soil systems

Review

The Research Gap between Soil Biodiversity and Soil-Related Cultural Ecosystem Services

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Abstract: Soil and soil biodiversity are often a neglected component in assessments of ecosystems and their services. One of the reasons is the increasing complexity of scientific investigation of biotic and abiotic interactions and mechanisms from soil biodiversity and soil components via ecosystem structures, processes, and functions that finally provide specific ecosystem services for human well-being. In particular, soil-related cultural ecosystem services are missing in the publications on interactions. We tested this hypothesis by using a systematic literature analysis and taking Germany as a case study. The findings revealed a huge research gap. Among 2104 peer-reviewed scientific papers, covering all types of soil-related ecosystem services, only 28 publications were related to soil-related cultural ecosystem services in Germany. Furthermore, the terminological awareness of "ecosystem services" is still limited. The following five main categories for cultural soil-related ecosystem services were identified: (1) place of sense, (2) spiritual value, (3) recreation, (4) forecasts and measures, and (5) soil as an archive. Soil as an archive was further divided into storage, archaeological site, and reconstruction of the past. By highlighting the importance of cultural soil-related ecosystem services and their interactions with soil biodiversity, this study underlines the urgent need to better consider soil biodiversity and soil processes in ecosystem service assessments. This systemic and interdisciplinary approach increases also the societal and political relevance of soil.

Keywords: soil; ecosystem services; knowledge gap; society; Germany; literature review

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1. Introduction

Soils provide habitats for different plant and animal species, supply raw materials, offer a gene pool, filtrate water, regulate water, and serve as a basis for food production by storing and transforming nutrients for plants, among others [1]. It is common knowledge that soil components and soil organisms are key players in essential ecosystem processes and functions [2–5]. Those processes and functions, in turn, provide ecosystem services (ESs) that are crucial for human well-being (e.g., [6]). The concepts of soil functions and soil quality enhance our understanding of the contribution of soil and soil biodiversity to the provision of ESs [7]. Soil functions describe the functions (co-)facilitated by soils within ecosystems, defining the range of soil-related ESs. Soil quality itself is determined by biological, physical, and chemical properties and processes defining the extent of the supply of soil-related ESs. In this concept, soil properties resulting in high ES provision have a high soil quality [8,9]. It is important to consider that optimal soil properties are not the same for different ESs. E.g., a silt-rich soil with high water storage capacity is excellent for the provision of food, while sand soils with high percolation rates provide larger amounts of groundwater. Hence, soil-related ES supply is strongly influenced by combined biotic and abiotic soil properties, processes, and functions [10]. Soil quality determines, in combination with anthropogenic inputs and agricultural land management measures, crop growth for food, fodder, and biomass provision and, finally, forms the basis for human existence and health [11].

Several studies have summarized soil-related ESs in general, for example, [6,10,12–15]. The probable most prominent examples of soil-related ESs come from agricultural production [13], with agriculture being the dominating form of human land use. Final agricultural ESs are often heavily co-produced by anthropogenic inputs such as fertilizer, irrigation water, pesticides, machinery use, and labor [11]. In general, anthropogenic inputs to agricultural ES co-production can be measured and quantified, as proven for single farms by Bethwell et al. [16]. Because of the comparably large efforts needed for such quantifications, further applications remain limited. There is insufficient knowledge about the evidence-based (directly measured and analyzed) mechanisms and interactions along the complete causal chain from soil biodiversity to other biodiversity and biophysical components via ecosystem functions that finally provide specific ESs [15,17,18]—not to mention that soil biota and below-ground research itself is still not fully explored [19].

Following the concept of the ES cascade [20] that starts from biophysical structures of ecosystems to processes and leads to ES provision and human benefits and values, it is a complex venture to measure every step in the ES cascade consistently, which usually contains feedback loops in the social–ecological system by changes in driving forces, management, and other anthropogenic factors (Figure 1; [21,22]). However, while the ES concept has firmly established itself in scientific research over the years, with ESs increasingly investigated and serving as a conceptual bridge between ecological and social systems, it remains a persistent challenge to count soils and their profound significance in ES assessments directly. In most cases, soils are not comprehensively acknowledged in ES frameworks [23]. This fact coincides with the recognition of soil in multilateral environmental agreements: Even if soil was already addressed as a cross-cutting theme in all three Rio Conventions in 1992, only the text of the United Nations Convention to Combat Desertification (UNCCD) specifically includes soil [24]. Montanarella and Lobos Alva [24] emphasize the effort that was needed to put "soil on the agenda" and Keestra et al. [7] highlight the importance of soils, soil functions, and soil-related ESs to achieve several of the 17 United Nations Sustainable Development Goals (SDGs). Soil erosion, the loss of soil organic carbon, and soil quality are also addressed in the IPBES Global Report, while soil biodiversity is not specifically highlighted [25]. The FAO report on the state of knowledge on soil biodiversity helped to raise awareness of the importance of soil biota for our ecosystems and the provision of ESs [26]. The EU Soil Strategy [27], the Soil Mission [28], and the proposed Soil Monitoring Law [29] show that the relevance of soils and their contribution to ESs and human well-being have been recognized in the policy arena. Nevertheless, the societal and even political valorization of soils and soil biodiversity (SBD) is often neglected in ES assessments [7,26,30].

While provisioning and regulating ESs are most often represented in soil-related studies, cultural ES contributions of soils to human well-being are often hidden or neglected [13]. Cultural ESs relate to the spiritual, aesthetic, educational, and recreational values of nature that support human well-being. They are less tangible than provisioning ESs and, therefore, tend to be more difficult to measure [31]. It becomes even more difficult to investigate the direct causal links between SBD and cultural ESs, e.g., the impact of soil properties on landscape aesthetics. Even though cultural soil-related ESs might be regarded as less important for human survival than provisioning and regulating ESs, today, soil and SBD could gain importance as bequest value and future values. We still do not have sufficient knowledge of SBD in soil processes, and more soil-related ESs could be relevant and discovered in the future [13]. In addition, the missing societal valorization and comparably low political representation of soil-related ESs could also increase the risk of soil degradation, soil sealing, soil pollution, and other soil threats that could finally lead to a reduction in soil-related ESs (Figure 1; [32]) or even reverse the benefits from soil to disservices, e.g., soil-transmitted human diseases [33,34] or landslides. Consequently, we need to synthesize existing knowledge to raise awareness of this risk, and measures developed to increase the protection of soils need to be taken. In particular, the link between soils and SBD and the provision of cultural ESs is not well understood.

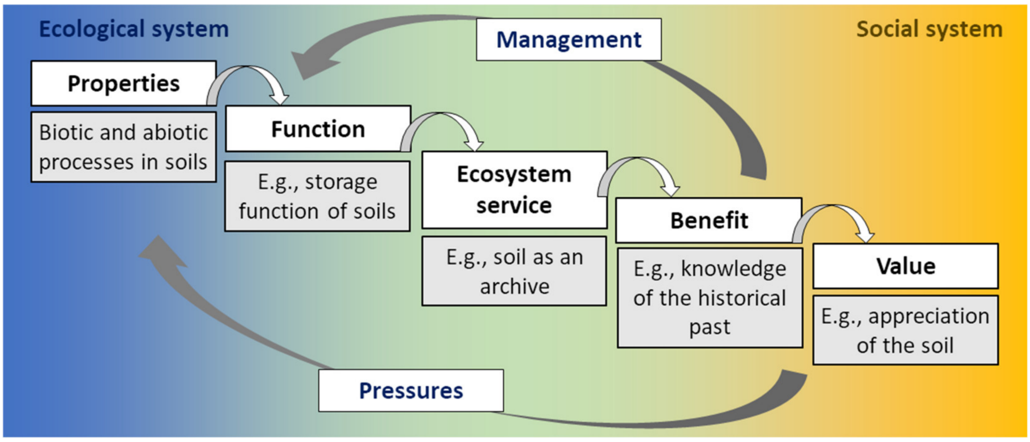


Figure 1. The ecosystem service cascade exemplifying cultural soil-related ecosystem services (modified from [20,21]).

As described, finding the scientific literature on evidence-based cultural soil-related ESs or scientific publications that show direct causal links between SBD and cultural ESs is notably challenging. However, we were interested in exploring this research field to summarize existing knowledge and identify gaps in our understanding. We selected Germany as a case study because it could be expected that Germany, as a high-income country with high investments in research and education, covers sufficient international scientific literature on this yet little-studied relation. Consequently, the main objective of this study was to provide a systematic overview of existing studies on cultural soil-related ESs, taking Germany as an example. Furthermore, it examines how soil biodiversity has been linked in the literature to cultural soil-related ESs and whether these elements interrelate or influence each other. The results systematically revealed the existing research gaps in the peer-reviewed scientific literature on soil, SBD, and the benefits of cultural soil-related ESs for human well-being.

2. Materials and Methods

2.1. The Systematic Literature Review

This study was based on a systematic literature analysis aimed at providing a comprehensive overview of the available peer-reviewed scientific literature on the topic of cultural soil-related ESs and SBD in Germany. In this work, soil is referred to not only when it occurs on the land surface but also when it exists beneath a body of water as layers from different ages, for example, soil samples from the bottom of a maar lake [35]. To delineate soil from other ecosystem compartments, the boundary above the soil exists between soil and living plants and air or, when covered by water bodies, between soil and water, as well as soil parent material that has not yet undergone weathering processes [35]. In this work, areas such as riverbeds extensively covered by rock bodies (e.g., gravel beds) were not considered as soil. "Soil-related ESs" summarizes all ESs whose provisions depend directly on soil properties. Soil biodiversity is defined as "... the variety of life belowground, from genes and species to the communities they form, as well as the ecological complexes to which they contribute and to which they belong, from soil micro-habitats to landscapes" [26].

The selection of topic-related search terms was based on discussions among experts in the frame of the German Biodiversity Assessment [36]. The purpose was to ensure that the search terms also covered ESs from the other ES categories (beyond cultural ESs, e.g., water retention, erosion control) in order to review the also literature where cultural ESs could have been mentioned indirectly. All Federal States of Germany, different biodiversity indices, specific soil species, and species families and synonyms for soil biodiversity and ESs were included as search terms (Appendix A). The analysis served the purpose of evaluating and synthesizing the content, contributing to evidence-based results, identifying potential research gaps, and presenting a systematic approach to minimize bias within the review process. As Booth et al. [37] highlighted, systematic approaches play a crucial role in reducing bias in reviews. Booth et al. [37] emphasized that the best evidence for decision-making often comes from a systematic review of all available evidence. The systematic approach allows for checking the consistency in the results across different studies and assessing variations across different criteria. These criteria, identified through hypotheses, can be evaluated during the analysis, such as examining whether values of specific parameters develop positively or negatively over a temporal frame. The analysis prioritizes reproducibility, ensuring a systematic procedure reflected in the stepwise inclusion or exclusion of literature based on defined characteristics. The criteria and decision pathways are outlined in Section 2.2 and illustrated in Figure 2, guaranteeing a quality standard for the texts used in the analysis [37]. This approach facilitated step-by-step traceability of the analysis and allowed us to understand the results from the initial to the final selection. For a literature search, the Web of Science (WoS) platform was utilized because of its status as the longest existing citation index, guaranteeing high-quality scholarly content [38]. WoS provides an extensive and continually expanding range of data sources, offering the advantage of high coverage in relevant subject areas (e.g., geosciences in the context of soil) [39]. Moreover, the platform's features, such as English-language accessibility, peer-reviewed papers, search operators, and filter options, aligned with our requirements for search term usage (Appendix A). Following the selection of texts for analysis, MAXQDA software (Version 22.8.0) was used for literature analysis. Within the program, codes were developed to answer research questions, and corresponding text passages were marked. The detailed process is explained in Sections 2.2 and 2.3. The coded content, along with descriptive details, was used to address research questions and hypotheses qualitatively.

2.2. Selection of the Appropriate Literature

The sequential progression of literature selection is outlined in the PRISMA diagram (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; [40]) depicted in Figure 2. The visual representation facilitates tracing the decisions and criteria governing the inclusion or exclusion of the literature across successive levels. For clarity, the conditions at each level are notably simplified herein, with detailed explanations provided in subsequent sections. The selection process entailed five distinct levels, each comprising various subcategories, each governed by its own set of criteria. The scientific papers in Level 5 were analyzed in detail in this paper.

2.2.1. Level 1

Level 1 comprises literature identified in WoS using the specified search terms (Appendix A). Complete literature reviews without integrating other methods in their results section were directly excluded. This decision was grounded in the fact that the work itself constitutes a review and should not incorporate pre-processed data that underwent another assessment system. However, publications mentioned in their results sections that used methods other than a review were included. If the authors of a paper collected additional data outside the analysis through further methods, these were considered to be of interest for the present literature review. Although this work focuses on cultural soil-related ESs, a preliminary test search for cultural soil-related ESs yielded very few results (no count given here, as it only provides an initial overview). Therefore, we initially decided to broaden the list of search terms to encompass all ESs to obtain a sufficient number of documents for further analysis. The search conducted in August 2022 resulted in 2104 papers.

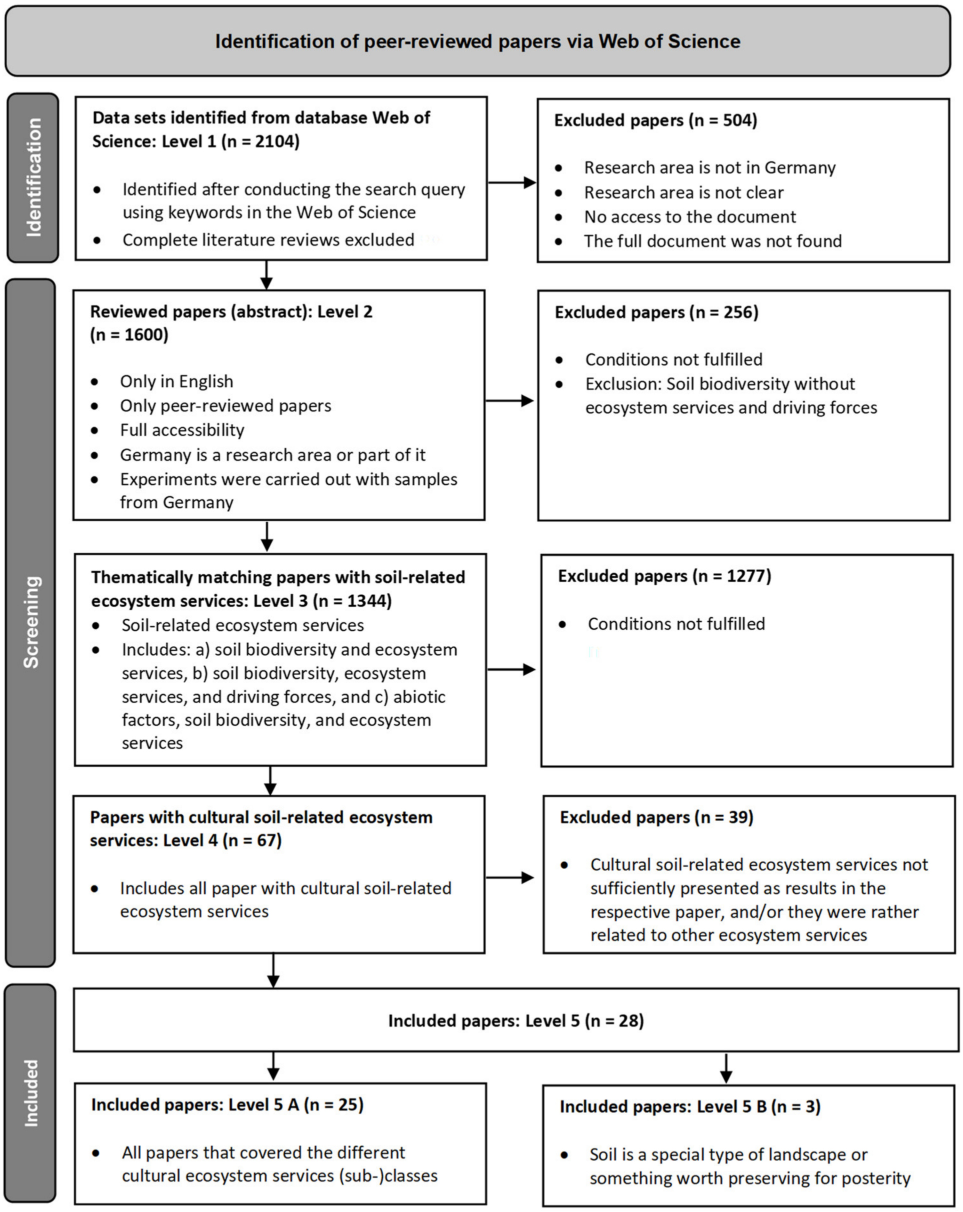


Figure 2. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA; [40]) diagram for literature selection including inclusion and exclusion criteria.

2.2.2. Level 2

In Level 2, various categories were initially established to subdivide the existing search query. It includes all papers that met the content-relevant criteria of Level 2. These papers had to be written in English, peer-reviewed (typically covered by WoS), and accessible via university accounts or downloadable for further text examination, and the research area (or at least a part of the research area) had to be located in Germany. Laboratory experiments conducted abroad with soil samples from Germany were also considered. This requirement stemmed from the focus of this research on cultural soil-related ESs in Germany, making soils in Germany relevant for analysis. To obtain the necessary information, the abstracts of all 2104 documents were screened. If relevant information could not be extracted from the abstract, the paper's full text was examined in more detail. Subsequently, a total of 1600 documents were included in Level 2.

2.2.3. Level 3

All documents sorted from Level 2 to Level 3 had to demonstrate a fundamental and substantive soil connection and soil-related ESs. More specifically, this meant that each document's abstract had to include SBD and/or soil-related ESs. The highlighting of soil-related ESs was based on Version 5.1 of CICES (Common International Classification of Ecosystem Services). CICES covers the three main ES sections, including provisioning, regulating and maintenance, and cultural services, and contains several subgroups (divisions, groups, and classes). We started with a total of 1344 papers in Level 3 that were screened according to the criteria shown in Figure 2.

2.2.4. Level 4

Level 4 included all documents that contained a cultural soil-related ES. Studies in which soil was the single focus of research were excluded from this level. This decision was based on the fact that each document in Level 4 had a soil connection and thus selected soil as the subject of research, but the paper was removed if the topic was not directly related to cultural soil-related ESs. A total of 67 documents were sorted into this group. Considering the full list of CICES for cultural ESs, the service "scientific investigation" was not further included because basically all scientific publications can be undoubtedly assigned to this ES.

2.2.5. Level 5

Within Level 5, only documents that thematically included cultural soil-related ESs were added. This included all papers from Level 4. Level 5 was further divided into two subcategories, Level 5 A and Level 5 B. All documents in Level 5 were screened in full text, i.e., beyond the abstract and selected information.

Level 5 A

In this category, documents were included in which soil was further subdivided into the different cultural ES classes. An exception was made for papers that were designed as long-term studies. Papers in which soil was exclusively used as an archive for long-term sampling were not included. This decision was justified by the fact that, solely through long-term sampling, there was no necessary additional connection to cultural soil-related ESs. If these documents had been included, many papers would have been represented thematically that had no relevance to the research questions as they would have merely depicted the archival function of soils. To avoid distorting the results towards the archival function of soils, these contents were removed. In contrast, papers that, for example, examined specific pollen archives or other sequences stored in the soil were considered. Long-term studies themselves do not represent cultural soil-related ESs, as they merely utilize the soil's function as an archive without establishing a direct connection to cultural ESs. They merely document changes in soil properties over time and do not consider the cultural interactions or meanings that soils can have in various contexts. Therefore, this decision ensured that this study maintained its focus on the cultural aspects of ESs.

Level 5 B

This category only included papers in which soil or SBD harbored or represented something valuable worth protecting for posterity (future or option value), e.g., soil as cultural heritage.

2.3. Literature Analyses with MAXQDA

The systematic literature analysis was conducted using MAXQDA software. MAXQDA is a computer-assisted software designed for analyzing qualitative data [41]. MAXQDA features are especially useful for creating hierarchical code systems, allowing for the splitting of main codes into multiple sub-codes. Additionally, the software offers the possibility to create memos for text passages in the papers as well as for the codes themselves [41].

All 28 documents from Level 5 A and Level 5 B were included in the systematic literature analysis and coded based on the schema provided by Mayring [42] for qualitative content analyses. Papers were coded along main and subcategories, where main categories were occasionally further divided into subcategories. The initial development of categories followed a deductive approach and was later complemented by an inductive approach during the analysis. Initially, codes were formulated based on preselected categories from our literature analysis in the deductive approach. As the analysis progressed, there was a need to revise code definitions, delete entire codes, and add entirely new codes (inductive approach). This iterative process was repeated multiple times. It is important to note that changes to a code definition, for instance, required a reassessment of all previously coded text passages within the code category for further content-related relevance, and they were adjusted accordingly if needed (iterative process). During the evaluation of the results, the presentation of the findings was also divided based on the code development with regard to quantitative and qualitative analysis. It is possible and desirable to code a text passage with several codes from different categories so that co-occurrence can be better recognized in the subsequent analysis. The results of each category were assigned to the paper in a grid structure. The matrices were assigned to the respective codes, as shown in Table 1.

Table 1. Representation of code-to-code relationships as a finding during the literature analysis. The darker the color, the higher the co-occurrence. The numbers indicate the number of papers (28 publications in total).

Code System	Place of Sense	Spiritual Value	Recreation	Forecasts and Measures	Storage	Archaeological Site	Reconstruction of the Past
Place of sense	0	2	0	3	6	5	8
Spiritual value		0	0	0	1	4	4
Recreation			0	0	0	1	1
Forecasts and measures				0	1	0	2
Storage					0	12	22
Archaeological site						0	18
Reconstruction of the past							0

The preselected categories included the following (details are provided in the Appendix A, Table A1):

- Year of publication;
- Spatial dimension;
- Type of landscape;
- Used data and materials;
- Used methods;
- Cultural soil-related ESs;
- Provisioning soil-related ESs;
- Regulating and maintenance soil-related ESs;
- Soil functions;
- Soil biodiversity;
- Connection between SB and soil-related ESs.

Thus, a single ecosystem service can encompass multiple soil-related cultural ESs. For example, a specific area in the soil can possess spiritual value while simultaneously providing recreational benefits and experiencing spirituality. Such multiple coding enabled the identification of specific code relations during analysis, leading to new insights into the distribution of soil-related cultural ESs.

3. Results

The results were divided into a quantitative part (Section 3.1) and a qualitative part (Sections 3.2–3.4), where the analyzed literature was described according to the preselected categories and the range of content that was synthesized and compiled through the literature analysis.

3.1. General Findings

This analysis covered 28 publications from the years 2003 to 2022 (see the list in the Supplementary Materials, file S1). The number of papers indicated a slight overall increase per year, with a relatively constant pattern observed for papers containing SBD, and a noticeable shift towards more frequent publications in recent years, particularly evident in papers without SBD (Supplementary Materials, Table S1). The analysis of the spatial dimension showed that the research areas were described differently in the various publications. In the literature analysis, the local scale (plot level) was the smallest spatial unit and the global (=international) scale was the largest spatial unit. While most papers, both with and without SBD, focused primarily on small-scale dimensions such as local and regional levels, the papers with SBD also extend to supra-regional and international levels, indicating a broader spatial scope of SBD-related studies. The distribution of the spatial dimension, divided into papers with and without SBD, is shown in Figure 3.

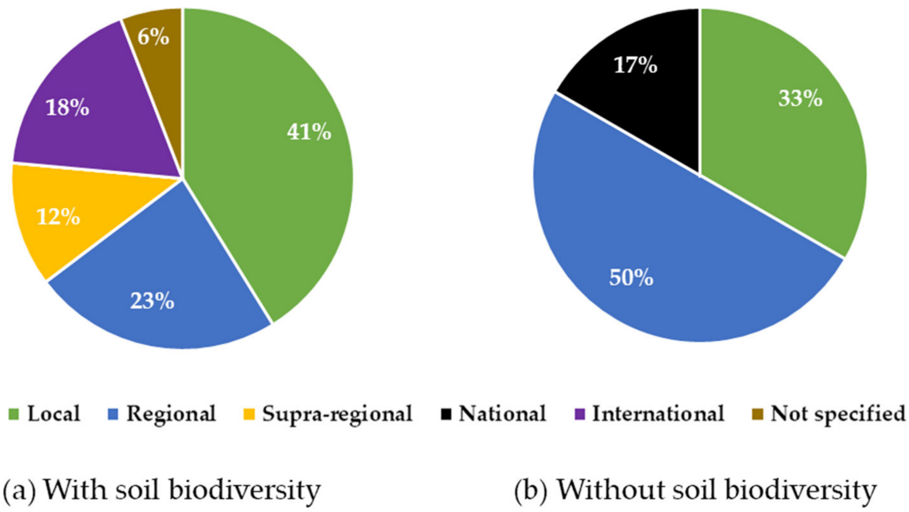


Figure 3. (**a**) Distribution of the spatial dimension for cultural ecosystem services including soil biodiversity in the analyzed publications. The national level was not represented in the data. (**b**) Distribution of the spatial dimension for cultural ecosystem services without soil biodiversity in the analyzed publications. The supra-regional and international levels were not represented in the data.

The classification of landscape types, for which the soil-related cultural ESs were investigated, distinguished between primary and secondary types, considering the proportional spatial representation of each landscape type. Since there was no maximum limit placed on the mentions of different landscape types, a paper could exhibit multiple primary and secondary landscape types. The primary landscape type represents the dominant landscape in the study area. However, since landscapes can be highly heterogeneous, and the aim was to capture all landscape types considered in the literature, the secondary landscape type was also included. This represents the landscape forms present in the study area that were less pronounced or covered a smaller portion of the area. However, it is crucial to note that multiple mentions, especially of the secondary landscape type, occurred because the primary landscape type often presented a dominant landscape. Hence, there is a different total count of mentions for primary and secondary types (Figures 4 and 5).

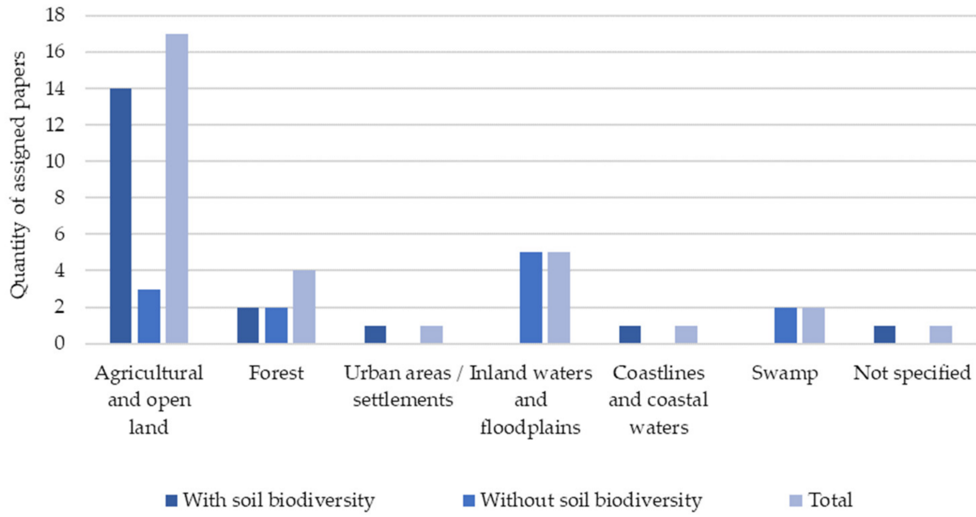


Figure 4. Primary type of landscape in the investigated studies. Multiple counting was possible. See Appendix A, Table A1 for landscape-type explanations.

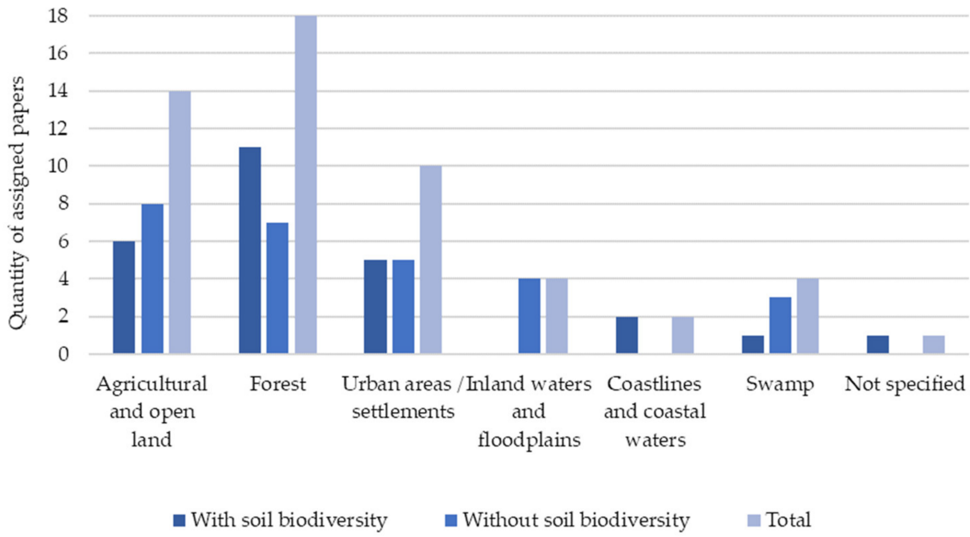
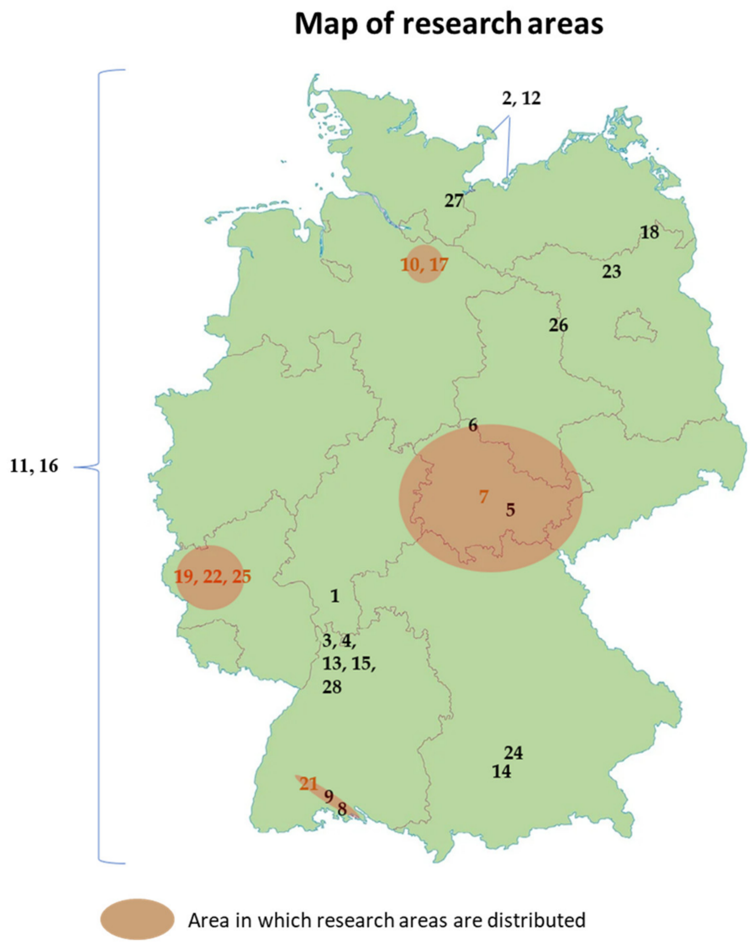


Figure 5. Secondary type of landscape in the investigated studies. Multiple counting was possible. See Appendix A, Table A1 for landscape-type explanations.

For primary landscape types that were mentioned in combination with SBD, there was a clear majority of assignments, with 14 mentions for the agricultural and open land type (Figure 4). Regarding landscape types without SBD, the inland waters and floodplains type was the most represented with five mentions. Regarding the secondary landscape type for papers with SBD, forest was the most prominent with 11 mentions, followed by agricultural and open land. For papers without SBD, the most represented secondary type was agricultural and open land with eight mentions, followed by forests with seven mentions (Figure 5). Figure 6 provides an overview of the respective research locations identified in the 28 papers considered in the literature analysis. In 2 of the 28 cases (No. 11 and No. 16), it was not possible to determine an exact study area.

The distribution of data and materials in the category of cultural soil-related ESs with SBD, comprising 15 papers, and without SBD, consisting of 9 papers, reveals that soil data were most frequently employed (Figure 7). This affirms the literature selection's emphasis on soil-related aspects. While papers with SBD, in addition to soil data, predominantly utilized software and databases (11 papers), papers without SBD mainly used materials related to soil data (9 papers) and (archaeo-) botanical data (8 papers). Data from surveys or water sources were not employed by papers with SBD at all. Generally, the distribution of utilized data and materials in papers with SBD appeared significantly more homogeneous, whereas the distribution in papers without SBD was somewhat more heterogeneous.



No.	Authors	No.	Authors
1	Dlussky & Wedmann (2012): **Messel Pit**	15	Gocke et al. (2010): **Nussloch**
2	Acksel et al. (2019); **Poel, Fehmarn**	16	Wedmann et al. (2009): **Not specified**
3	Prud'homme et al. (2018): **Nussloch**	17	von Oheimb et al. (2008): **Lüneburg Heath**
4	Gocke et al. (2013): **Nussloch**	18	Wulf et al. (2021): **Kiecker Forest**
5	Köhler et al. (2018): **Schöps in Thuringia on the Saale river**	19	Birk et al. (2022): **Holzmaar and Ulmener Maar Western Eifel**
6	Köhler et al. (2019): **East Harz region**	20	Nelle et al. (2010): **Kugelstattmoss / Hirschenstein, Bargstedter Moor, Kleiner Tornowsee**
7	Köhler et al. (2020): **Thuringia**	21	Rösch (2018): **Northern Black Forest, Lake Constance**
8	Scherer et al. (2021a): **Hegau near Anselfingen**	22	Fuhrmann et al. (2004): **Meerfelder Maar, Holzmaar**
9	Scherer et al (2021b): **Fürstenberg**	23	Kaiser & Ahlborn (2021): **Havel region**
10	Heitkamp et al. (2008): **Lüneburg Heath**	24	Toncala et al. (2020): **Erding**
11	Altermann et al. (2005): **not specified**	25	Herbig & Sirocko (2013): **Maarseen in the Eifel**
12	Acksel et al. (2016): **Poel, Fehmarn**	26	Zerbe & Brande (2003): **Menzer Heath**
13	Gocke et al. (2014): **Nussloch**	27	Corradini et al. (2020): **Duvensee Schleswig-Holstein**
14	Albrecht & Haider (2013): **Urban sites North of Munich**	28	Maxwell et al. (2016): **Rauenberg**

Figure 6. Map showing the investigation areas and sampling locations in Germany for the 28 papers analyzed [30,43–69]. The papers by Altermann et al. ([30], no. 11) and Wedmann et al. ([62], no. 16) did not specify the study location. Study areas that are described as a region or occupying a region are shown in red (own representation, based on the map of https://pixabay.com/de/illustrations/deutschland-%C3%BCberblick-karte-7402045/ (accessed on 29 August 2024)). The numbers in red belong to a highlighted red area, in which the research areas were distributed over a generalized area, or where the area was named as a larger region (e.g., Thuringia). The black numbers show location details without distributions.

Various methods were employed by the authors of the analyzed papers to answer their respective research questions (Figure 8). Among the documents with SBD, field investigations were most frequently conducted (15), followed by the use of software (14), calculations and statistics (13), the utilization of chemical laboratory analyses (11), and other laboratory analyses (9). In documents without SBD, the most commonly used method was also field investigation (10), followed by chemical laboratory analyses (8), other laboratory analyses (7), and calculations and statistics (6).

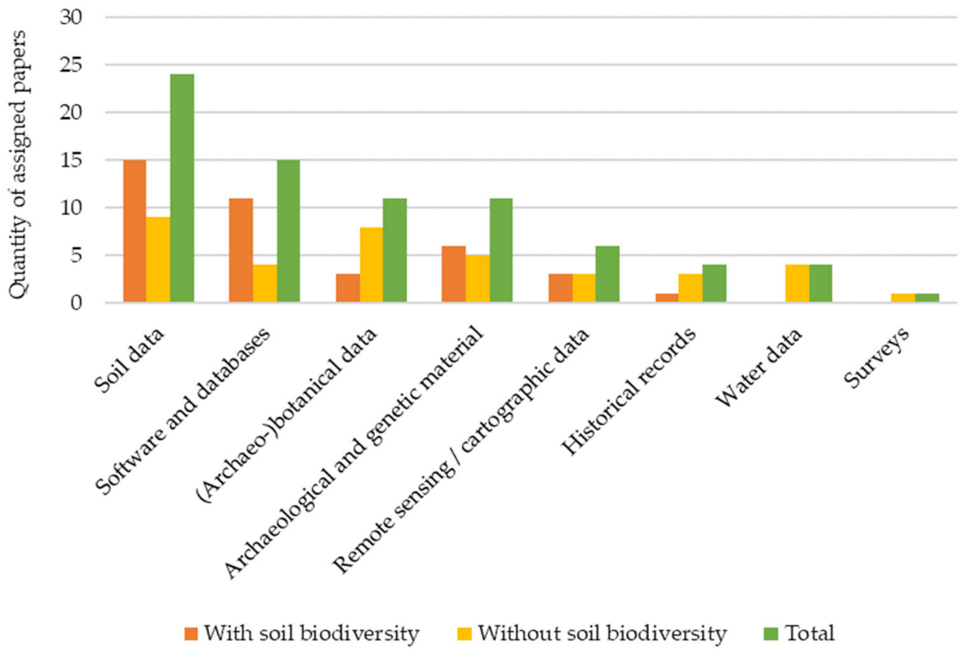


Figure 7. Distribution of data and materials used in the investigated studies. Multiple counting was possible. See Appendix A, Table A1 for an explanation of the categories.

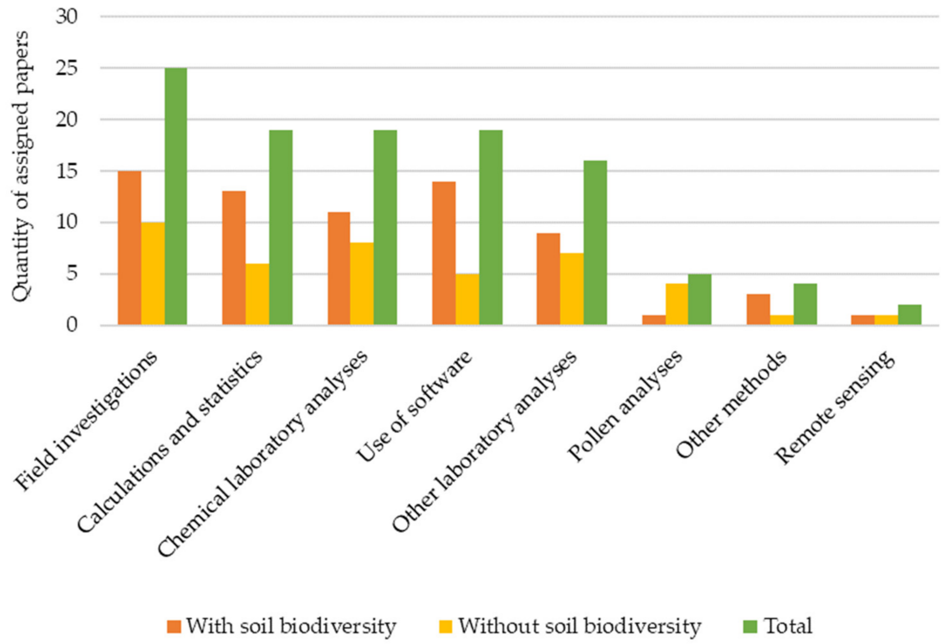


Figure 8. Distribution of methods used in the investigated studies. Multiple counting was possible. See Appendix A, Table A1 for an explanation of the categories.

3.2. Cultural Soil-Related Ecosystem Services

The iterative categorization process (see Section 2.3) within the literature analysis yielded five main categories for cultural soil-related ESs, namely, (1) place of sense, (2) spiritual value, (3) recreation, (4) forecasts and measures, and (5) soil as an archive. The latter, soil as an archive, was further subdivided into three subgroups as follows: storage, archaeological site, and reconstruction of the past (classification aligned with CICES 5.1). The majority of codes were distinctly allocated to these three subgroups. An important factor to consider when interpreting the results is that none of the examined documents explicitly mentioned cultural soil-related ESs. The assignment of codes to the respective categories was solely based on code definitions. Some passages in the papers were not only coded with a single code but also met the criteria of multiple categories. In Table 1, the code relations are presented, with the specified value indicating the total occurrences. This value signifies how many of the 28 analyzed papers exhibited dual codes among the respective codes. The strongest relation was found between the codes "reconstruction of the past" and "soil as an archive", co-occurring in a total of 22 papers. This was followed by the combination of archaeological site and soil as an archive with 18 papers. The third-strongest code relation was identified between archaeological sites and storage, found in 12 papers. Secondarily mentioned regulating, maintenance, and provisioning ESs were also coded. The categories assigned to the respective papers can be found in the Supplementary Materials, Table S2.

The cultural soil-related ESs that were analyzed in the studies are summarized below.

3.2.1. Spiritual Value

Soil can be meaningful in a spiritual context, for example, when soils are used as burial sites [43–45], as quoted in [46,47,70] (spiritual value).

3.2.2. Recreation

An increased occurrence of flowering plants in calcareous dry grasslands can enhance the recreational value of outdoor activities, and some grasslands have already been converted into recreational areas [48] (places of sense and recreation). Additionally, the hobby of fossil collecting, often related to the occurrence of limestone, can be considered a cultural soil-related ES [49] (recreation).

3.2.3. Place of Sense

Soils in Germany are significant for various reasons. On the one hand, soils can represent (subjective) natural beauty [30] (place of sense). For instance, calcareous soils provide the base for the development of dry grasslands, which belong to the species-richest ecosystems in Europe and also to the most threatened ecosystems [48] (quoted [71,72]). On the other hand, soils can gain importance because of what they provide or represent, as they play a central role in essential ecosystem processes [30]. For example, Chernozem cannot be formed anymore in Germany because of changes in climate conditions and is, at the same time, fundamental for many soil functions, for example, water retention and high soil fertility [30].

Soils and their contribution to human well-being require more appreciation, including protective measures. To generate this appreciation, initiatives such as the appointment of the "Soil of the Year" have been undertaken [30] (place of sense). The necessity of protective measures has been recognized in various areas. Consequently, several locations are now under nature protection [48] (place of sense), [50,73]. It should be mentioned that not only soils in their natural form were emphasized as a place of sense, but specific landscape forms in this context were also acknowledged, such as the conservation value of urban areas [45,48,70]. Heathlands can also take on the role of a place of sense in the form of a cultural landscape [71]; Lüneburg Heath, for example, has been a well-known nature reserve since 1921 [72].

3.2.4. Forecasts and Measures

Because of the mainly good ecological conditions of protected areas, they can serve as reference areas that support science and politics in the formulation of restoration goals or conservation measures [47,50]. Such reference areas need not necessarily establish an ideal state but may focus on achieving improvement or restoring good ecological conditions, also considering biodiversity [47] (quoted from [51]). The scientific value of soils extends further. For example, significant fossil discoveries, including valuable fossil collections, have been recorded [49,51]. Besides fossil findings, archaeological discoveries of animal bones were reported, e.g., bones from goats, sheep, birds, pigs, fish, and cattle [52,74] (quoted from [75–78]). In Rauenberg, close to Heidelberg (see Figure 6, No. 28, for the location), the Unterfeld clay extraction site is a significant location for fossil flora and fauna [49,72].

3.2.5. Soil as an Archive—Storage

Loess sequences, for example, are of immense importance for paleoclimate research [53,79]; (quoted from [73,80]). Valuable indicators are present in colluvial deposits, providing a valuable contribution to the understanding of historically anthropogenic land use [54]. Pollen types in the soil can reflect essential changes in vegetation and land-use history [55]. The soil can preserve phytoliths, and degradation products of plants that are decomposed in the soil can be used as biomarkers [56] (quoted from [74]; ref. [45], quoted from [77]). A volcanic ash layer, the Eltville Tephra, serves as a chronostratigraphic marker horizon in the Nussloch region (see Figure 6, No. 13, for the location) [53] quoted from [78,81,82]. Colluvial deposits can shed light on historical land use and the prehistory of land use-related phases of sedimentation [45,54]. Lipids in terrestrial sediments are also suitable for paleo-environmental research [57], quoted from [83–87]. Soil organic matter (SOM) is a characteristic indicator of Chernozem development in the Baltic Sea region that includes Germany [58]. A- and O-horizons can be used as complementary indicators for former land use practices [59]. For example, phosphorus stored in the A-horizon can provide indications of past fertilization practices [52,59].

3.2.6. Soil as an Archive—Archaeological Site

The Hegau region (see Figure 6, No. 8, for the location) is of outstanding importance for the research of the Bronze Age because of the accumulation of archaeological sites [45] (quoted from [88]). Sites in the North German Lowlands, on the other hand, are known for the archaeology of Mesolithic hunters and gatherers [60] (quoted from [89]). The cemetery of Altenerding has approximately 1450 graves and is significant for archaeological and anthropological research [46] (quoted from [90–94]). Moreover, specific soil horizons contain archaeological records [60].

3.2.7. Soil as an Archive—Reconstruction of the Past

Fossil discoveries are crucial because they can provide information on past biodiversity and land use, leading to insights into the development of individual species, human activities, and entire ecosystems [51] (quoted from [51,61,62,95,96]). Furthermore, organisms in the soil and their residual biomaterials, such as terrestrial mollusk communities and Earthworm Calcite Granulates (ECGs), can serve as proxies for the reconstruction of paleoclimate [79] (quoted from [63,97–104]). In general, it can be asserted that soil provides immense benefits for archaeological research [60]. Sediments from maar lakes or remains such as charcoal segments, pollen, and fecal biomarkers in sediment can provide insights into past land use practices and paleo-environments [61,64–67].

Soil responsiveness under large-scale rapid climatic changes can also be obtained [79]. When earthworms in permafrost soils are confined to the active layer, the mixing of ECGs is significantly reduced, allowing for an accurate chronology of horizons through ECG dating [79] (quoted from [101]). To characterize soils that have been prehistorically used, specific rRNA profiling of microbial communities can be a significant scientific tool [44]. The analysis of soil bacteria can differentiate archaeological residues [44] (quoted from [105]). The material found within urn graves has the potential to yield new or rare soil bacterial strains and indications of prehistoric sites in the form of microbial signatures [43]. Residues of microbiological origin can generally provide insights into historical anthropogenic land use [43] (quoted from [106,107]). Microbiological community profiling in the soil can be used to characterize soils from prehistorically used areas. The associated results suggest that a long-term ecological memory regarding early land use can be reflected [44]. The proportion of slow-growing and dormant microorganisms, such as *Polymorphobacter*, *Isoptericola*, *Rupridepita*, and *Hardesarchaeaeota* in the soil reflects long-term processes and can be termed as long-term memory in intact soils [43,68]. Today's microbial soil communities in a site may have developed depending on its prehistoric use. Furthermore, microbiological residues can be an indication of past anthropogenic activity [43].

3.3. Soil Biodiversity

In 17 of the 28 (61%) analyzed papers, references to soil biodiversity (SBD) were identified. The majority of these codes, specifically, 13 of the 17 papers (77%) fell under the category of microbes and microorganisms. For example, *Nitrospira*, *Chloroflexi*, *Bacteroidetes*, *Verrucomicrobia*, *Gemmati-monadetes*, *Actinobacteria*, *Planctomycetes*, *Firmicutes*, *Acidobacteria*, and *Proteobacteria* were mentioned [43] (quoted from [108]). However, only 5 of these 13 papers (39%) contained information on cultural soil-related ESs and SBD that went beyond the description of microbes and microfauna. In these cases, it was further specified that these microorganisms were bacteria or fungi, for example, *Proteobacteria* [43,44] and *Imperialibacter* [68]. The five papers that provided scientific names of soil organisms were Acksel et al. [58], Köhler et al. [43,44,68], and von Oheimb et al. [59]. The category of mesofauna was coded in one paper, but no specific examples of species were given [54]. In the macrofauna category, a total of 8 of the 28 papers were assigned, making it the second most frequent category. Seven of these cases specified that the organisms belonged to insects, more specifically, ants and leaf-cutting bees, earthworms, and terrestrial mollusks. The scientific names that were mentioned included the following: *Casaleia eocenica*, *Pseudectatomma eocenica*, *Pseudectatomma striatula*, *Pachycondyla eocenica*, *Pachycondyla lutzi*, *Pachycondyla messeliana*, *Pachycondyla minuta*, *Pachycondyla petiolosa*, *Pachycondyla petrosa*, *Protopone germanica*, *Protopone dubia*, *Protopone magna*, *Protopone oculate*, *Protopone sepulta*, *Protopone vetula*, *Cephalopone grandis*, *Cyrtopone microcephala*, *Cyrtopone curiosa*, *Cyrtopone elongate*, *Cyrtopone striata*, *Messelepone leptogenoides* [51], *Eisenia nordenskioldi*, *Dendrobaena octaedra*, *Lumbricus terrestris*, *Succinella oblonga* [63], and *Friccomelissa schopowi* [62]. Two papers were assigned to the megafauna category, namely, Scherer et al. [54] and Altermann et al. [30]. In Altermann et al. [30], the hamster (*Cricetinae*) and the European Ground Squirrel (*Spermophilus citellus)* were named as the megafauna. An overview of which papers contained SBD can be found in the Supplementary Materials, Table S1.

3.4. Connection between Soil Biodiversity and (Cultural) Soil-Related Ecosystem Services

The investigation of the link between SBD and cultural soil-related ESs was of central importance in this work. Although the primary emphasis was on examining cultural soil-related ESs, connections between SBD and regulating or provisioning ESs were also discovered in the evaluation. Supplementary information regarding these connections can be found in the Supplementary Materials, Table S2. A total of 11 of 28 the papers (39%) demonstrated a connection between SBD and cultural soil-related ESs. It became evident that SBD influences not only soil-related ESs but is also crucial for entire ecosystems [43] (quoted from [109]). Specifically, when considering the role of SBD in soil, the "…composition of soil microbial communities is of crucial importance for all terrestrial habitats" [44], quoted from [110]. The diversity of soils is largely determined by SBD and its interaction with other components of an ecosystem [44] (quoted from [111]). SBD can take on specific tasks. Long-term effects can be demonstrated for microbial communities [43] (quoted from [85]). Thus, the identification of dormant microorganisms can be used as long-term ecological memory. Moreover, the results suggest that soils have an ecological memory reflecting both current and past ecological situations [44] (quoted from [112]). The composition of the current SBD is influenced by factors such as environmental pollution over recent decades, as well as past human influences, among others [44]. These past effects can be understood as soil microbial memory that date backs to the Iron Age [44] (quoted from [107]). Such time spans allow SBD to be utilized in connection with archaeological findings. SBD can assist in the interpretation of archaeological finds, serving as "… a valuable tool for the characterization of soils from prehistorically used areas" [44]. For example, SBD profiles can be used to interpret archaeological findings, thus contributing to the understanding of the effects of anthropogenic influences on soil microbial diversity [44].

In detail, the frequency of thermophilic bacteria (extremophiles) could be used as a tool for interpreting archaeological findings [41]. However, negative associations between SBD and cultural soil-related ESs exist, as SBD can contribute to the decomposition of animal bones stored in the soil, for example [45]. Nevertheless, SBD can not only be a useful tool in archaeology but can also itself provide evidence as a fossil of terrestrial SBD, shedding light on the development of a species in terms of its distribution and adaptation to the environment [51] (quoted from [113]). The examination of ant fossils, for instance, resulted in "... unique insights into the Eocene ecosystem." [51] (quoted from [95]). Furthermore, the examination of the influence of climatic events using terrestrial mollusk assemblages was conducted (ref. [79], quoted from [100,114,115]). Substances generated through the life cycles of SBD can serve as information carriers. For example, steroid compounds originating from digestion processes by Edaphon, among others, can provide insights into the ways of life of certain organisms [54] (quoted from [116]). This leads to another connection, as SBD not only produces substances that reveal information about their ways of life but also substances that can be used as indicators for other environmental factors. Residues from microbial decomposition processes can indicate, e.g., past fires and high-temperature burns [54] (quoted from [117]).

Therefore, the microbial biomass in the soil can also be understood as an indicator that is sensitive to changes in environmental conditions [69] (quoted from [118–120]). ECGs, produced by earthworms during soil formation, have been discovered as new climate proxy [79] (quoted from [101,113,118,121–124]). Information contained in ECGs provides inferences for paleo-environmental reconstructions [79] (quoted from [63,101,102,113]). Generally, ECGs "... help to better understand the response of terrestrial archives to the millennial climate variations highlighted in ice-cores" [100] and thus represent a tool for reconstructing past environmental conditions. Chemical elements resulting from microbial reduction can be used as indicators of past land use practices (e.g., fertilization with organic matter [45], quoted from [125]). Alkanes produced by microorganisms, among other sources, have historically been used to determine the source of organic matter (OM) [57] (quoted from [83–87,126]). Moreover, microbial biomass carbon serves as a proxy for microbial activity in the soil and can be related to urease activities as an indicator of historical soil eutrophication [45]. The identification of microbial biomass has also been used as an indicator of soil quality in agricultural and heavy metal-contaminated soils [30] (quoted from [127–129]). Such evidence of historical land use or soil environmental conditions is often associated with SBD. The composition of existing SBD can be influenced by residues from prehistoric use, and, conversely, residues of SBD can indicate human activity [43] (quoted from [107]). These factors can be understood as cultural soil-related ESs that are directly linked to SBD.

4. Discussion

This systematic literature analysis revealed that within the analyzed 28 papers, no precise definitions of cultural soil-related ESs were found. Nevertheless, cultural soil-related ESs could be identified indirectly based on the context, even though they were not included as part of the studies' results sections. One reason for this absence might be that none of the authors of the analyzed papers specifically or systematically addressed cultural soil-related ESs in their analyses or ESs in general. Consequently, no statements can be made regarding potential classifications of cultural soil-related ESs. Nevertheless, it is positive to note that, despite the relatively small number of papers selected for analysis, i.e., 28 out of 2104 documents from the search query, a slight upward trend in the number of assigned documents per year was observed from 2013 onwards. This might indicate an increasing interest in cultural soil-related ESs, albeit more focused on the services themselves labeled as cultural ESs (e.g., archaeological site) rather than the cultural ES of the soil. Thematically, the literature is divided into soil as an archive (the majority—25 papers; 89%) and soil as cultural heritage (3 papers; 11%).

The configuration of historical landscapes significantly differs from the contemporary landscape. Forests have been displaced by deforestation and usage, making way for agricultural areas, settlements, and other forms of land use [130]. Consequently, the investigations in the papers mostly pertained to current agricultural and open land, which is not only extensive but also expected to hold archaeological significance in the context of soil as an archive. The results indicate that the examinations in the respective papers predominantly represented spatial levels at smaller scale, focusing on local and regional contexts. This is particularly relevant when considering SBD, which, as the literature analysis confirmed, varies because of various locally determined factors (e.g., [19,44,131]. The slightly increased representation at the international level can be explained by the fact that multiple small, local to regional study areas were still considered, albeit extending beyond national borders. Given the challenges in quantifying cultural soil-related ESs, it might be beneficial to examine them at smaller scales to develop better indicators and metrics for their assessments.

The identified cultural soil-related ESs include soil as a site for recreation, the ability to provide forecasts and measures through the soil, the spiritual value of soil, soil as a place of sense, soil as an archive, more specifically divided into archaeological site and storage, and the possibility of making reconstructions based on the information contained in the soil. When examining the proportional distribution of codes and code relationships in the literature analysis (Table 1), it is noticeable that the sub-codes of soil as an archive, storage, archaeological site, and reconstruction are the categories with the most codes overall. This indicates that soil as an archive is already recognized in the scientific literature, e.g., [12], although not explicitly in the context of cultural soil-related ESs (not labeled as such).

In 17 of the 28 documents, SBD was thematically addressed or at least mentioned. The designation of species groups aligned with existing knowledge from the literature was consistent with the classification used by the FAO [26]. The crucial role of SBD in the "healthy" ecological condition of (terrestrial) ecosystems and thus for human well-being was emphasized multiple times (e.g., [43,44], quoted from [110]). SBD and cultural soil-related ESs can be directly related to each other. It is essential to note that SBD can influence not only cultural soil-related ESs but entire ecosystems [43] (quoted from [109]). Terrestrial ecosystems have undergone profound changes because of anthropogenic interventions, affecting SBD and associated cultural soil-related ESs [43,59,68]. In total, 14 papers connected SBD and cultural soil-related ESs. Useful relationships for humans were identified, such as SBD as a microbial memory, SBD as a tool in archaeology, SBD as a fossil, SBD as an environmental indicator for historical landscapes, and SBD as a proxy for environmental and climate reconstructions. However, trade-offs with soils were also identified. For example, the decomposition of material by SBD can be regarded as positive by regulating soil-related ESs, but, e.g., the decomposition of fossils by SBD negatively influences cultural soil-related ESs. It is noteworthy that there could be also a negative influence of cultural soil-related ESs on SBD. For example, forest paths could be frequently used by hikers (recreational value of forests), but soil-dwelling SBD could be disturbed (e.g., destruction of food sources and nesting sites, trampling of organisms).

The connection between SBD and cultural soil-related ESs, along with their interactions and mutual influence, occurs bidirectionally. This means that SBD can influence cultural soil-related ESs and cultural soil-related ESs can influence SBD. The presented results provide insights into the changes in cultural soil-related ESs over time and illustrate the complex interactions among human activities, environmental changes, SBD, and soil condition. Anthropogenic drivers, especially land use, land use changes, and industrial activities, have caused profound changes in soils. The diversity of cultural soil-related ESs is influenced and threatened by the loss of soils, agricultural activities and management, the development of new infrastructure, and the resulting soil degradation or even soil sealing. However, it is essential not only to categorize present anthropogenic activities in terrestrial systems as problematic but also to assess historical land use practices that led to changes in the provision of cultural soil-related ESs. This is particularly crucial for SBD as the microbial memory of the soil. Parts of soil microbes may change gradually (over a long period), whereas others may change rapidly (over a short period), and they are subject to influences from changing climate and weather conditions, historical land use, and other human-induced changes. The mutual influence of SBD and human activities leads to complex interactions. Despite significant disturbances, soil and SBD can recover and adapt. However, the resilience of the soil and SBD is significantly influenced by the duration and intensity of these disturbances. The factor of time is extremely important and decisive when considering and contextualizing cultural soil-related ESs. Overall, these results illustrate the dynamics and complexity of changes in cultural soil-related ESs over time, where anthropogenic influences and environmental factors are key drivers.

Considering the methodological approach, this literature review provided a comprehensive understanding of the role of soils with a cultural focus, emphasizing their importance for science and human well-being. However, only publications from natural science formed the basis of our analysis even though WoS also covers journals from social sciences and search terms from social science were included (e.g., cultur* OR soci* OR religio* OR tradition* symbol* OR creat* OR artistic* OR educat* OR train* OR entertain* OR aware* OR inspir* OR stimul*). This finding either shows a selection bias or that the research topic is rather unexplored in the peer-reviewed literature beyond natural sciences. The socio-cultural aspects of soil or SBD can be found in flyers, reports, news, etc. ("grey literature"), e.g., in the publication on the "Soil of the Year" in Germany [132] and the World Soil Day [133]. In addition, entertainment, representation, and educational values of soils and SBD for the wider society, e.g., for schools, students, and museums, were not considered in our study, which may be due to the focus on pure academic aspects. However, environmental education for SBD is essential [134] and is already reflected in curricula, exhibitions, public events, and TV [135,136]. Furthermore, we could assume a potential distortion of the literature because several studies were published by the same authors in the same study locations (e.g., Nussloch in Figure 2). Even though our study only considered Germany, the lack of peer-reviewed studies related to SBD and links to cultural soil-related ESs can be assumed to transferred to others countries in the world. There could be several reasons behind this identified research gap, which may include the following:

(1) Cultural ESs are mainly represented in the non-peer-reviewed literature and where the term "cultural ecosystem service" is not specifically mentioned [137,138]. In general, the term "ecosystem service" seems to be less represented in soil science studies even though clear links between soil properties and ESs can be detected, e.g., in [8]. "Soil functions" seem to be the more commonly used term in this context.

(2) Soil and SBD is a research field of mainly natural sciences [6] and, therefore, socio-cultural aspects/human valuation, which comprise the concept of ESs, might be inherently neglected in the peer-reviewed literature.

(3) Quantifying cultural ESs is in general more difficult than measuring provisioning and regulating ESs [9]. Measuring soil-related and SBD-related cultural ESs is a very specific niche. When ES classifications and assessments of cultural soil-related ESs were conducted, Motiejūnaitė et al. [139] identified that these assessments focused on abiotic structures and soil in general (e.g., sand) rather than the biotic contributions to the final ES.

(4) Many cultural ESs (e.g., the aesthetic quality of a landscape) depend on land use patterns at the landscape level. In the existing literature, these have not been primarily associated with variation in soil properties (including SBD) in space.

(5) Directly measured connections among SBD, structures, processes, functions, services, and benefits and values published in one paper is almost impossible because of their complexities (see e.g., the reasons in [21]). Therefore, information along the ES cascade [20] might be fragmented and cannot be directly connected to specific case studies. Even research within the compartments of the ES cascade are not yet fully understood or explored in soil science, e.g., the mechanisms behind SBD and below-

ground processes [17]. In addition, maintaining high data quality in an assessment along the ES cascade with meaningful output might be challenging [8].

(6) Soils and their components receive less focus in policy and society than other natural resources [26]. Furthermore, because of the undeterminable and unquantifiable contributions of SBD to ES provisions, the direct benefits of soils on humans and their well-being are often hidden.

5. Conclusions

A detailed qualitative literature analysis was conducted to ascertain the representation of soil-related cultural ESs and SBD in peer-reviewed scientific publications, taking Germany as a test case. Out a total of 2104 potential documents, 28 suitable papers were identified based on specific criteria. These papers were then coded and analyzed. The results revealed that the representation of active research on cultural soil-related ESs in relation to SBD is still largely missing. There exists a huge research gap in the investigation of direct causal links among soil organisms, their contributions to soil functions, and, finally, their contributions to ES provisioning. Therefore, this study underlines the urgent need to better link and consider SBD and the processes of and among soil components in ES assessments. The soil science community is likely unaware that some soil functions can be labeled as "ecosystem services", and SBD is rarely directly measured in ES assessments because of the increasing methodological complexity in these assessments, among other reasons.

When developing future soil conservation measures, it is essential to consider and incorporate findings from soil science comprehensively in management and policy decisions. A future task for soil science will be to further explore cultural soil-related ESs, make them more measurable, and establish more in-depth content connections, integrating the concept into other scientific research areas. Inter- and transdisciplinary studies across different disciplines are required to better connect soil properties (including SBD) and processes with ESs and human well-being in a more systemic approach. From this holistic perspective, the societal relevance of soils and SBD will increase, e.g., for the achievement of the UN Sustainable Development Goals. Simple narratives and symbols of soils (which are also cultural ESs) can also gain relevance as political measures to increase public awareness. Additionally, suitable measures for the preservation and restoration of cultural soil-related ESs must be developed. These processes can only be successful if they are considered in combination with SBD and historical and current land uses. The protection of SBD is as fundamental and necessary for human well-being as the protection of soils and their associated cultural ESs.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/soilsystems8030097/s1. Supplementary Materials: S1: List of references from the systematic literature in alphabetical order. Table S1: Overview of the selected literature with regard to soil biodiversity, the link between soil biodiversity and soil-related ecosystem services, and other components/factors. Table S2: Secondarily mentioned regulating and maintenance and provisioning ecosystem services (ESs) of the respective papers.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Search String Used for the Systematic Literature Review in Web of Science

TS = (((ecolog* OR environment* OR ecosystem* OR landscape* OR natur* OR provisioning OR regulating OR cultural OR supporting) AND service*) OR "contribution* to people" OR NCP OR "natur* capital" OR "ecosystem health" OR health OR mental OR well-being OR recreation* OR relax* OR tranquil* OR archaeolog* OR fitness OR sport* OR mov* OR leisure OR skill* OR destress* OR recov* OR rehab* OR cultur* OR soci* OR religio* OR tradition* OR indigen* OR tourism* OR ecotourism* OR aesthetic* OR spirit* OR desir* OR destin* OR intellect* OR symbol* OR creat* OR artistic* OR educat* OR train* OR entertain* OR "physical experience*" OR "psychologic* experience*" OR enjoy* OR know* OR exper* OR learn* OR activ* OR adventur* OR amus* OR aware* OR inspir* OR stimul* OR heritage OR "habitat creation" OR "habitat maintenance" OR cultivat* OR rear* OR breed* OR domestic* OR livestock OR "plant* material*" OR construct* OR fish OR aqua* fibre* OR energ* OR biogas OR biomass OR nutrition* OR harvest* OR yield OR timber OR wood OR lumber OR food OR grain* OR cereal* OR crop* OR product* OR meat OR "raw material" OR stock OR fuel OR water OR freshwater OR irrigat* OR agricult* OR farm* OR wild OR gene* OR seed* OR spor* OR commerc* OR trad* OR income* OR benefit* OR money OR profit OR econom* OR monet* OR pharmac* OR medic* OR "carbon cycl*" OR "water retention" OR "water purification" OR "water storage" OR "water cycle" OR "water quality" OR filt* OR "air purification" OR "climate regulation" OR "soil quality" OR fertil* OR "soil fertility" OR "fire protection" OR "wind protection" OR "noise reduction" OR "flood regulation" OR "flood protection" OR "micro climate" OR "flood control" OR "erosion protection" OR "erosion control" OR "disease control" OR "pest control" OR pollinat* OR "seed dispersal" OR cooling OR "carbon sequestration" OR "waste decomposition" OR detoxificat* OR "invasion resistance" OR albedo OR bioturbat* OR "soil formation" OR "nutrient cycl*" OR "nitrogen fixation") AND (German* OR "central europ*" "Lower Saxony" OR Thuringia OR Saarland OR Berlin* OR Brandenburg* OR Saxon* OR "Saxony-Anhalt" OR Bavar* OR Baden-Wuerttemberg OR Bremen OR Hamburg OR Hess* OR "Mecklenburg-Western Pomerania" OR "North Rhine-Westphalia" OR "Rhineland-Palatinate" OR "Schleswig-Holstein" OR Rhineland* OR Rhenish OR "North German Lowlands" OR "North German Plain" OR "Central Uplands" OR "Upper Rhine Valley" OR "Alpine Foreland" OR Harz OR Alps) AND ("species richness" OR "species number*" OR "species identity" OR "species composition" OR "species abundance" OR "species divers*" OR "species evenness" OR diversity OR biodivers* OR "biodiversity hotspot*" OR "genetic* divers*" OR "genetic* richness" OR "landscape divers*" OR "landscape structure" OR "landscape composition" OR "habitat divers*" OR "habitat structure" OR "habitat composition" OR "seascape structure" OR "structur* divers*" OR "community composition" OR "ecosystem* divers*" OR "ecosystem* structure" OR "ecosystem composition" OR "phylogenetic* divers*" OR "phylogenetic* richness" OR "number of taxa" OR "taxonomic* divers*" OR "taxonomic* richness" OR "functional* divers*" OR "functional* richness" OR "functional* composition" OR "functional* evenness" OR "functional* dissimilarity" OR "function similarity" OR Shannon* OR simpson OR evenness OR richness OR biomass OR abundance OR density OR communit*) AND (soil OR "soil-dwelling" OR below$ground OR below-ground) AND (biota OR fauna OR micro$fauna OR micro-fauna OR meso$fauna OR meso-fauna OR macro$fauna OR macro-fauna OR mega$fauna OR mega-fauna OR protozoa* OR bacteria* OR proteobacteria* OR cyanobacteria* OR actinobacteria* OR firmicutes OR archaea OR euryarchaeota OR crenarchaeota OR thaumarchaeota OR protist* OR rhizaria OR ameb* OR amoeb* OR alveolat* OR stramenopile* OR excavata OR fung* OR ascomyc* OR basidiomyc* OR glomeromyc* OR zygomyc* OR chytridiomyc* OR blastocladiomyc* OR microb* OR animal* OR rotifer* OR nematod* OR mollusc*OR gastropod* OR snail* OR slug* OR annelid* OR oligochaet* OR earthworm* OR lumbricid* OR enchytrae* OR clitellat* OR haplotaxid* OR tardigrad* OR arthropod* OR micro$arthropod* OR micro-arthropod* OR macro$arthropod* OR macro-arthropod* OR chelicerat* OR arachnid* OR acari OR mite* OR araneae OR spider* OR pseudoscorpion* OR scorpion* OR myriapod*

OR chilopod* OR centiped* OR diplopod* OR milliped* OR pauropod* OR symphyla* OR crustacea* OR malacostraca* OR isopod* OR lice OR hexapod* OR entognath* OR collembol* OR springtail* OR protura* OR diplura* OR insect* OR hymenopter* OR sawfl* OR wasp* OR ant* OR isopter* OR termite* OR coleopter* OR beetle* OR dipter* OR fly OR flies OR hemipter* OR cicada* OR aphid* OR planthopper* OR leafhopper* OR bug* OR lepidopter* OR butterfly* OR moth* OR neuropter* OR lacewing* OR mantidfl* OR antlion* OR inverte* OR chordat* OR vertebrat* OR amphibia* OR frog* OR toad* OR salamander* OR newt* OR reptil* OR mammal* OR hamster* OR mole* OR "soil biodiversity" OR "below$ground biodiversity" OR "soil divers*" OR "below$ground divers*"OR "soil invertebrate*")

Table A1. Preselected categories for the literature analysis. Regarding the category "type of landscape", the primary type of landscape indicates the dominant landscape type prevalent in the study area and the secondary type of landscape indicates the forms of landscapes present in the study areas but less pronounced or covering a smaller proportion of the area.

Main Category	Subcategory	Definition
Year of publication	2003, 2004, 2005, 2008, 2009, 2010, 2012, 2013, 2014, 2016, 2018, 2019, 2020, 2021	The year that was specified in the document as the year of publication. The individual codes are the respective years.
Spatial dimension	Local dimension	The local dimension included all study areas that represent a largely uniform, contiguous landscape type (e.g., forest) and do not exceed an area of 10 km^2.
	Regional dimension	The regional dimension was defined as spatially coherent, representing different types of landscapes located within a federal state and covering an area of 10 km^2 to 1000 km^2.
	Supra-regional dimension	The supra-regional dimension was also spatially contiguous, but it could extend across federal states and cover an area of 1000 km^2 or more.
	National dimension	The national dimension was defined as cross-state, where the study area extended nationwide or across multiple non-contiguous study areas within Germany. From the national dimension onwards, no specific area size was provided since dispersed study areas, despite individually covering less than, e.g., 1000 km^2, were still categorized as national because of their spatial distributions.
	International dimension	The international dimension was attained when the study areas extended beyond the political boundaries of Germany.
Type of landscape	Agricultural and open land	The category of agricultural and open land encompassed areas that were non-forested, displaying agricultural structures such as fields, farm roads, windbreak strips, and pastures, as well as open, non-sealed, and unused spaces (e.g., fallow land).
	Forest	Forests were defined as landscapes exhibiting a larger contiguous area covered by trees or tree canopies in satellite images.
	Urban areas and settlement areas	Urban areas/settlement areas referred to inhabited areas predominantly covered by impervious surfaces with clear infrastructure, including residential houses, industrial halls, storage areas, and roads.
	Inland waters and floodplains	All study areas with water bodies (e.g., lakes, rivers) and/or floodplain structures were defined as inland waters and floodplains. It should be noted that floodplains were always defined as such in the texts.

Table A1. *Cont.*

Main Category	Subcategory	Definition
Type of landscape	Coastlines and coastal waters	The definition of coastlines and coastal waters was based on the description of the habitat provided by the German Biodiversity Assessment and according to Kelletat [140] "Coasts form a more or less broad band, thus creating a border zone between land and sea." (translated from German to English ([140] [p. 2]). Especially because of the demarcation of the sea, an inherent dynamic nature of water was expected, such as a shifting shoreline, the influence of surf, and the generated saline mist or spray, which also impacts landscape morphology [140]. Therefore, all landscapes or landscape sections were assigned to this type, which are subject to the influence of these dynamics or have emerged geomorphologically through such processes.
	Swamp	Since swamps were difficult to identify from the view of a simple satellite image alone, their statements or mentions in each text was the decisive factor here.
Used data and materials	Surveys	Data resulting from surveys, regardless of whether they were qualitative or quantitative.
	Historical records	Historical records included items such as old notes, documents, sketches, etc. This category also encompassed maps or aerial photographs, which may have a historical origin. The crucial distinction was in their remote sensing character, in contrast to historical records, which do not necessarily exhibit remote sensing characteristics.
	Remote sensing/cartographic data	Text passages that provided references to materials such as maps, aerial photographs, or photographs of areas were coded.
	(Archaeo-)botanical data	All data and all material of botanical origin, e.g., leaves and pollen, were coded. Both paleo- and recent samples were taken into account.
	Water data	All data and parameters related to water. Here, too, both current and historical data were coded insofar as they were relevant to the results of the respective paper.
	Soil data	All data and material related to soil, e.g., soil samples and soil horizons.
	Archaeological and genetic materials	This category encompassed all data and materials of archaeological origin, such as charcoal fragments, pottery shards, ancient foundations, and fossils. Additionally, genetic material, including bone findings, tooth enamel, and specific genetic primers, were categorized under this classification. Archaeological and genetic materials were particularly combined in the coding process as, for instance, distinguishing a bone finding from the subsequent analysis and the associated provision of genetic material can be challenging or even impossible.
	Software and databases	This category included all databases and software used to acquire data or processing it.
Used methods	Calculations and statistics	All text passages indicating the execution of mathematical calculations or the application of statistics were marked.
	Field investigations	Field investigations took place in the actual field and included activities such as the collection of soil samples, the discovery of fossils, or the interpretation of various soil horizons in an outcrop.
	Laboratory analyses	*Chemical laboratory analyses* Chemical laboratory analyses encompassed all procedures conducted in a laboratory using chemical reactions, the addition of additional substances, etc.
		Other laboratory analyses Other laboratory analyses included all analyses conducted in the laboratory without the necessity of a chemical examination, such as grain size analysis or specific drying procedures.

Table A1. *Cont.*

Main Category	Subcategory	Definition
Used methods	Remote sensing	The category of remote sensing included various remote sensing methods and investigations. These investigations could have been conducted both in the field and in the laboratory. They differed from the categories of field investigations and laboratory analyses in that they contributed to obtaining data that could not be directly sampled on-site or were more closely associated with typical remote sensing methods (e.g., radar, topography, cartography, . . .).
	Use of software	All software products that were used, for example, to record and analyze collected data were marked. As many programs or systems are also hybrids of, e.g., statistical and remote sensing methods, these were not assigned separately to the respective categories but collected in the use of software category.
	Pollen analysis	The category of pollen analysis included all investigations, descriptions, and evaluations of pollen. This encompassed the identification of individual pollen grains as well as the analysis of entire pollen profiles.
	Other methods	Some methods were mentioned extremely infrequently or only once during the literature analysis, and, therefore, they were grouped under the "other methods" category. Various techniques and scientific fields, such as taphonomy, standardized text description, photography (no orthophotography), and the creation of drawings, were included in this category.
Cultural soil-related ESs	Place of sense	Text passages were marked where the soil was described as something particularly beautiful, worth preserving for future generations, such as a nature reserve or a historically significant site (monument). Additionally, instances were marked where the soil held significant scientific value, contributing to new scientific insights. It was essential to ensure that this coding went beyond merely sampling the soil (which falls under the method category) and emphasized the distinct value of the soil at that location. This coding was also valid when highlighting the soil's value in its particular significance for humans.
	Recreation	This code was used where soil and its elements were described as the basis for recreation and leisure activities, such as the hobby of collecting fossils.
	Forecasts and measures	Through the exploration of the soil, new insights are gained, for example, in the form of soil values or specific sediment layers that allow for the derivation of forecasts and measures regarding soil management. These serve as political and economic decision-making aids or guides, for instance, in preserving and improving the environment. The soil may have also contributed to the development of new research methods or have been designated as a reference site for future research or management measures. This coding differs from the "place of sense" code in that "place of sense" views the soil as something worthy of protection, and forecasts and measures at the operational level illustrate that the soil must be protected and how this could potentially be implemented. This category was not explicitly mentioned in CICES Version 5.1 and can be considered "other" within abiotic cultural ecosystem services.

Table A1. *Cont.*

Main Category	Subcategory	Definition
Cultural soil-related ESs	Soil as an archive (Soil as an archive was subdivided into three subgroups because it was noticed that the description as an archive alone was not sufficient and was quite complex. This differentiates storage, archaeological site, and the possibility of reconstruction. The exact definitions can be found in the subsections.)	*Storage* Soil serves as a storage location for various elements, such as soil layers, chemicals, and pollen. A soil seed bank could be coded as a storage location when the text indicated that the focus was not on the genetic diversity of the soil seed bank but solely on the housing of seeds in the soil. In general, a storage medium was considered to exist when something is housed in the soil that typically has no human origin. An exception was made in Scherer et al. [54], where anthropogenically induced colluvial deposits were mentioned. Despite being sediments, they still fall under the coding of storage medium. The soil was also considered a storage medium when it functions as an ecological memory, housing information about the aforementioned elements. In this context, memory was understood as something that stores information, and the recall or reproduction was seen as reconstruction (see the reconstruction code). Charcoal fragments could also be coded under storage medium if the context suggested that they were not of anthropogenic origin, such as remnants of natural wildfires rather than fireplaces in settlements. It was crucial to infer from the text that something could be derived from the stored cargo or that a reconstruction could follow. This was important to avoid unnecessary coding of simple investigations and to obtain only content-relevant results. For example, the occurrence of a specific sediment sequence alone did not carry insight, but it became relevant when it could lead to new understanding.
		Archaeological site Soil hosts various discoveries, such as fossils, ancient relics like shards, remains of houses and settlements, urns, and charcoal fragments of anthropogenic origin like those from fireplaces, animal bones, and feces. In general, these findings were primarily of anthropogenic or animal origin. Macrofossils were also considered as animal findings unless the text explicitly pointed to plant fossils (then coded under storage medium). Macrofossils of animal origin also includes crawl traces or construction traces of animal origin. The passage was also marked as a discovery site when the text mentioned archaeological findings, and it was evident from the context that these findings were of anthropogenic origin. If this was not clearly apparent in the text or if there were previous mentions of findings in the storage medium category, the text passage was labeled with both codes. It is also important that the marked text passage or context indicated that the discovery was in the soil or at the study site, to distinguish it from the reconstruction code (see the reconstruction code).
		Reconstruction of the past Soil allows inferences about evolution, landscape, climate, and agricultural practices and includes indicators that allow for drawing conclusions (if indicators are stored, also coded as storage medium and/or discovery site). It also enables the reconstruction of ecological conditions and logical conclusions about, for example, sediment origins. Reconstruction is not purely historical; rather, it refers to the ability to trace or deduce a circumstance or its origin based on traces left in the soil. A non-historical example would be the discovery of a crater in the soil, indicating an asteroid impact. The following quote was also considered a form of reconstruction: "Besides crops, their weeds also have attracted the interest of archaeo-botanists and were regarded as a good proxy for evaluating agriculture and environment." ([67] p. 75). This is because archaeo-botanty and archaeo-zoology are ". . .important cornerstones for the exploration and reconstruction of the economic and natural foundations of past epochs of human history." (translated to English from German from [70]).

Table A1. *Cont.*

Main Category	Subcategory	Definition
Provisioning soil-related ESs	Genetic refuge	Soil provides or harbors genetic material. Since soil always contains genetic material through, for example, soil organisms, the code had to be further refined. This was achieved by considering only genetic material from extinct or rare species. Additionally, coded instances included soil seed banks or cases where pronounced biodiversity was mentioned.
	Habitat for animals	Soil or specific soil layers serve as habitats for animals, either as a permanent residence or breeding ground.
	Soil as resource	*Soil as Foundation* Soil serves as a foundation or surface for purposes such as building sites, pastureland, agricultural areas, or infrastructure like roads.
		Soil as biomass Soil or its components are utilized as material, for example, in the production of fertilizers.
Regulating soil-related ESs	Resilience	The soil's ability to adapt to changing environmental conditions or self-regulate, significantly contributing to the response potential of ecosystems. This was not explicitly mentioned as a separate soil-related ecosystem service in CICES Version 5.1 but was evident from the cumulative impact of multiple regulating soil-related ecosystem services.
	Protection from environmental influences	Soil or the utilization of soil, for example, contributes to flood protection or safeguards against slope erosion.
	Bioturbation	Soil is altered by soil biodiversity by burrowing, changing its layers, enriching it with nutrients, and facilitating aeration [46].
	Remediation	The ability of the soil or soil biodiversity to perform remediation of the soil after, for example, pollutant contamination or extensive use, restoring a natural state, such as the mineralization of insecticides or the retention of pollutants. This was not explicitly mentioned as a separate soil-related ecosystem service in CICES Version 5.1 but was evident from the cumulative impact of multiple regulating soil-related ecosystem services.
	Nutrient cycling	Soil serves as a site or prerequisite for various nutrient cycling processes, such as water filtration, soil development, and the transformation of litter.
Soil functions		The code for soil functions was deduced based on the second research question. Coding was applicable when the term "soil function" was explicitly mentioned in the text of the respective paper under analysis.
Soil biodiversity	Microbes and microfauna	The microbes and microfauna group included entities such as viruses, bacteria, single-celled organisms, and fungi. Text passages referring to "microorganisms" or "microbial biomass" were also assigned to this coding.
	Mesofauna	The mesofauna category comprised organisms such as tardigrades, mites, or springtails (Collembola).
	Macrofauna	The macrofauna category included, for example, text passages related to earthworms, ants, beetles, and snails.
	Megafauna	The megafauna category represented the group of the largest organisms, including mammals like hamsters, as well as reptiles and amphibians.

Table A1. *Cont.*

Main Category	Subcategory	Definition
Connection between SBD and soil-related ESs		The connection between SBD and soil-related ESs represents an association between soil organisms and soil-related ESs. As all three cultural, regulatory, and provisioning soil-related ESs were coded during the analysis, the connection applied to all categories of soil-related ecosystem services. This linkage could be either direct or indirect. A direct connection exists when, for example, SBD has a direct impact on a soil-related ES or is directly involved in its existence. An indirect connection, on the other hand, arises from situations where a change in SBD causes a shift in the chemical equilibrium in the soil, resulting in a deviation in soil-related ESs. The term "deviation" was intentionally chosen here, as the existing connection can have both positive and negative effects on soil-related ecosystem services. Conversely, a change in a soil-related ESs, driven by a factor like a driver, can also lead to a change in SBD. In general, coding the category connection between SBD and ESs illustrated an interaction between these two components and made it evident or deducible from the text passage.

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