing the best use of the resource and the generation of investment options in nature conservation, which can translate into benefits for both people and ecosystems (Peh et al., 2017).

The contributions provided by models and/or tools to measure, assess, and/or model SE are recognized, however, it is identified that scientific research within the framework of SES can find an opportunity to reorient itself, in light of current reflections on Open Science and its relationship to community development. Aiming to contribute that the data obtained and the information available on soil can be understood and, above all, used for decision-making at both the local level and for national public policies. It is important to note that according to UNESCO (2021), Open Science is defined as "an inclusive construct that combines diverse movements and practices, in order to make multilingual scientific knowledge openly available and accessible, as well as reusable by all, scientific collaborations and the exchange of information are increased for the benefit of science and society, and the processes of creation, evaluation and communication of scientific knowledge are opened to social agents, beyond the traditional scientific community" (UNESCO, 2021, p7).

In order to create effective policies, conservation scientists have stressed the importance of considering the socioeconomic context of NC loss (Tyler DesRoches, 2020). Given the unparalleled degradation of the biosphere, this emphasis becomes imperative (Bongaarts et al., 2019). Insofar as economic growth is a crucial component of this development, investigating how it affects natural capital could bolster the diagnosis of biodiversity decline and aid in the creation of a workable solution (Daly, 2020). In Colombia, since the first Mission of Science, Education and Development carried out in 1993, currently known as the Mission of Wise Men (Gobierno de Colombia, 2019), the opportunity was opened for the generation of a science that enables social and cultural development and promotes the Social Appropriation of Knowledge (ASC for its acronym in Spanish) as a path towards the generation of intellectual wealth, necessary for better harmony between people and their environment. Similarly, the Public Policy of ASC within the framework of Science, Technology and Innovation (CTeI) of Colombia, assumes ASC as "an intentional process that calls on all social actors to participate in practices of exchange, dialogue, analysis, reflection and negotiation that promote understanding and intervention in their contexts. Process that is generated through the management, production and application of science, technology and innovation in environments of trust, equity and inclusion, which makes possible the transformation of realities and the generation of social well-being" (Ministerio de Ciencia, Tecnología e Innovación de Colombia – Minciencias, 2021, p.20).

The methodologies for SES assessment have been mostly designed and created by developed countries, therefore, it is necessary to make adaptations to our context, where decision-making and participation are differentiated in economic, political and sociocultural terms. The success of actions oriented towards sustainability also implies the redefinition and reinterpretation of existing cultural aspects (Ángel-Maya, 2000) which is possible through social learning that occurs as a result of ASC processes. Therefore, five principles can be considered: (*i*) Recognition of context; (*ii*) Participation; (*iii*) Dialogue of knowledge and understanding; (*iv*) Critical reflection and (*v*) Transformation, which would allow generating evaluations from the "bottom-up" logic, which has demonstrated the possibility of achieving achievements in a more efficient and sustainable way over time (Ostrom, 2000). It was noted that the SES studies identified in Colombia are mainly based on evaluations that offer scientific-technical or economic information and data, but the results obtained are not analyzed or discussed in terms of social learning, collective actions, transformation or impact on communities, or exchange of knowledge. In the literature, paradigms predominantly based on developmental models, market logic and scientific rationality were recognized, leaving apart to the diverse worldviews present in the territories (de Sousa, 2011).

In this context, the ASC is an opportunity to enrich SES research through participatory methodologies and tools of practical and simple application, through which dialogue and the recognition of epistemic diversity allow for the establishment of agreements for assertive decision-making that results in the social and ecological well-being of the territories, where beyond the data and information obtained from the application of methodologies, social transformations can be generated based on the practical use of scientific knowledge in dialogue with the knowledge of the communities.

6. Conclusions

Soil provides a wide variety of ES, such as carbon capture, regulation of the hydrological cycle, and biodiversity reserve, among others. As a complex element with a considerable role in different ecosystems, the study of soil requires the consideration of inter and transdisciplinary approaches that contribute to understanding its dynamics and its role in providing such services. Likewise, it is highlighted that the study of soil and its ES have taken on greater relevance at a global level due to their role in addressing problems such as climate change, the decrease in biodiversity, water and energy security, the eradication of hunger, or food security.

The first SES studies reported for Colombia in the academic literature were applied in very different contexts (floriculture companies, lands used for agricultural purposes, mining, suburban areas, or watersheds), although with the same purpose of highlighting how land use can be a determining factor in the provision of SE. The most recent research highlights the tendency to evaluate alternatives that allow the integration of the SES study with planning on the use and management of the territory. Additionally, the research outlines a propensity to carry out assessments and propose indices that generate information to identify how land use can affect the provision of services and how these contribute to integrating scientific knowledge with the practices carried out in the territories.

The focus on zoning areas in Colombia has been based mainly on their production capacity or their relationship with food security, however, the contribution of soils to human well-being, beyond this, requires an evaluation that can be addressed from the recognition of ES. Likewise, scientific research within the framework of the SES can find this opportunity to reorient itself through the current reflections on Open Science and Social Appropriation of Knowledge. In order to contribute to ensuring that the data obtained and the information available on the soil can be understood and used effectively for decision-making at both the local and national public policy levels, as well as in the establishment of use and management plans that favor the preservation of the SES.

It is important to recommend that it's crucial to prioritize studying soil biota's functional diversity and spatial aspects like water purification, genetics, and climate regulation. There's a notable lack of research on biological and hydrological properties and supporting services. Examining land use, management, erosion, carbon loss, and biodiversity is vital, given their impact on global food security. Future research should focus, in greater detail, on the possible future impacts of the expansion of other economic activities such as legal and illegal mining, oil and gas exploitation, oil palm, and the expansion of other types of agricultural systems.

The review of Soil Ecosystem Services (SES) studies in Colombia reveals a growing concern regarding the negative impacts of unsustainable land use and management on the provision of key services, which are essential for environmental sustainability and human well-being. While the reviewed studies emphasize the importance of integrating scientific knowledge into territorial planning policies and practices, they also highlight the urgent need to adopt sustainable approaches, such as agroforestry systems, ecological restoration strategies, and clear regulations to mitigate the adverse effects of land-use change. Therefore, strengthening interdisciplinary research and fostering cooperation among productive sectors, local communities, and governmental entities is crucial. This approach will promote responsible land use and ensure the conservation of SES as the foundation for the country's ecological, economic, and social stability.

Conflict of interest

The authors declare no conflict of interest.

Author Contributions

Andrea A. Bernal-Figueroa: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review and editing. **Natalia Sánchez-Gómez, Francisco Gutiérrez-Bonilla, Germán E. Cely-Reyes**: Supervision, Validation, Visualization, Writing – review and editing. All authors read and approved the final manuscript.

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