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# A bibliometric analysis on economic valuation of ecosystem services provided by soil biodiversity

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## Abstract

The soil ecosystem services (SES) concept is often used as a synonym for soil functions and soil processes in the perspective of improving environmental decision-making and representing soil's many benefits to people. In the present paper we conducted a bibliometric analysis on the economic valuation of ecosystem services (ES) provided by soil biodiversity and identified trends in the field worldwide. The baseline data for the analyses were retrieved from queries of an online scientific database, from which articles that contained the term "ecosystem services" and terms related to "economic valuation" and "soil biodiversity" were selected. The use of economic valuation methods as a means to address trade-off scenarios in the maintenance of certain ES has evolved in meaningful ways. A range of studies have estimated the value (individual or combined) of ES related to soil biodiversity provided by agricultural and natural landscapes, although there is a lack of integrative biophysical-social research that characterizes SES changes, coupled with multi-metric qualitative valuation, and context-appropriate decision-making. As soil biodiversity has important potential contributions to ES and human well-being, we hope that this article will contribute to increasing the visibility of soil biodiversity, raise awareness among policymakers, and help promote public policies aimed at biodiversity conservation.

**Keywords:** soil organisms, public policies, soil conservation, soil ecosystem services.


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## 1. Introduction

The ecosystem services (ES) concept has become of great importance as a tool to integrate nature's contributions to people into decision-making for programs and policies on ecosystem management (van Oudenhoven et al. 2018), landscape planning (De Groot et al. 2010), selection of conservation priority areas (Egoh et al. 2007), and for the development of sustainable agricultural systems (Bennett et al. 2021).

Soil ecosystem services (SES) often have been used as a synonym for soil functions and soil processes and can be understood as the flows of soil natural capital stocks that benefit humans (Dominati et al. 2014, Pascual et al. 2015), and can be classified into supporting, regulating, provisioning, and cultural services (MEA 2005). The performance of soil functions and the delivery of ES are affected by changes in soil biodiversity, because soil organisms are important promoters of several essential ES (FAO 2020).

Soil biodiversity comprises the variation in soil life, from genes to communities, and the ecological complexes of which they are part, i.e., from soil microhabitats to landscapes (Turbé et al. 2010). However, management practices have a strong effect on belowground communities, and the resulting declines in soil biodiversity can reduce and impair their benefits to humans and ecosystems (Wall et al. 2015). Following welfare economics theory, an economic valuation can provide useful information about changes resulting from the management of organisms that directly affect SES (Plaas et al. 2019).

Environmental valuation focuses on the interaction between environmental and economic data, supporting planning and decision-making for policies and incentives. Preliminary estimates of the value of ES provided by biodiversity on Earth are on the order of trillions of US dollars annually (Costanza et al. 1997, 2014), but global estimates of all services associated with soils and its biodiversity are still lacking, with the only preliminary and incomplete estimate (over 1.5 trillion USD year$^{-1}$) performed years ago (Pimentel et al. 1997). The idea of valuing nature is anthropocentric and can only grasp a limited aspect of the whole value of an ecosystem or service (De Groot et al. 2010). However, this approach can shed light on the role of economic valuation of SES. Hence, identifying the productive and insurance values of soil biodiversity is an important step to understanding the role of soil biodiversity conservation in climate change adaptation (Pascual et al. 2015) and in influencing management decisions (Vanermen et al. 2021). However, one of the major obstacles to the development and implementation of conservation strategies is the lack of knowledge about the economic value of non-marketable benefits generated by natural and productive systems (Alcon et al. 2020). As most ES are freely delivered without markets and without pricing systems, their long-term value is not included in economic estimates. Therefore, the identification and biophysical and economic measurement of the benefits provided by ecosystem dynamics in the form of goods and services to society is a major challenge for the proper management of ecosystems and of the economic system (Costanza et al. 2017).

### 1.1 Economics of ES valuation

Economic valuation approaches depend on the availability of market price information and can be divided into direct and indirect market valuation (Figure 1). Direct market valuation derives the value of ES directly from available market price information, that is, the prices provided by market transactions relating directly to the ES. It encompasses four main approaches: (i) the market price-based approaches, (ii) the cost-based approaches, (iii) the net factor income approach, and (iv) approaches based on production functions (Pascual et al. 2012, Zandebasiri et al. 2023).

The indirect market valuation can be divided into the revealed- and the stated-preference approach, depending on whether market transactions associated indirectly with the respective ES are available or not. The revealed-preference approach estimates the value of ES by analyzing how people act (i.e., by revealing the value they implicitly attribute to a service through their observable choices in the surrogate market), so that the price information from parallel market transactions associated indirectly with the ES can be valued (Pascual et al. 2015, Jónsson & Davíðsdóttir, 2016, Richter et al. 2021).

When hypothetical markets are created to elicit values of the ES, and both direct and indirect price information on ES is absent, we have stated-preference approaches, which simulate a market and demand for ES by means of surveys on hypothetical (policy-induced) changes in the provision of ES. The main types of this approach are Contingent valuation (CV), Choice modelling (Willingness to pay - WTP and Willingness to accept - WTA) and Group valuation (Hanley and Perrings 2019, Richter et al. 2021) (Figure 1). Non-market and market price-based approaches also can be represented together, as Total Economic Value (TEV), calculated from the sum of the economic values of the assets (direct use) and the values estimated (indirect use).

Current research on economic valuation of ES provided by soil biodiversity is still incipient and not comprehensive (Adhikari & Hartemink 2016, Motiejūnaitė et al. 2019, O'Riordan et al. 2021, Rodrigues et al. 2021). Hence, the research groups involved in these activities are still pioneers. In this context, we conducted a bibliometric analysis on the economic valuation of ES provided by soil biodiversity to identify the trends and recent advances in this field worldwide.

## 2. Material and Methods

An online literature search was performed to obtain information available on the economic valuation of ES provided by soil biodiversity. First, we defined a temporal interval from 2014 to 2023, covering 10 years of scientific literature. The economic valuation of ES is a relatively recent area of study, and we considered that period to be sufficient for the bibliometric analysis. The search was conducted in February 2024. Next, we selected search criteria and used them as queries in the Web of Science (WoS) main collection, the online database with the world's largest comprehensive academic resource library. The types of documents searched were articles, book chapters, and reviews, representing, from our perspective, the most important categories of peer-reviewed published research material.

Document retrieval included the title, abstract, and keywords, called topics. In order to eliminate the interference of unrelated literature and ensure the precision and recall rate of research papers on the topic searched, the study performed four search strings and each of them contained two groups (Table 1). Strategies were used to expand the results for the term "soil biodiversity", with use of quotation marks to retain the joint meaning of the words, asterisks to ensure the conjugation of the word and the inclusion of plural words, as well as the operator AND to inform that all keywords used were in the publications so that they appeared in the results. Also, the operator OR was used to indicate the presence of at least one of the terms and the operator NEAR/10 was used in the second search to find records where the terms soil and biodiversity, were within ten words of each other. The documents were searched without language restriction. Duplicates in the results of the four searches were eliminated using the merge feature within WoS. The resulting records were exported in BibTeX format, providing crucial bibliometric information, such as authors name and affiliations, publication title and year, journal name, abstract, etc. The abstracts of the final list were manually checked to confirm search requirements and verify the economic valuation estimates. The final list is reported in Dataset S1 in the online Supplementary Materials.

All bibliographic analyses and evaluation of the data collected in WoS were performed using the bibliometrix R-package. Graphic layouts were plotted using the Bibliometrix user-friendly interface Biblioshiny v.4.0 (Aria & Cuccurullo 2017) or MS Excel. Based on these software packages, a descriptive analysis of the current research obtained from bibliometric indicators was

**Table 1.** Search criteria used in collection of literature on economic valuation of soil biodiversity in the Web of Science online database for the period 2014-2023, using two groups of keywords.

| Search string | Group 1 | Group 2 |
|---|---|---|
| 1 | "ecosystem service* of soil*" OR "soil ecosystem service*" OR "soil service*" OR "ecosystem service* approach" AND | "valuation of ecosystem service*" OR "ecosystem service* valu*" OR "economic *valu*" OR "monetary valu*" OR "soil valu*" OR "value of soil*" OR "market price*" OR "market-based" OR "insurance value" OR "intrinsic value" OR "opportunity cost*" OR "cost* of restoration" OR "cost* of erosion" OR "contingent valuation" OR "choice experiment*" OR "willingness to pay" OR "willingness to accept" |
| 2 | (soil NEAR/10 biodiversity OR earthworm* OR "soil organisms") AND "ecosystem service*" AND | |
| 3 | "soil carbon" AND "ecosystem service*" AND | |
| 4 | ("soil health" OR "soil quality" OR "soil-based" OR "multifunctional agriculture") AND "ecosystem service*" AND | |

performed using the number of documents related to the topics by year, most relevant sources, annual growth rate of the documents (%), authors, authors of single-authored documents, international co-authorship (%), co-authors per document, author's high-frequency keywords, references, document average age (years) and number of citations per document.

Taking into account that publications in different countries can reflect research efforts and trends, the distribution of the authors of the publications was analyzed by country. Co-authors were also counted, affecting the number of authors per nation. For example, a paper with three authors from the same country was counted three times.

Based on Jónsson & Davíðsdóttir (2016), we reported estimates of the economic values for ES associated with soil biodiversity. For that, we compiled the data (obtained from reading publications) of the review period 2014-2023. The data were classified by continent, country, land use, ES considered and valuation method.

# 3. General publication trends and results on SES valuation

## 3.1 Overall trends

A total of 1,068 authors published 238 documents on economic valuation of soil biodiversity, in 126 sources for the decade of 2014 to 2023 (Table 2). The values of the most frequently used keywords (DE) and keywords plus (ID) were similar. Most documents were recent (less than 5 years), and only 10 (4%) documents were single-authored. The average number of co-authors

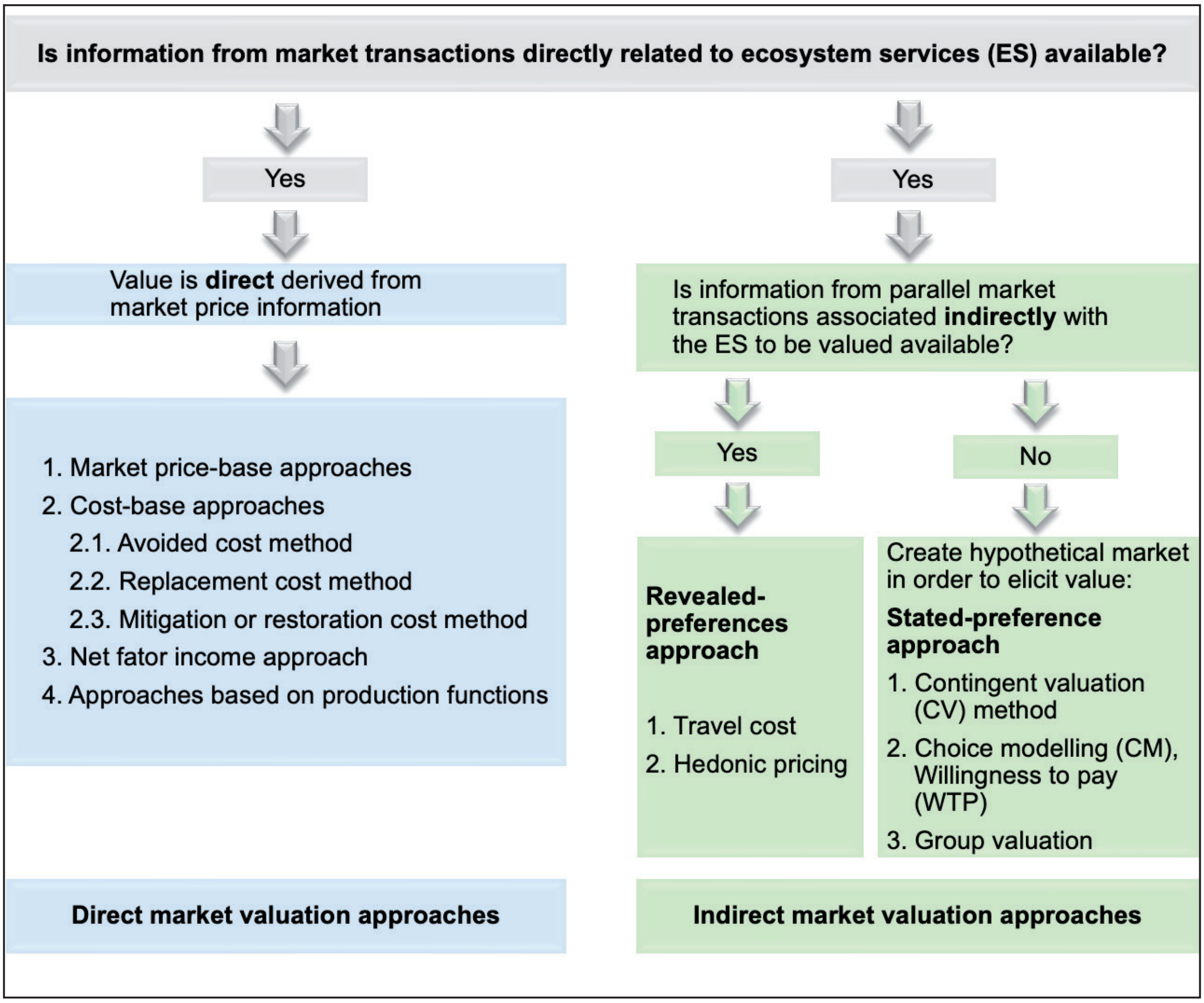


**Figure 1.** Categorization of the available techniques to valuate ES based on market information availability (Source: Richter et al. 2021).

per document was five, and 34% of the documents had international co-authorships. Documents were cited on average 23 times, and all the documents together totaled over 14 thousand references.

The number of publications in the most productive sources are shown in Figure 2. The Ecosystem Services Journal was responsible for 9% of all publications in the period, followed by Science of the Total Environment, with 5.6%. There were 202 peer-reviewed articles, 23 reviews, 11 conference papers and 2 book chapters. The trend in scientific production from 2014 to 2023 (Figure 3), revealed increases and decreases in the yearly number of publications, with twice as many during the pandemic period (2020-22) than in the initial period (2014-15). However, the number of documents overall increased linearly ($r^2 = 0.36$). The annual growth rate, which reveals the increase in the number of papers, was 5.7% (Table 1).

The total number of publications on SES is still relatively small (238) and represents only 4% of the total on economic valuation of ES in general (5,836 publications), obtained using the string "ecosystem service*" and the terms of Group 2 over the same period. After 2014 the use of the ES concept became increasingly recognized by scholars and prominent in the agricultural sciences, while the economic perspective of ES brought environmental issues into the economic debate over the last two decades.

**Table 2.** Main results concerning documents and authors of the WoS online searches as analyzed by the Bibliometrix dataframe for the 2014-2023 time-period.

| | DESCRIPTION | RESULTS |
|---|---|---|
| Main information | Timespan | 2014-2023 |
| | Sources (Journals, Books, etc) | 126 |
| | Documents | 238 |
| | Annual Growth Rate (AGR %)[1] | 5.7 |
| | Document average age | 4.9 |
| | Average citations per document | 23 |
| | References | 14,554 |
| Document contents | Author's Keywords (DE)[2] | 880 |
| | Keywords Plus (ID)[3] | 824 |
| Authors | Authors | 1,068 |
| | Authors of single-authored docs | 9 |
| Authors collaboration | Single-authored docs | 10 |
| | Average co-authors per doc | 5 |
| | International co-authorships (%)[4] | 34 |

[1] The annual growth rate was calculated as AGR = ∑ (Current year - Previous year/ Previous year*100)/Number of years. (Verma and Shukla 2019).
[2] Author's Keywords (DE): keywords defined by the authors.
[3] Keywords Plus (ID): designated by the WoS database.
[4] International co-authorships (%): documents with two or more authors from different countries.

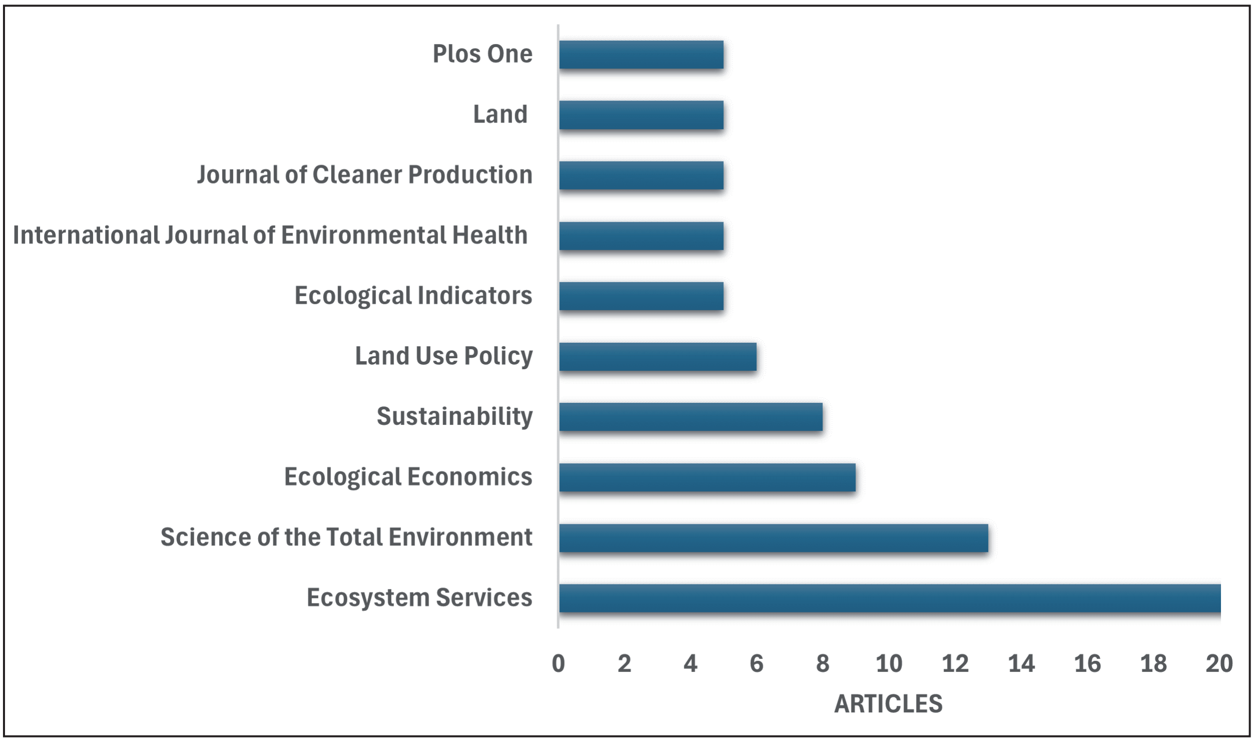


**Figure 2.** Main sources by number of publications (with at least 5) on economic valuation of soil ecosystem services from 2014 to 2023.

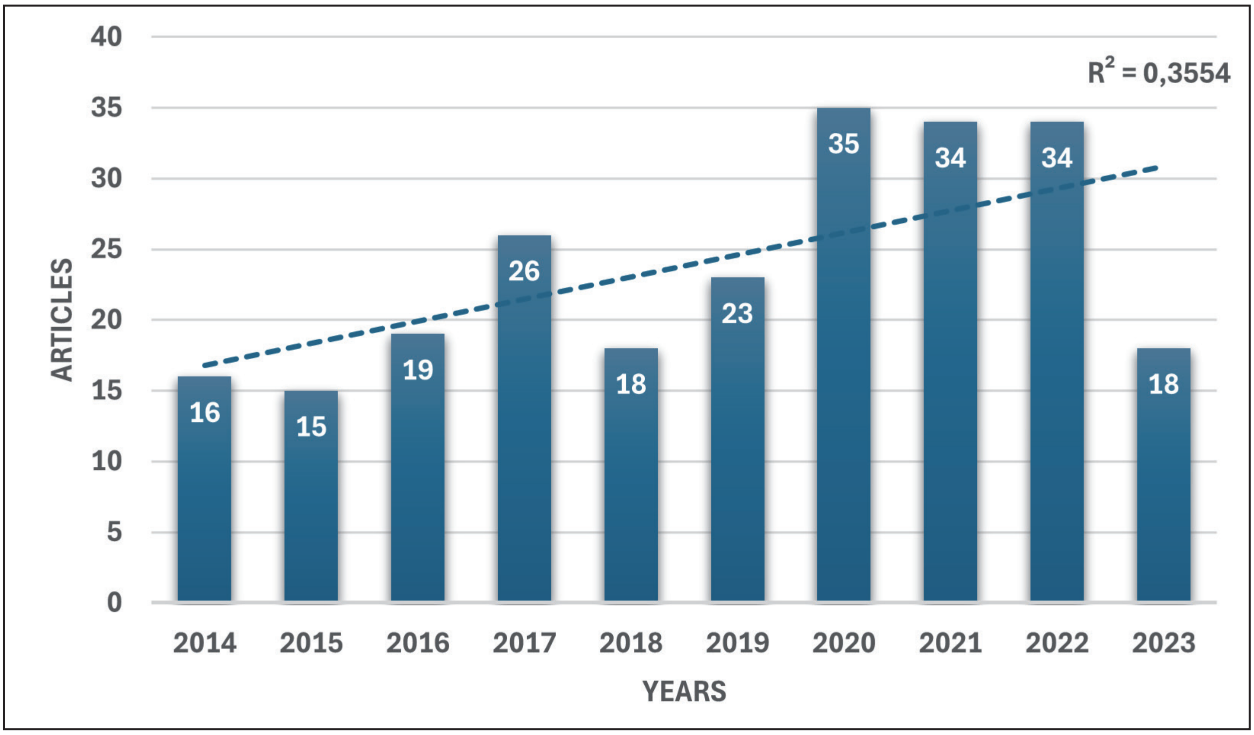


**Figure 3.** Annual scientific production in the field of economic valuation of ecosystem services provided by soil biodiversity for the period 2014-2023.

**Table 3.** A non-exhaustive list of case studies worldwide (by continent and country), estimating economic valuation for ES associated with soil biodiversity, reported in publications in the period of 2014-2023.

| Continent and Reference | Region/ Country | Land use(s) | Ecosystem services considered or indicators associated with soil ecosystem service delivery | Valuation method(s) | Economic values* |
|---|---|---|---|---|---|
| **Asia** | | | | | |
| Abulizi et al. (2017) | Charchan County, China | Grasslands, farmlands, water bodies, and forest lands | Carbon sequestration, climate regulation, water supply, soil formation and regulation, waste treatment, biodiversity protection, food production, raw materials, aesthetic value | Mapping and total economic value | US$17,425 $ha^{-1}$ $yr^{-1}$ |
| Fan et al. (2019) | Min River watershed, Sichuan Province, China | Woodland, Grassland, Cropland, Water body | Carbon sequestration, climate regulation, water supply, soil formation and regulation, waste treatment, biodiversity protection, food production, raw materials, aesthetic value | Mapping and total economic value | US$28,608 $ha^{-1}$ |
| Akhtar et al. (2020) | Lahore, Pakistan | Vegetation, Built-up land, Water body, Unused land | Carbon sequestration, climate regulation, water supply, soil formation and regulation, waste treatment, biodiversity protection, food production, raw materials, aesthetic value | Mapping and total economic value | US$285,497 $ha^{-1}$ $yr^{-1}$ |
| Dimal and Jetten (2020) | Island of Luzon, Philippines | Crops such rice, vegetables, root crops, mango, corn, and banana | Carbon sequestration, water storage, erosion control | Willingness to pay | US$3-7 $person^{-1}$ $year^{-1}$ |
| **Europe** | | | | | |
| Fan et al. (2016) | Taastrup, Denmark | Organic cereal crop production systems | Crop, straw and fodder yield, carbon sequestration, nitrogen mineralized, symbiotically fixed nitrogen, soil water storage, aphid predation rate, earthworm population | Market prices, replacement cost, provision cost, defensive expenditure | US$561-6,743 $ha^{-1}$ $yr^{-1}$ |
| Plaas et al. (2019) | Lower Saxony, Germany | Annual crops | Pollination, disease suppression and pest control, nutrient regulation, water regulation and erosion control | Standard gross margin | US$584-720 $ha^{-1*}$ |
| Eusse-Villa et al. (2019) | Veneto, Italy | Permanent crops, pastures and heterogeneous agricultural areas | Carbon sequestration, earthworm density, rainfall water infiltration, nitrogen in groundwater | Willingness to pay | US$29 $person^{-1}$ $yr^{-1*}$ |
| Dazzi et al. (2019) | Sicily, Italy | Annual crops | Food production, water regulation, biodiversity protection, climate regulation | Cost-benefit analysis | US$50,470 $ha^{-1}$* |

**Table 3** continud.

| Continent and Reference | Region/ Country | Land use(s) | Ecosystem services considered or indicators associated with soil ecosystem service delivery | Valuation method(s) | Economic values* |
|---|---|---|---|---|---|
| Bernués et al. (2015) | Fjords and mountains, Norway | Natural grasslands, forest, scarce agricultural and livestock farms | Landscape, biodiversity, soil fertility, quality products linked to territory | Willingness to pay | US$875 person$^{-1}$ yr$^{-1*}$ |
| De Leijster et al. (2020) | Andalusia, Spain | Annual crops (conventional tillage, no-tillage, green manure and compost) | Erosion control and carbon sequestration | Opportunity costs | US$252-5,305 ha$^{-1*}$ |
| Bernués et al. (2019) | Aragon, Spain | Shrub rangelands, forest and crops | Landscape biodiversity, soil fertility, quality products linked to territory | Willingness to pay | US$525 person$^{-1}$ yr$^{-1*}$ |
| Alcon et al. (2020) | Murcia, Spain | Permanent woody crops | Landscape biodiversity (including increment in soil microbial richness), erosion, carbon balance, cultural heritage | Willingness to pay | US$927-1,442 person$^{-1}$ yr$^{-1*}$ |
| Huber et al. (2022) | Solothurn canton, Switzerland | Grasslands | Forage provision, carbon sequestration and habitat maintenance | Willingness to pay | US$150-720 ha$^{-1}$ |
| **North America** | | | | | |
| Alam et al. (2014) | Quebec, Canada | Agroforestry systems | Nutrient mineralization, water quality, soil quality, pollination, biological control, air quality regulation, windbreak, timber provisioning, agriculture provisioning, climate regulation | Total economic value | US$54,782 ha$^{-1}$ yr$^{-1}$ |
| An et al. (2022) | Alberta, Canada | Agroforestry systems | Carbon stocks in the vegetation | C value of CO$^2$-equivalent | US$25,000-28,421 ha$^{-1}$ |
| Mikhailova et al. (2021) | South Carolina, USA | Woody wetlands, shrubs, forests, herbaceous, pastures, cultivated crops | Total soil carbon | Mapping and social cost of carbon | US$30,345 ha$^{-1}$ |

**Table 3** continud.

| Continent and Reference | Region/ Country | Land use(s) | Ecosystem services considered or indicators associated with soil ecosystem service delivery | Valuation method(s) | Economic values* |
|---|---|---|---|---|---|
| Campbell (2018) | Maryland, USA | Forest and freshwater wetlands | Carbon sequestration, stormwater runoff mitigation, groundwater recharge, nutrient uptake, erosion prevention, wildlife habitat | Market ecological price | US$5,767-9,693 $ha^{-1}$ |
| **Latin America** | | | | | |
| Rodriguez et al. (2019) | Pará, Brazil | Mangrove | Marine and forest products, capture of atmospheric $CO_2$ and storage of $CO_2$ in the soil | Total economic value, carbon credits | US$24,837 $ha^{-1}$ $yr^{1}$ |
| Parron et al. (2022) | Paraná, Brazil | Natural forests, annual and perennial crops and rangelands | Visual amenity, soil conservation, carbon storage, biodiversity | Willingness to pay | US$19-96 $person^{-1}$ $yr^{1*}$ |
| Grima et al. (2020) | Andes region, Colombia | Mountainous forests | Flood mitigation, stormwater runoff mitigation | Opportunity costs | US$470 $ha^{-1}$ |
| **Oceania** | | | | | |
| Dominati et al. (2014a) | Waikato region, New Zealand | Permanent pasture | Food quantity/quality, support for human infrastructure and for animals, flood mitigation, filtering of N, P and contaminants, recycling of wastes, carbon flows, $N_2O$ regulation, $CH_4$ oxidation, regulation of pest and disease populations | Market prices, replacement cost, provision cost, defensive expenditure | US$9,834 $ha^{-1}$ $yr^{1*}$ |
| Dominati et al. (2014b) | Hawke's Bay region, New Zealand | Permanent pasture | Food quantity/quality, support for human infrastructure and for animals, flood mitigation, filtering of N, P and contaminants, detoxification and recycling of wastes, net carbon accumulation (soil), $N_2O$ regulation, $CH_4$ oxidation, regulation of pest and disease populations | Market prices, replacement cost, provision cost, defensive expenditure | US$2,230 $ha^{-1}$ $yr^{1*}$ |

* Economic values in other currencies were transformed into US$, using exchange rates for the month of March, 2024: €1 = US$1.03, NZ$1 = US$0.60. Decimals were rounded up or down to full US$ values.

## 3.2 Publications by country

Authors and co-authors (n = 1,068) of the publications were from 53 countries and the 20 countries with the highest number of publications are depicted in Figure 4. Chinese authors were the most frequent, and China and United States together accounted for 39.3% of all publications, while Germany, Spain, and the UK followed with 6.6 to 4.9% each. Data on author affiliations from the journals tracked by the Nature Index also show that China has overtaken the United States as the number one ranked country or territory in terms of papers published in high-quality natural science journals (Baker 2023). India and Brazil were the only developing countries in the top 20 and accounted together for 6.7% of all publications. This contribution is small considering their importance as megadiverse countries (Carrasco et al. 2014). The limited number of studies in developing countries especially in the African continent is also concerning, considering current anthropogenic pressures on natural and agricultural systems. Countries with different levels of development face different soil biodiversity issues and the focus on economic valuation of ES also changes. Greater efforts are needed to increase knowledge and economic valuation on soil biodiversity throughout the world, especially in natural habitats that play key roles in climate mitigation and in improving landscape ES delivery.

## 3.3 Estimates of the economic values of soil biodiversity

Among the 238 publications, we found 28 case-studies on ES valuation around the world including soil biodiversity (Table 3). Not all of the publications included economic valuation estimates, since many of them were reviews, or only biophysical assessments including ES inventories and/or mapping. For that reason, we listed only case-studies that clearly showed economic values by land use types and ES considered.

Economic valuation is an explicit, intentional process in which agreed upon methods are applied to show the diverse values that people consider for ES. The type and quality of the information obtained from valuation depend on how, why and by whom valuation processes are designed and implemented (IPBES 2022).

The compilation of estimates of the economic values for ES associated with soil biodiversity showed that the studies used different methodologies for the same indicators, the methods applied to the same issues were variable, and a mix of different methods were used in some studies with multidisciplinary approaches. The possible reasons behind the author's choice of the different methodologies for the same indicators may be due to availability of data and/or the biophysical models, the economic objectives of the study, the academic training of the researchers, as well as the social aspects of the populations involved. In the following paragraphs, we discuss these different methodologies and the results of these valuations.

In Europe, willingness to pay (WTP) was the most frequently used method to estimative ES values (Table 3). The WTP method explores the idea that, since soil biodiversity protection is correlated with environmental practices, consumers may be willing to pay a premium price for products including biodiversity specifications. For instance, the introduction of a biodiversity protection certification system could meet consumers' expectations (Rusch et al. 2022). However, several papers did not have adequate biophysical grounding, and values for WTP varied greatly between countries. For instance, WTP ranged from a minimum of US\$29 person$^{-1}$ in the Veneto region of Italy (Eusse-Villa et al. 2019) up to US\$1,442 person$^{-1}$ in Murcia, Spain (Alcon et al. 2020), although both regions have a relatively similar human development index (HDI).

Considering that incorporating traditional knowledge, skills, and know-how in agricultural development are important prerequisites for rural development (Robinson-Pant 2018), the WTP method can also be used in an inverse strategy, i.e., the willingness to accept (WTA). Hence, some case studies addressed local farmers' preferences and constraints towards WTA compensation for the conservation of soil and water as well as the conservation of soil biodiversity (Vanermen et al. 2021, Schulze et al. 2023). This means that the criteria for providing an economic evaluation take on different characters and gradations depending on the economic context, but also on the degree of awareness of the consumers regarding soil biodiversity and its related effects on human well-being. It should be noted that the WTP method is particularly relevant in the evaluation of cultural ES in which the aesthetic and existence values have are influenced by the sensitivity of the civil society, the socio-economic conditions, and the agricultural system in question.

In Asia, most studies used mapping of ES associated with calculations of total economic value (TEV). For instance, Abulizi et al. (2017), Fan et al. (2019) and Akhtar et al. (2020) used ES values per unit area for each land-use category based on the nearest equivalent ecosystem suggested by Costanza et al. (1997), who classified the global biosphere into 16 ecosystems and 17 service function types and estimated the ES value of each type. In this method, once the parameters are set, the equivalent weighting factor

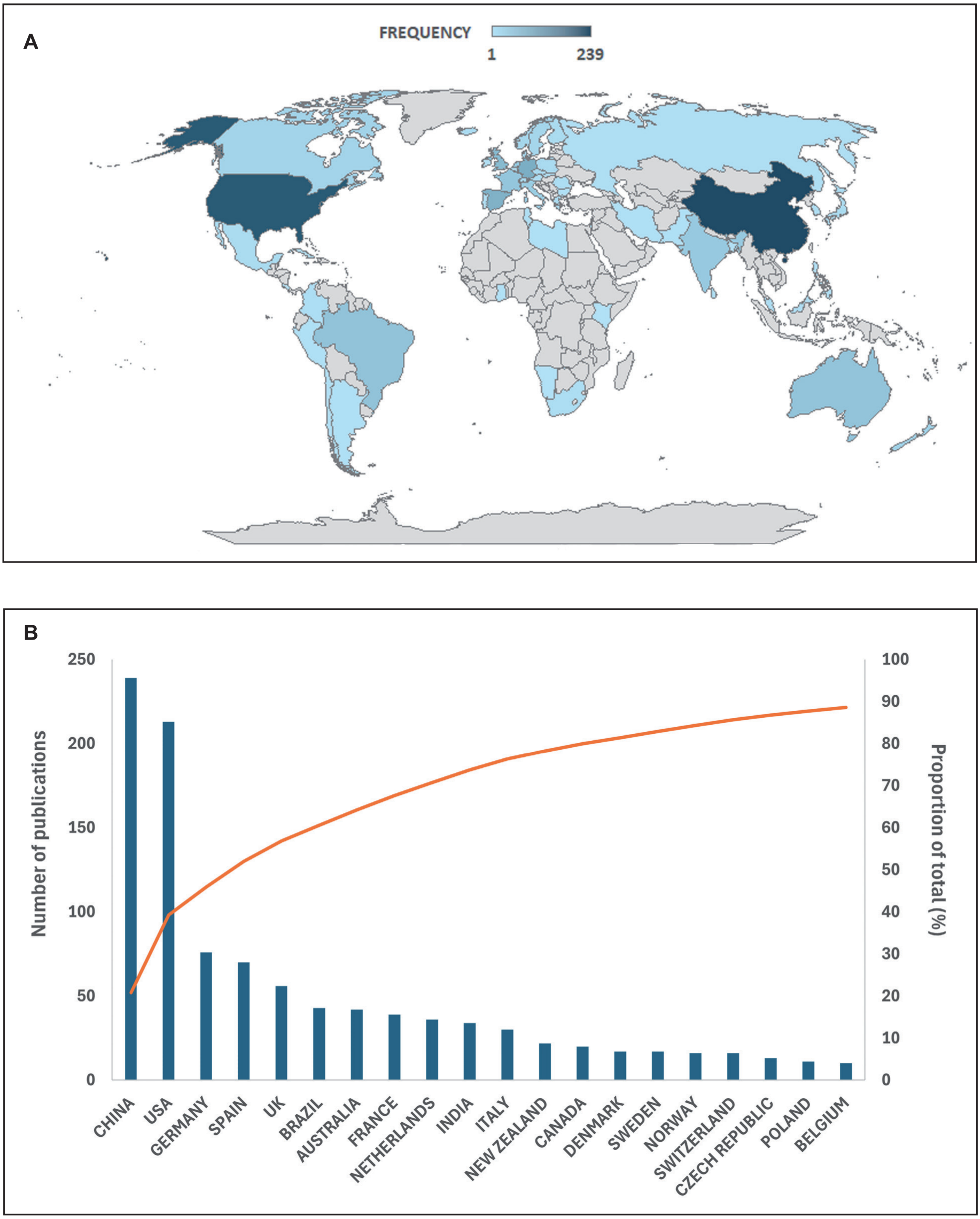


**Figure 4.** (**A**) Most productive countries by number of publications on economic valuation of soil ecosystem services from 2014 to 2023. Number of articles is based on the country of origin of authors according to WoS. (**B**) The top-20 countries with the most publications on economic valuation of soil ecosystem services from 2014 to 2023. The line represents the proportion of total studies attributed to each country.

for ES per hectare for terrestrial ecosystems is extracted and used to correct the ES values per unit area for each ecosystem (Fan et al. 2019). To users of this method, a limited amount of field sampling combined with satellite data can lead to reasonably accurate large-scale analyses at a relatively low cost. However, to conduct these analyses which are useful for formulating land use policy, one must obtain coefficients that accurately reflect local conditions.

In North America, Alam et al. (2014) also used TEV to estimate the value of SES. To estimate soil quality, they calculated the amount of soil formed, based on earthworms and other soil invertebrate data, which was then multiplied by the market price of soils. Mikhailova et al. (2021) also used mapping as a framework to provide monetary values of total soil carbon for soil depths up to 200 cm across South Carolina in various land uses. They calculated the monetary values based on the social cost of carbon (SC-$CO_2$), a comprehensive estimate of climate change damages quoted at \$46 Mg $CO_2^{-1}$ (EPA 2016). The limitation of SC-$CO_2$ is that it can underestimate the true damages and cost of $CO_2$ emissions due to the exclusion of various important climate change impacts recognized in the literature.

In Latin America, only three studies were found, all of them using different methods to estimate the value of SES: TEV and carbon credits in Amazonia (Rodriguez et al. 2014), WTP in Paraná (Parron et al. 2022) and opportunity costs in the Colombian Andes (Grima et al. 2020).

In Oceania, neoclassical economic valuation methodologies, including market prices, productivity change, defensive expenditures (cost of supplying animals with trace elements to prevent deficiencies), replacement costs and provision costs were chosen by Dominati (2014a, 2014b) to value SES. Those techniques seem to be relevant at the local scale, and databases for them are commonly available. The information on the market value of human-made infrastructures/management practices such as fertilizer cost, construction costs, maintenance costs, and the cost of using insecticides are also available. However, in the use of these neoclassical methodologies it is important to highlight that the market price of the infrastructure might not reflect the high value of the service, and the main challenge is when no human infrastructure can replace the natural capital.

In the bibliometric search, several studies focused on the potential use of insurance as a climate change adaptation mechanism (Pascual et al. 2015, Sidibé et al. 2018, Soto-Montes-de-Oca et al. 2021). The capacity of biodiversity to enhance the flow of ES and their stability has been conceptualized as the natural insurance value of biodiversity (Sidibé et al. 2018), whereby soil biodiversity confers to ecosystem users an insurance against income variations. Underlying this concept is the notion that ecosystems with higher biodiversity levels tend to use biotic and abiotic resources more efficiently and are more productive and stable (Turnbull et al. 2013). Hence, measuring and validating the economic benefits and costs of multiple soil conservation and soil health practices is a method of economic valuation of these ES.

In rainfed agriculture under rainfall uncertainty, for example, soil biodiversity through its water storage function acts as natural insurance against drought, and is therefore considered a key asset that determines expected yields (Sidibé et al. 2018). Furthermore, soil biodiversity can be managed, i.e., through investment in natural capital, since the soil serves as a buffer to store at least a certain fraction of water received after a period of rainfall (Pascual et al. 2015). Hence, the crop insurance risk assessment associated with reducing yield risk for producers is relevant for rural and urban financial management (Soto-Montes-de-Oca et al. 2021).

## 4. Outlook on the economic values of soil biodiversity

### 4.1 Increasing assessments and the use of soil biodiversity to indicate and value SES delivery

Both soil biodiversity and habitat maintenance are key ecological functions, and their restoration is costly. The concepts of soil quality and soil health have been broadened in the last decade to include impacts on ES delivery, which is the basis for frameworks like the soil management assessment (Andrews et al. 2004, Cherubin et al 2017). Soil quality is the ability of soil to perform its functions within an ecosystem, such as supporting plant and animal life, maintaining water quality, and supporting human health (Karlen et al. 2003), while soil health is the capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans, connecting agricultural and soil science to policy, stakeholder needs and sustainable supply-chain management (Lehmann et al. 2020). These frameworks integrate information from soil indicators and involve a dynamic view of soil quality in the management decision process, by adopting soil quality indices (Lima et al. 2013).

To understand and use soil quality indices as a tool for sustainability, physical, chemical, and biological properties should be employed as indicators, although their responses to soil use and management are often reflected in different time frames. Attributes with rapid responses to natural or anthropogenic actions are normally considered better indicators of soil health for management purposes (Lima et al. 2013). Both soil invertebrate and microbial communities have been proposed and widely used as bioindicators of soil quality and SES due to their relatively rapid response rates to changes (Pulleman et al. 2012, Bünemann et al. 2018, Menta et al. 2018, Velasquez & Lavelle, 2019, Mendes et al. 2024). Furthermore, they are part of the current essential variables proposed by SoilBON (Guerra et al. 2021, Potapov et al. 2022) and the new EU soil monitoring law (EC, 2023). These indicators are powerful tools in the evaluation and monitoring of soil health changes and in the provision of SES, associated with management practices and restoration programs.

The use of the direct market valuation approaches (Figure 1) may be suitable for estimating the value of soil biodiversity-based ES using the biophysical value of soil quality obtained from surveys and inventories of soil biotic communities and of various other soil health attributes. For instance, applying the replacement cost method (Dominati et al. 2014a, 2014b), avoided cost method (Lopez-Hoffman et al. 2014) or the mitigation or restoration cost method (Richter et al. 2021) the provision of soil biodiversity-based ES can be estimated, resulting in the valuation of SES from the implementation and maintenance costs in the area affected by the loss of these ES. The cost of restoring soil quality in the sense of eliminating soil compaction to improve porosity and nutrient retention can be calculated by the associated cost of using techniques like no-tillage, crop rotation or mixed cropping (Lal et al. 2013, Kik et al. 2021), and increasing soil organic matter content with compost application (Pereira et al, 2018, Bellè et al. 2022), and vegetation restoration (Vermat et al. 2016). For instance, Sandhu et al. (2010) assessed soil formation by considering the market value of topsoil produced by earthworms, while the mineralization of plant nutrients was evaluated by considering the market value of nitrogen that would otherwise need to be added. In short, all the costs involved in the acquisition of inputs, land preparation and labor to restore soils are the values of the ES of a given area.

### 4.2 Promoting public policies to better protect and sustainably use soil biodiversity

Despite its potential impacts on SES delivery, soil biodiversity is still ineffectively protected under current conservation public policies. Although there are several ongoing global conventions targeting biodiversity conservation, like the Convention on Biological Diversity (CBD 1993), the Nagoya Protocol (2014), the United Nations Framework Convention on Climate Change (UNFCCC 1994), the Paris Agreement (2015), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES 2012), and the 2030 EU Biodiversity Strategy (2021), nature conservation management has not adequately considered or protected soil organisms and its associated ES, such as life-support for more charismatic taxa like birds, mammals or plants (Zeiss et al. 2022). Neither the preservation of soil functions nor the management of soil threats are comprehensively regulated by current legislation, and soil protection seems to be merely the by-product of different provisions which are mainly preventive, qualitative, and non-strictly binding (Stankovics et al. 2018).

Often the measures relating to financial support aimed at farmers are based on the average costs of implementing good practices and they do not always guarantee adequate levels to reward the farmers for providing, privately, an agri-environmental public good such as the adoption and maintenance of correct practices for soil conservation.

Concerning soil conservation, regulating services are the most valuable services because of the changes in land use during the last decades. Therefore, if the market does not recognize this value, the use of public resources can be justified to preserve regulation services. In this sense, further research is needed to determine more precise values of compensation for regulation services and to provide more coherent recommendations to policy makers.

Studies and efforts addressing SES, and the intrinsic value of soil biodiversity could also support the development of more effective conservation policies, including the establishment of new protected areas, and put more emphasis on policy solutions to optimize the conservation of soil biodiversity and soil ecosystem functioning (Zeiss et al. 2022). Using simple and illustrative awareness-raising campaigns related to the importance of soil biodiversity and its relationship with forest management, policymakers could increase the valuation and acceptance of management practices that support soil biodiversity amongst citizens (Vanermen et al. 2021).

Furthermore, another method that enables managing and protecting ecosystems and improving management practices using economic incentives, includes the payment for ecosystem services (PES) (TEEB, 2010). These are incentives offered to natural resource managers (i.e., farmers or landowners) that could be provided directly by central government in favor of managers to secure and improve the provision of ES on behalf of society.

In this manner, public policies should be in-line with agricultural management oriented towards the delivery of multiple ES in response to global challenges.

To overcome issues in soil biodiversity conservation, Zeiss et al. (2022) proposed an eight step-process towards a more soil-targeted perspective: 1) expand existing activities, 2) consider a full ecosystem approach, 3) set baselines as references, 4) monitor threats to soil biodiversity and ecosystem functioning, 5) define species lists for nature conservation, 6) establish a soil indicator system, 7) improve access to information for all stakeholders and 8) identify priority areas for soil ecosystems. While every country has the right to develop their own agricultural models to feed their citizens, national and global public policies should promote the sustainable and efficient use of soil as a natural resource, protect its biodiversity, and prevent overexploitation and degradation of land and natural resources which may compromise the delivery of SES (Koninger et al. 2022). This is particularly the case because the impacts of actions related to soil conservation and use or the lack-of them in one country may affect SES delivery in other countries as well. Take, for instance, the impacts of soil erosion in cross-boundary rivers. In this light, greater efforts are needed to combine economic and environmental performance in the value of soil as natural capital and asset.

## 5. Conclusions

There is an important body of soil ecological knowledge linking ES and processes to soil biodiversity and the value of natural capital. Nevertheless, this value is closely associated with the valuation method(s) used. The adoption of different methods is driven by their cost-effectiveness and efficiency. Additionally, the use of stated preference aligns with the increasing trend in the literature for estimating ES based on public preferences. However, limitations in the economic valuation of ES could emerge when estimating provisioning and regulating services using stated preference. Specifically, these could arise from misspecification problems and the complexity of ecological interactions, which are often beyond human perception, leading to overestimations or underestimations. Conversely, economic valuations using benefit transfer can be computed using unit value transfer and benefit function transfers considering the links between certain ecological conditions and benefits to people. Nevertheless, further methodological adjustments are needed to address the identified gaps and employ the specific economic valuation methods for estimating ES under investigation within specific socio-ecological contexts, thereby ensuring more accurate and comprehensive valuations.

Most of the research on SES in the period of 2014-2023 came from the Northern Hemisphere and agricultural ecosystems (Vidaller-Dutoit 2022; Liu et al. 2022). This is likely due to the economic importance of agricultural production worldwide, though further efforts to estimate SES in natural land use systems and in tropical countries is warranted, considering the importance of soil biodiversity for SES delivery in native vegetation and the level of biodiversity present in the tropics.

Additionally, although a range of studies estimated the value (individual or combined) of soil biodiversity-based ES provided in agricultural and natural landscapes, most of them focused on only one ES at a time, ignoring multiple services and not providing an overall value of the assets that produced them. A few studies focused on the environmental assets, directly noting the multiple ES they produced, rather than attempting to value the individual services and adding these up to provide TEV. Hence, the valuation of multiple ES associated with soil biodiversity in different political, economic, social, and geographic conditions would be differential and innovative, especially in global biodiversity hotspots.

Unfortunately, despite its potential contributions to SES and human wellbeing, soil biodiversity continues to be little considered by policy makers (Montanarella & Panagos 2021, Zeiss et al. 2022), and even IPBES has made little effort to support soil biodiversity and its role in its reports (IPBES 2019, Guerra et al. 2021). Further estimates of the value of soil-based ES highlighting the role of soil biota in providing these services is sorely needed, particularly considering that these ES are under increasing pressure and considerable deterioration because of human activities worldwide (IPBES 2018, FAO 2015, 2020).

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