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The unexplored links between soil, soil biodiversity, and soil-related ecosystem services*

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Abstract

Soil and its biotic and abiotic components have a huge impact on human well-being, but, on the other hand, they are often neglected in scientific studies or by policy and society in comparison to other ecosystem components. In this study, we provide an overview of the direct and indirect positive and negative influences of soil and soil biodiversity (SBD) on the supply of regulating, provisioning, and cultural (soil-related) ecosystem services. We selected Germany as an example of a well-funded country for research, but we found only a small collection of described and analyzed interactions between SBD and soil-related ecosystem services considering the huge amount of species in the soil. Positive effects of SBD on soil-related ecosystem services in Germany were especially found for the regulation of soil quality and, therefore, the potentially positive impacts on plant cultivation. In addition, interactions between soil, SBD, and cultural ecosystem services were documented, for example, for physical and emotional interactions, aesthetic, soil as an archive, soil as a habitat for species, and soil for education and science. No publications on national and international level were found, for example, on the negative influence of SBD on the cultural ecosystem services tourism / recreation, spiritual interactions, entertainment, and non-use values which underlines the dominance of positively documented interactions. Even though the analyses of causal interdependencies in the nexus between soil, SBD, and soil-related ecosystem services might be challenging due to its complexity, more comprehensive assessments of this nexus should be encouraged.

Keywords: Natural capital, knowledge gap, society, literature review, Germany

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1. The links between soil, soil biodiversity, and ecosystem services

Soils provide the base for the supply of multiple Ecosystem Services (ES) that are essential for human well-being, such as the regulation and filtration of water, the storage and transformation of nutrients for plants, the supply of raw materials, and habitats for flora and fauna (Adhikari & Hartemink, 2016; Comerford et al., 2013; European Commission, 2006; Pascual et al., 2015). These soil-related ES (hereafter referred to as "soil-ES") are therefore essential for the human society (Eisenhauer et al., 2024a). Especially agriculture and forestry are highly dependent on soil and the interactions of their biotic and abiotic components (Banerjee & van der Heijden, 2023; Swift et al., 2004; van der Heijden & Wagg, 2013; Wall et al., 2015). For example, bioturbation by larger soil organisms such as earthworms aerate and mix the soil, thereby creating structures that improve ecosystem functionality (Eisenhauer, 2010; Fonte et al., 2023). Microbial metabolic products and the dead plant and microbial biomass (necromass) form the basis of the organic soil substance. Overall, soil biota ensure the formation of stable soil structures (Angst et al., 2024). Another relevant soil-ES is the provision of habitats for soil-nesting species such as wild bees that are important pollinators for different crops (Antoine & Forrest, 2021; Klein et al., 2007). In addition, soil biodiversity (hereafter referred to as SBD) contributes significantly to the control of pests and pathogens (Northfield et al., 2013). Higher SBD increases the interplay within complex food webs offering more possibilities to handle parasites and consequently leads to a higher resilience of ecosystems against pests (Letourneau et al., 2009; Sánchez-Moreno & Ferris, 2007). This regulating ES is important for the agricultural sector, especially in organic farming. In light of direct and indirect interrelationships between ecological and social systems, functioning soil microbiomes are fundamental for "healthy" plant, animal, and human communities (One Health Concept; Banerjee & van der Heijden, 2023; Singh et al., 2023).

Soil and sub-soil biodiversity are also relevant for the water supply sector. They are important for the absorption, drainage, storage and release of water and, therefore, they have a significant role for the landscape water balance, the recharge and purification of drinking water, and the regulation of floods and droughts (Keesstra et al., 2021). Assessments of benefits of these ES for humans have shown the added value or saved costs of the soil-ES filtration of contaminants (Jónsson et al., 2017). Furthermore, in relation to cost savings, the storage of carbon in soils is another prominent example of SBD-related ES. Soil organisms change the organic carbon through decomposition (positive flow equilibrium), but also respiration (negative flow equilibrium). In a positive flow equilibrium, SBD contributes to humus formation and thus to carbon storage (Crowther et al., 2019; Dilly et al., 2005; Graaff et al., 2015; Lange et al., 2015; Minasny et al., 2017). Relevant sources for the release of greenhouse gases are drained peatlands (negative C flow equilibrium) or the fertilization of agricultural areas resulting in nitrous oxide emissions from the soil. Here, it becomes obvious that soil interactions can cause positive as well as negative effects for the environment and the human society.

The term "soil-ES" summarizes all ES whose supply is directly dependent on biotic and abiotic soil properties and measurable (or estimable) by these (Paul et al., 2021). Soil-related ecosystem functions provide the biophysical basis for soil-ES supply and SBD strongly influences ecosystem functions. SBD refers to 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." (FAO, 2020, p. 7). From a conceptual perspective, considering interlinked social-ecological systems (Berkes & Folke, 1998), there is a causal interrelation between SBD via soil communities, soil structures, soil functions (the ecological system) to soil-ES and values and benefits for people (the social system) as defined in the ES cascade (Potschin & Haines-Young, 2011). ES link the ecological system with the social system. The systems influence each other. For example, humans (embedded in the social system) influence via land management (e.g., tillage, fertilizer input, irrigation) the ecological system and increase or decrease the supply of ES (Scherzinger et al., 2024; Vries & Wallenstein, 2017).

Paul et al. (2021) identified 29 ES that are directly related to soils, their properties, processes and functions. In addition, agricultural soil management affects another set of 40 ES. Bakker et al. (2019) systematically analyzed the relationships between SBD and ES in forests of Europe. They combined terms and types of ES and biotic groupings of plants, fungi, and prokaryota (which resulted in 518 combinations and 574 studies) in the Web of Science core collection, and identified that 92% of these terminological combinations for a specific group and separate ES were not covered by data or were only mentioned by very few studies. The quantification of soil-ES, their underlying properties, biodiversity, ecological interactions and usage potential are therefore important to assess their multiple values and benefits for human society (Eisenhauer et al., 2024a; Pascual et al., 2015; Scherzinger et al., 2024).

In general, ES assessments are comparatively easy to implement when trade numbers or economic market values (applicable especially for provisioning ES) or biophysically measurable components (especially for regulating ES; e.g., Scherzinger et al., 2024) are applied. In contrast, quantifying the direct contributions of SBD to cultural soil-ES is more difficult, because cultural soil-ES comprise inherent and / or indirect use values and individual preferences that cannot be assessed by easily measurable indicators (Comerford et al., 2013). Another issue is the potential for double-counting of ES due to overlapping properties of different ES (Fu et al., 2011), e.g. between habitat provision for soil-nesting hymenopterans, pollination of crops, and food provision from crops. Furthermore, co-production of ES emerges when natural and human resources jointly provide the final ES (Lavorel et al., 2020). This connection is especially obvious in heavily human-influenced social-ecological systems. Taking ES co-production into account becomes especially relevant in agricultural, semi-natural, and urban systems. Human influence through management, e.g. by the application of fertilizer or irrigation, contributes similarly, like soil fertility and other soil-related characteristics, to the provision of food (Bethwell et al., 2021).

The examples of soil-ES show clear links between the biotic and abiotic components of soils. However, many connections between SBD and ES are still unexplored in international research. The lack of knowledge about the connections between soils and human health is striking (Brevik & Sauer, 2015; FAO, 2020) and we are just starting to systematically collect the huge variety of soil-human health interactions (Banerjee & van der Heijden, 2023). In this study, we focus on the national research gaps within the field of international literature on SBD and soil-ES, taking Germany as an example of a relatively well-funded and well-equipped country for research. Historically, chemical soil properties, physical processes, and the description and analysis of soil types have been in the focus of soil science in Germany (Walther, 1935). Accordingly, the causal relations between SBD, ecosystem functions, and ES were rarely considered in soil science (and in society). If there has been an indirect link to ES, it was rather via soil management for crops, grassland, and forests – especially for plant growth (Ehwald, 1964). Above- and below-ground communities have been scientifically analyzed rather separately than integrative in the past (Jochum & Eisenhauer, 2022; Scheu, 2002; Wardle et al., 2004). In addition, soil science and soil ecology were rather disconnected with separate research agendas, publications, and conferences.

2. Methodological approach

For this study, we conducted a non-systematic literature search of peer-reviewed (primarily original research) papers about SBD and soil-ES in English and German in Google Scholar. In addition, "grey" (not peer-reviewed) literature in German language was screened between June 2022 and December 2023. This literature search was repeated from June to August 2024 in order to update the search. The focus was set on recent peer-reviewed papers (published between 2014-2024) although older publications were also included. This type of literature search can be considered as a rapid review where time and resources are too limited to conduct a comprehensive review (Booth et al., 2009). The search was conducted within the frame of the German Biodiversity Assessment ("Faktencheck Artenvielfalt", Wirth et al., 2024a) where approximately 150 experts from Germany were involved. This assessment, conducted between 2022 and 2024, provided a comprehensive overview of information on the current status and potential future trends of biodiversity in Germany. Within this framework, a dedicated working group focused on the assessment of SBD in Germany (Eisenhauer et al., 2024b).

With regard to the soil-ES classification in this study, we applied the Common International Classification of Ecosystem Services (CICES version 5.1; Haines-Young & Potschin, 2018), which is based on the ES cascade (Potschin & Haines-Young, 2011). CICES is structured within the sections provisioning ES (e.g., the provision of food, energy, and biomass), regulating and maintenance ES (e.g., the regulation and infiltration of water, erosion control), and cultural ES (e.g., recreation, spiritual values). In our study, the CICES cultural ES groups physical and experiential interactions with natural environment (CICES Group 3.1.1.) and emotional / intellectual interactions (CICES Group 3.1.2.) were used in addition to the ES on the CICES Class level (which is the more detailed level), because, partially, clear assignments to one specific CICES Class was not possible. However, this approach could have led to duplicates in the results (Table 1).

Regarding the terminological delimitation of SBD, Bakker et al. (2019) included also plant roots as SBD. We excluded plant roots from our search term due to the definition of SBD used in our research (Eisenhauer et al., 2024b). Furthermore, soil as a system provides a better basis for research than SBD, especially for cultural soil-ES, due to the larger scale of reference (i.e., landscape scale) that can be assigned to soil, e.g. for landscape aesthetics and tourism-related ES. In addition, some CICES terms better fit to soil as a system and not specifically to SBD, e.g., the services "soil as an archive" and "soil as habitat for species".

3. Results

3.1 Insights from the international literature

Most of the international literature for positive links between SBD and soil-ES was available for global climate regulation (Creamer et al., 2016; Crowther et al., 2019; Graaff et al., 2015; Minasny et al., 2017), pest control (e.g., Corato, 2020; Crowder & Jabbour, 2014; Letourneau et al., 2009; Northfield et al., 2013), regulation of soil quality (e.g., Bender & van der Heijden, 2015; Sofo et al., 2020; van der Heijden et al., 2008), wild plants, fungi, and animals for nutrition, materials or energy (e.g., Belluco et al., 2013; Menta & Pinto, 2016; Pérez-Moreno, 2021; Uprety et al., 2012; Yun & Hall, 2004), and genetic material (e.g., Hyman, 2019; Ling et al., 2015; Pepper et al., 2009; Riesenfeld et al., 2004). Table 1 shows an overview of soil-ES that are or can be influenced by SBD based on evidence from the review of German as well as international literature. Even though literature for material / biomass (CICES Group 4.3.1, 4.3.2) was less reflected in Table 1, it should be regarded as basic knowledge that soil fauna contributes to soil formation (e.g., see Angst et al., 2024; Zanella et al., 2018) and that there are overlaps with soil organic carbon (organic matter) and soil quality. Therefore, it is overlapping with the literature on the ES global climate regulation (CICES Class 2.2.6.1) and the regulation of soil quality (CICES Class 2.2.4.1, 2.2.4.2).

Negative relations between SBD and soil-ES in the international literature have been reported especially regarding pest and disease control for plants (Fisher et al., 2012), livestock (Hugh-Jones & Blackburn, 2009), wildlife (Fisher et al., 2012), and humans (Brooker et al., 2006; Jourdan et al., 2018; Wall et al., 2015). Some bacteria (e.g., Salmonella spp.; Schierstaedt et al., 2020), fungi, protists, and nematodes can constitute a serious health risk as ecosystem disservices. However, considering the amount of soil organisms on earth, only a few cases (be it positive as pest control or negative as disease) have been reported in science up to now (Wall et al., 2015).

Regarding cultural soil-ES in the international literature, positive as well as negative interactions have been mentioned for physical interactions (e.g., Brevik & Burgess, 2013; Kecinski et al., 2018; Motiejūnaitė et al., 2019) and intellectual / emotional interactions (e.g., Brevik et al., 2018; Craig et al., 2016; Hanyu et al., 2014). Fungi from soil (saprotrophs) can also negatively affect historical or cultural heritages such as monasteries and churches (Zucconi et al., 2022). Spiritual interactions (e.g., Comerford et al., 2013; Pérez-Moreno, 2021), and "characteristics or features of living systems that have an option or bequest value" (CICES Class 3.2.2.2; e.g., Decaëns et al., 2006; Phillips et al., 2020) were only positively related.

3.2 Focus on literature for Germany

Regarding SBD and regulating ES for Germany, literature is available for the positive connections between SBD and the regulation / maintenance of soil quality (e.g., Cesarz et al., 2017; Eisenhauer et al., 2012; Leimer et al., 2016; Plaas et al., 2019). A well-known example is the symbiosis between mycorrhizal fungi and plants (Cortois et al., 2016). In addition, studies on global climate regulation represented by the positive links between SBD and carbon storage in the soil were found for Germany (Dewitz et al., 2023; Dilly et al., 2005; Lange et al., 2015). For example, Lange et al. (2015) showed in "The Jena Experiment" (an experimental grassland area close to the city of Jena; Roscher et al., 2004) that a causal influence from higher plant diversity to more microbial activity and higher carbon storage exists. Higher carbon storage supports global climate regulation ES to combat climate change. Within the frame of the new European Union ecosystem restoration regulation (European Parliament, 2024), especially the focus on rewetting of peatlands is of increasing importance and the reduction of greenhouse gas emissions within the sectors of land use (change) and forestry (LULUCF sector). Here, the rewetting of formerly drained grassland is a delicate matter in finding the right balance between aerobic and anaerobic processes in the soil that either store or release carbon dioxide and other climate-relevant gasses (Gelbrecht et al., 2008).

Several German books, reports and publications also mentioned soil (rather in general and not SBD-specifically) as the regulating ES "maintaining nursery populations and habitats" (e.g., Amelung et al., 2018a; StMLU, 2006). In most of the cases, this regulating soil-ES was also linked to the cultural soil-ES environmental education (Table 1, "Soil for education") because the found literature was school curricula and textbooks.

Seed dispersal as regulating soil-ES by soil organisms had been studied in Germany, e.g., by Zaller & Saxler (2007) with earthworms (*Lumbricus terrestris*). The effects on seed dispersal were positive as well as negative due to a selective seed transport by earthworms, mainly dependent on the seed size (Eisenhauer & Scheu, 2008; Forey et al., 2011). Especially *Rumex obtusifolius* is transported by earthworms, which is a grassland weed throughout Europe (Zaller, 2004), but is also likely eaten by cattle (Zaller & Saxler, 2007). Therefore, it has a positive and negative connotation.

The evidence of positive and negative influences of SBD on regulating soil-ES within one study – either nationally or internationally – was shown by, e.g., Manici et al. (2013) for plant disease control and Zaller & Saxler (2007) for seed dispersal. Literature reviews have revealed positive and negative effects in a collection of studies, e.g.

by Wall et al. (2015) for biological pest control, Barber & Gorden (2015) for SBD-influenced plant–pollinator interactions, and Blanchart et al. (1999) for the effect of different earthworm species on infiltration (i.e., water regulation). The drivers of changing influences are related to varying environmental conditions, e.g. rainfall regime, soil regime or SBD composition, emphasizing the complexity of biotic and abiotic interactions within environmental regimes.

The positive impact of SBD on provisioning soil-ES is obvious for soil formation (material / biomass as provisioning soil-ES). In addition, positive impacts of SBD on provisioning soil-ES are apparent for mushroom picking, e.g. see Dörfelt et al. (2022) for Germany; Menta & Pinto (2016) and Pérez-Moreno (2021) for international literature. The higher the genetic diversity, the more variety of potentially edible mushrooms. In addition, the huge genetic material and, therefore, the genetic "treasure" in the soil could be used in the future in pharmaceutics and medicine (for Germany, e.g., Collins et al., 2023; for international literature, e.g., Hyman, 2019; Ling et al., 2015). For cultural soil-ES in relation to SBD, in most of the cases, soils were mentioned in a broader sense – in the international as well as Germany-focused literature. For Germany and cultural soil-ES, SBD can be specifically and positively linked to environmental education, e.g. by international touring exhibitions like "The thin skin of the earth - Our soils" which had about one million visitors at 15 locations in three European countries (e.g., Kucharzyk, 2022; Xylander, 2020, 2024; Xylander & Zumkowski-Xylander, 2018) and to "elements of living systems used for entertainment" such as the dance performances on ants by Ziv Frenkel, music on soil biodiversity loss by Kevin Mooney or the theater play "Critters" of the "Theatre of the Anthropocene" initiated by Frank Raddatz as well as paintings and video installations by Alexandra Toland (CICES Class 3.2.1.3, see chapter "Bodenbiodiversität" Eisenhauer et al, 2024b; Toland & Wessolek, 2009; Xylander, 2024. In TV, series and animated movies for kids, bees ("Biene Maja" or "Bee Movie"), ants ("Antz" or "Das große Krabbeln"), or moles ("Der kleine Maulwurf") are portrayed - animals related to soil. Furthermore, TV programmes in Germany like "Löwenzahn" or "Planet Wissen" were broadcasted during the last years, introducing various scientific phenomena related to soil functions and biodiversity to different target groups (Xylander, 2024). The Senckenberg Museum for Natural History Görlitz and the digital designers from .hapto (Cologne) developed a new digital immersive format to experience the virtual reality animation "Adventure Soil Life" where the user is "shrunk" to the size of a wood louse and can experience various soil habitats in a completely unknown approach (Wesenberg et al., 2019; Westermann et al., 2018; Xylander, 2019). About 70% of the users emphasized that they gained a deeper understanding for soil biodiversity by experiencing this digital format (Baber et al., 2019).

Regarding the cultural ES aesthetics (e.g., Feller et al., 2015; Ullrich, 2021) and soil as an archive (e.g., Köhler et al., 2018, 2019, 2020; Prud'homme et al., 2018), the identified links to SBD were positive and negative. For example, insects whose life cycle is partially in soils served as aesthetic objects in arts, such as the stag beetle (Ullrich, 2021). On the other hand, many people feel disgusted by the woodlouse, earthworm, and other organisms living on or in the ground (Gebhard, 2020). For example, Randler et al. (2013) tested the situational disgust of students while observing or dissecting species of different taxa during a seminar of animal anatomy at the University of Heidelberg. The authors could identify that among other organisms, woodlice and earthworms belonged to the most disgusting species and that the disgust was negatively related to the interest and competence of the students (= ecosystem disservice). This example shows that there can be connections between aesthetics, intellectual interaction, and environmental education. Other examples showed that there can be connections between cultural heritage, aesthetics, spiritual values, and entertainment / representation. For example, Dugan (2008) explored the use and interpretation of fungi as soil organisms in ancient rituals, folktales, poetry, and paintings on an international level. Similar connections can be found in Germany, e.g. for fly agaric (*Amanita muscaria*) and other mushrooms (Wagner, n.d.).

For soils as an archive, soil organisms can be markers in prehistoric sites (Amendt et al., 2020; Köhler et al., 2018, 2020; Prud'homme et al., 2019) or destroy historical or paleontological remnants in the soil (only international references: Cahn, 2023; Davidson, 2002). Oberreich et al. (2024) further subdivided soil as an archive into storage (i.e., the preservation of biological material), archaeological site (i.e., historically valuable archaeological sites), and reconstruction of the past (i.e., fossils and sediments for the reconstruction of paleoclimate).

An obvious cultural soil-ES with positive and negative links to SBD is "soil and soil biodiversity for science" (CICES Class 3.1.2.1), because every research that directly or indirectly investigates links between SBD and soil-ES can be regarded as objects of research. Authors might not have directly mentioned or identified the soil-ES as such. For example, the study by Oberreich et al. (2024) identified in the analyzed publications that authors rather use the term "ecosystem functions" than "ecosystem services" even though some soil functions could have been already regarded as soil-ES. Regarding recreation and tourism (CICES Classes 3.1.1.1, 3.1.1.2) as cultural

ES, direct links between SBD and soil-ES can only be detected when considering mushroom picking also as recreation ES (compare the references in Table 1 for "Wild plants, fungi and animals for nutrition, materials or energy"; CICES Class 1.1.5.1). In addition, soil in general has been mentioned in literature for recreation and tourism, e.g., the geoparks of the UNESCO (UNESCO, 2024) but also as part of exhibitions in museums and national park centers.

For some soil-ES, we could not find negative relations to SBD – for Germany as well as in the international context (see Table 1) – e.g., for the regulating ES of "Bioremediation", the provisioning ES "Material / Biomass", and the cultural ES "Spiritual, symbolic and other interactions", "Sport and recreation / Tourism", "Entertainment or representation" and "Non-use values and other cultural services". Regarding the cultural soil-ES, direct links are anyway difficult to quantify and the connotation of the terms, e.g., "entertainment" and "option values", are already positive. For example, if there would be a negative effect of SBD on "entertainment", it might not even be published. Motiejūnaitė et al. (2019) also mentioned that classifications and assessments of cultural soil-ES are rather focused on abiotic structures and processes (e.g., soil as spiritual value, soil management and garden work as physical experience) than on the biotic characteristics that lead to the ES provision.

Looking at specific below-ground species of the analyzed publications, especially earthworms (Lumbricidae) often seem to be in the focus of scientific soil studies nationally and internationally (e.g., see Eisenhauer, 2010; Ferlian et al., 2018; Fonte et al., 2023; Schaefer & Filser, 2007; Scheu, 2002; Schrader et al., 2020; Zaller & Saxler, 2007). However, even if the family of Lumbricidae is more studied than other below-ground taxa, influences of earthworms on soil-ES remain complex due to varying direct and indirect effects, e.g. on plants and soil, and differences in effects on soil-ES within earthworm groups in different soil types and conditions (e.g., Scheu, 2002).

4. Recommendations for further research needs – with a focus on Germany

Despite the huge role of SBD and soil for the supply of important ES for human well-being, the total amount of national and international studies remains rather small. For both, direct and indirect positive and negative links between SBD and soil-ES exist. Interestingly, mainly the negative aspects of SBD on ES seem to be unexplored, unpublished or nonexistent (Table 1). This finding could be also related to the tendency that mainly "positive" scientific results are published. However, Bakker et al. (2019) also identified in the 574 analyzed studies of forests in Europe that SBD is in general positively related to ES supply. In contrast, they mentioned that the links between SBD and cultural ES were better captured than the links to provisioning and regulating ES, which is rather the opposite to our findings and the publications, e.g., Oberreich et al. (2024), and Wirth et al. (2024b).

In many publications, the transition between ecosystem functions to ES is smooth and, terminologically, more often "ecosystem functions" or "intermediate ES" are described in the publications even though conceptually, the authors mean "ecosystem services" (see also Oberreich et al., 2024). It is often difficult to clearly separate soil functions from soil-ES because especially studies on regulating ES are part of ecosystem services and ecosystem functions. Furthermore, only few studies exist that directly quantify the benefits for society from SBD, ecosystem functions to several ecosystem services, e.g. Scherzinger et al. (2024).

Considering literature in Germany, in some cases, negative aspects of SBD were found on the international level but not for Germany, e.g., for erosion control, water flow regulation or pollination and seed dispersal (Table 1). This finding was identified across regulating, provisioning, and cultural soil-ES. In addition, some national and international references mentioned positive and negative aspects of SBD in one paper. For example, for mushrooms (CICES Groups 1.1.5, 1.1.6), the national source Dörfelt et al. (2022) as well as the international source Palandysz & Borovička (2013) identified both, positive and negative aspects. However, these findings are just tendencies that might be revised in a systematic literature review.

Even though many examples for environmental education (as cultural ES) have been identified in this study in relation to SBD, its implementation in schools, universities and the wider public seems to be marginal – at least in Germany. Public awareness of SBD needs to be strengthened even though the lacking awareness could be also interpreted as a lack of public interest or, in some cases, the negative image or disgust of particular soil organisms as we have described above. But – as often – disgust originates from alienation and lack of knowledge. Therefore, information and education on SBD and its multiple benefits and values for humanity should be communicated at all levels to improve the image and view on soil and soil life as an indispensable element of humankind´s benefits and survival. The increasing threats and losses of soil due to soil sealing, soil erosion, land degradation, and pollution are not least due to the lack of suitable appreciation of land.

Table 1. Overview of ecosystem services that are or can be influenced positively (= green) and / or negatively (= red) by soil biodiversity. The references are exemplarily (non-exhaustive) provided for Germany and on an international level (countries outside Germany) for comparison. Ecosystem services are listed here according to CICES version 5.1 (CICES = Common International Classification of Ecosystem Services). If only the CICES Group level is given, the literature does not allow a detailed distinction of the ecosystem services on class level.

Green = Positive influence of soil (as a system) or soil biodiversity on ecosystem service supply.

Red = Negative influence of soil (as a system) or soil biodiversity on ecosystem service supply.

Yellow = In general positive and / or negative influence of soil (as a system) or soil biodiversity on ecosystem service supply.

? = No suitable sources were found (within this rapid literature review).

“Soil in general” means that the focus is on interaction with abiotic processes.

Ecosystem service	CICES Class or Group	National references from Germany	International references
Regulating and maintenance soil-related ecosystem services			
Control of erosion	2.2.1.1	(Pérès et al., 2013)	(Burri et al., 2013; Le Bayon & Binet, 2001; Shuster et al., 2002)
		?	(Matthews & Wilson, 2005; Reichman & Seabloom, 2002)
Bioremediation	2.1.1.1, 2.1.1.2	(Schaefer & Filser, 2007)	(Bala et al., 2022; Dangi et al., 2019; Grenni et al., 2009; Kayalvizhi & Kathiresan, 2019)
		?	?
Water flow regulation	2.2.1.3	(Amelunget al., 2018b; Botschek et al., 2002)	(Huang et al., 2024)
		?	(Mao et al. 2018)
Pollination and seed dispersal	2.2.2.1, 2.2.2.2	(Hausmann et al., 2016; Zaller & Saxler, 2007)	(Barber & Gorden, 2015; Carvalheiro et al., 2021; Christmann, 2022; Lengyel et al., 2010; Rostás & Tautz, 2011)
		?	(Barber & Gorden 2015)
Maintaining nursery populations and habitats	2.2.2.3	(Amelung et al. 2018a; Eisenhauer, 2010; StMLU, 2006)	(Boll & Leal-Zanchet, 2015; Carvalheiro et al., 2021; Christmann, 2022)
		(Eisenhauer, 2010)	(Boag & Yeates, 2001; Ferlian et al., 2018)
Pest control and disease control for plants and livestock	2.2.3.1, 2.2.3.2	Plants: (Meyer-Wolfarth et al., 2017)	Plants: (Compant et al., 2005; Corato, 2020; Crowder & Jabbour, 2014; Letourneau et al., 2009; Northfield et al., 2013)
		Plants: (Koenig & Huth, 2003; Manici et al., 2013)	Plants: (Fisher et al., 2012; Leroux et al., 2002; Wall et al., 2015); Livestock: (Hugh-Jones & Blackburn, 2009; Wall et al., 2015): Wildlife: (Fisher et al., 2012)
Disease control for humans	2.2.3.2	(Schierstaedt et al., 2020)	(Hanski et al., 2012; Ling et al., 2015; Pepper et al., 2009)
		(Ehrmann et al., 2018; Lahiri et al., 2014)	(Brooker et al., 2006; Jourdan et al., 2018; Wall et al., 2015)

Ecosystem service	CICES Class or Group	National references from Germany	International references
Regulating and maintenance soil-related ecosystem services			
Regulation of soil quality	2.2.4.1, 2.2.4.2	(Cesarz et al., 2017; Cortois et al., 2016; Eisenhauer et al., 2012; Leimer et al., 2016; Plaas et al., 2019; Schrader et al., 2020)	(Bender & van der Heijden, 2015; Delgado-Baquerizo et al., 2016; Sofo et al., 2020; van der Heijden et al., 2008; Vries & Wallenstein, 2017)
		When temperature rises: (Lang & Luster, 2022)	(Blouin et al., 2007; Wijnhoven et al., 2006)
Water filtration / Regulation of water quality	2.2.5.1, 2.2.5.2	(Andriuzzi et al., 2015; Bandowe et al., 2019; Leimer et al., 2016)	(Blanchart et al., 1999; Frankenberger & Arshad, 2001; Kayalvizhi & Kathiresan, 2019)
		?	(Blanchart et al., 1999; Mao et al., 2019; Wijnhoven et al., 2006)
Global climate regulation	2.2.6.1	(Dewitz et al., 2023; Dilly et al., 2005; Don et al., 2008; Lange et al., 2015)	(Creamer et al., 2016; Crowther et al., 2019; Graaff et al., 2015; Minasny et al., 2017; Rillig, 2004)
		(Karsten & Drake, 1997)	(Lubbers et al., 2013; Schädel et al., 2016)
Micro and regional climate regulation & Ventilation and transpiration	2.2.6.2	(Huang et al., 2024)	?
		?	(Couradeau et al., 2016)
Provisioning soil-related ecosystem services			
Cultivated terrestrial plants for nutrition, materials or energy	1.1.1	See „Regulation of soil quality“ (CICES 2.2.4.1, 2.2.4.2)	
Wild plants, fungi and animals (terrestrial and aquatic) for nutrition, materials or energy	1.1.5, 1.1.6	(Dörfelt et al., 2022)	Mushrooms: (Falandysz & Borovička, 2013; Menta & Pinto, 2016; Pérez-Moreno, 2021; Uprety et al., 2012; Yun & Hall, 2004); Insects: (Belluco et al., 2013; Nicholas B. Comerford et al., 2013; Del Toro et al., 2012; Paoletti et al., 2000; van Huis, 2003)
		(Dörfelt et al., 2022)	Mushrooms: (Falandysz & Borovička, 2013; Motiejūnaitė et al., 2019; Persson, 2016)
Genetic material	1.2.1	(Collins et al., 2023)	(Hyman, 2019; Ling et al., 2015; Mergeay et al., 2003; Pepper et al., 2009; Riesenfeld et al., 2004; Yamaki et al., 1994)
		(Leroch et al., 2013; Peters et al., 2014)	(Leroux et al., 2002)
Surface water, groundwater and freshwater for drinking, energy and material (water storage and water provision)	4.2.1	(Overholt et al., 2022)	(Blanchart et al., 1999; Overholt et al., 2022)
		?	(Blanchart et al., 1999; Blouin et al., 2007; Mao et al., 2019)
Material/Biomass	4.3.1, 4.3.2	Soil in general (Amelung, et al., 2018b) For soil organic matter, see also „Regulation of soil quality“ (CICES 2.2.4.1, 2.2.4.2) and soil organic carbon (Global climate regulation, CICES 2.2.6.1)	(Angst et al., 2024; Zanella et al., 2018); Soil in general (Comerford et al., 2013; Mumtaz et al., 2019)
		?	?

Ecosystem service	CICES Class or Group	National references from Germany	International references
Provisioning soil-related ecosystem services			
Foundation / Basis for infrastructure	-	(Morel et al., 2015)	(Dominati et al., 2010; O'Riordan et al., 2021)
		?	(Matthews & Wilson, 2005; Reichman & Seabloom, 2002)
Cultural soil-related ecosystem services			
Physical and experiential interactions	3.1.1.	(AGUM, 2024; Bundesverband Boden e.V., 2024; Senckenberg Museum für Naturkunde Görlitz, 2024) and Table 8.6 in (Wirth et al., 2024a)	(Bere & Westersjø, 2013; Brevik & Burgess, 2013; Kecinski et al., 2018; Motiejūnaitė et al., 2019)
		?	(Brevik & Burgess, 2013; Kecinski et al., 2018)
Sport and recreation / Tourism	3.1.1.1, 3.1.1.2	Soil in general: (Bundesverband Boden e.V., 2024; BvBoden – Bundesverband Boden e. V., 2023)	Soil in general: (Motiejūnaitė et al., 2019; UNESCO, 2024); Mushroom picking as activity: (Bere & Westersjø, 2013); see also CICES 1.1.5.1
		?	?
Intellectual and representative/emotional interactions	3.1.2	(AGUM, 2024; Milbert, 2024; Senckenberg Museum für Naturkunde Görlitz, 2024; Xylander, 2020) and Table 8.6 in Wirth et al. (2024a)	(Brevik et al., 2018; Craig et al., 2016; FAO, 2024; Hanyu et al., 2014; Motiejūnaitė et al., 2019)
		(Gebhard, 2020; Ullrich, 2021)	(Brevik et al., 2018; Cooper et al., 2012; Craig et al., 2016; Polák et al., 2020)
Soil as archive	3.1.2	Soil biodiversity: (Amendt et al., 2020; Dlussky & Wedmann, 2012; Köhler et al., 2018, 2019, 2020; Moine et al., 2017; Prud'homme et al., 2015, 2016, 2018); Soil: (Acksel et al., 2016; Acksel et al., 2019; Maxwell et al., 2016; Morel et al., 2015)	Soil biodiversity: (Prud'homme et al., 2018); Soil: (Acksel et al., 2019)
		?	Soil biodiversity: (Cahn, 2023; Davidson, 2002; Motiejūnaitė et al., 2019; Tryon, 2006; Walimbe, 2021)
Soil and soil biodiversity for science	3.1.2.1	All scientific studies related to soil/soil biodiversity	
Soil for education	3.1.2.2	(AGUM, 2024; Beugnon et al., 2024; BvBoden – Bundesverband Boden e. V., 2023; Kucharzyk, 2022; Senckenberg Museum für Naturkunde Görlitz, 2024; StMLU, 2006; Xylander, 2020; Xylander & Zumkowski-Xylander, 2018) and Table 8.6 in (Wirth et al., 2024a)	(Beugnon et al., 2024; ICBA, 2025; Motiejūnaitė et al., 2019; Paoletti et al., 2000); Soil: (FAO, 2024; ISRIC, 2025)
		(Randler et al., 2013)	?
Culture or heritage	3.1.2.3	(Acksel et al., 2016; Köhler et al., 2018, 2019)	Soil in general: (Brevik et al., 2016; Feller et al., 2015; Landa et al., 2009); Mushrooms: (Dugan, 2008; Yamin-Pasternak, 2008)
		?	(Zucconi et al., 2022)

Ecosystem service	CICES Class or Group	National references from Germany	International references
Cultural soil-related ecosystem services			
Aesthetic	3.1.2.4	Soil in general: (BvBoden – Bundesverband Boden e. V., 2023; Feller et al., 2015; Toland & Wessolek, 2009; Ullrich, 2021); Insects whose life cycle can be partially in soils: Ullrich, 2021	(Feller et al., 2015; Motiejūnaitė et al., 2019)
		(Gebhard, 2020; Randler et al., 2013)	Disgust: see CICES 3.1.2, (Dugan, 2008; Polák et al., 2020)
Spiritual, symbolic and other interac-tions	3.2.1.1, 3.2.1.2	Soil in general: (Feller et al., 2015; Toland & Wessolek, 2009; Wagner, n.d.); Mushrooms: (Wagner, n.d.)	(Comerford et al., 2013; Dugan, 2008; Motiejūnaitė et al., 2019; Pérez-Moreno, 2021; Yamin-Pasternak, 2008)
		?	?
Entertainment or representation	3.2.1.3	(NABU, n.d.) Soil in general: (AGUM, 2024; Kucharzyk, 2022; Milbert, 2024; Senckenberg Museum für Naturkunde Görlitz, 2024; Xylander & Zumkowski-Xylander, 2018), and Table 8.6 in Wirth et al. (2024a)	(Feller et al., 2015; Motiejūnaitė et al., 2019); Soil in general: (FAO, 2024)
		?	?
Non-use values and other cultural services	3.2.2.1, 3.2.2.2	(Xylander, 2020)	(Decaëns et al., 2006; Motiejūnaitė et al., 2019; Phillips et al., 2020)
		?	?

Considering potential uncertainties in our findings, it should be mentioned that the aim of this literature review was not to be exhaustive or complete, but to get an idea about knowledge and research gaps on the national level in Germany in comparison to internationally available peer-reviewed literature. The type of a literature review depends, among others, on the scale, scope, the definition of terms and, therefore, the differentiation between the terms (setting the boundary of investigation), and the used search terms in the query (Grant & Booth, 2009). Still, it is striking that more than half of all species in the world are found in the soil (Anthony et al., 2023), but the share of globally published peer-reviewed research on SBD remains marginal.

5. Conclusion

The analysis of the causal chain (ES cascade) from SBD via soil communities, soil structures, soil functions to soil-related ES and values for people is challenging: 1) due to the multiple interactions with the biosphere, pedosphere, atmosphere, and anthroposphere, 2) the indirect influences and interactions that are not easy to measure, and 3) lack of respective data and monitoring programs. Therefore, the complexity of data collection and analysis is already a huge challenge. However, more ambitious studies should be encouraged, e.g. by funding respective science and education programs. In view of data collection, monitoring and analysis, (physical) soil science and soil ecology should work more integrative in the future in order to merge efforts and resources.

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References

Acksel, A., Amelung, W., Kühn, P., Gehrt, E., Regier, T., & Leinweber, P. (2016). Soil organic matter characteristics as indicator of Chernozem genesis in the Baltic Sea region. Geoderma Regional, 7(2), 187–200. https://doi.org/10.1016/j.geodrs.2016.04.001

Acksel, A., Baumann, K., Hu, Y., & Leinweber, P. (2019). A Look into the Past: Tracing Ancient Sustainable Manuring Practices by Thorough P Speciation of Northern European. Soil Systems. https://doi.org/10.3390/soilsystems3040072

Adhikari, K., & Hartemink, A. E. (2016). Linking soils to ecosystem services—A global review. Geoderma.

AGUM. (2024). Arbeitsgemeinschaft der Umweltmobile (AGUM). https://www.umweltmobile.de/

Amelung, W., Blume, H.-P., Fleige, H., Horn, R., & Kandeler, E. 2018a. Bodenorganismen und ihr Lebensraum: In: W. Amelung, H.-P. Blume, H. Fleige, R. Horn, E. Kandeler, I. Kögel-Knabner, R. Kretzschmar, K. Stahr, B.-M. Wilke (Eds.): Lehrbuch der Bodenkunde.

Amelung, W., Blume, H.-P., Fleige, H., Horn, R., Kandeler, E., Kögel-Knabner, I., Kretzschmar, R., Stahr, K., & Wilke, B. 2018b. Bodenentwicklung und Bodensystematik: In: W. Amelung, H.-P. Blume, H. Fleige, R. Horn, E. Kandeler, I. Kögel-Knabner, R. Kretzschmar, K. Stahr, B.-M. Wilke (Eds.): Lehrbuch der Bodenkunde.

Amendt, J., Zissler, A., Lutz, L., Szelecz, I., Habermann, A., & Pittner, S. (2020). Interdisziplinarität in der Forensik. Biologie in Unserer Zeit, 50(1), 58–64. https://doi.org/10.1002/biuz.202010698

Andriuzzi, W. S., Pulleman, M. M., Schmidt, O., Faber, J. H., & Brussaard, L. (2015). Anecic earthworms (Lumbricus terrestris) alleviate negative effects of extreme rainfall events on soil and plants in field mesocosms. Plant Soil, 397(1-2), 103–113. https://doi.org/10.1007/s11104-015-2604-4

Angst, G., Potapov, A., Joly, F.-X., Angst, Š., Frouz, J., Ganault, P., & Eisenhauer, N. (2024). Conceptualizing soil fauna effects on labile and stabilized soil organic matter. Nature Communications, 15(1), 5005. https://doi.org/10.1038/s41467-024-49240-x

Anthony, M. A., Bender, S. F., & van der Heijden, M. (2023). Enumerating soil biodiversity. Proceedings of the National Academy of Sciences of the United States of America, 120(33), e2304663120. https://doi.org/10.1073/pnas.2304663120

Antoine, C. M., & Forrest, J. R. (2021). Nesting habitat of ground-nesting bees: a review. Ecological Entomology, 46(2), 143–159. https://doi.org/10.1111/een.12986

Baber, K., Wesenberg, J., & Xylander, W.E.R. (2019). Perzeption und Evaluierung von Virtual Reality (VR) – Formaten im Naturkundemuseum. Natur Im Museum(9), 37–39.

Bakker, M. R., Brunner, I., Ashwood, F., Bjarnadottir, B., Bolger, T., Børja, I., Carnol, M., Cudlin, P., Dalsgaard, L., Erktan, A., Godbold, D., Kraigher, H., Meier, I. C., Merino-Martín, L., Motiejūnaitė, J., Mrak, T., Oddsdóttir, E. S., Ostonen, I., Pennanen, T. L., . . . Soudzilovskaia, N. A. (2019). Belowground Biodiversity Relates Positively to Ecosystem Services of European Forests. Frontiers in Forests and Global Change, 2, Article 6. https://doi.org/10.3389/ffgc.2019.00006

Bala, S., Garg, D., Thirumalesh, B. V., Sharma, M., Sridhar, K., Inbaraj, B. S., & Tripathi, M. (2022). Recent Strategies for Bioremediation of Emerging Pollutants: A Review for a Green and Sustainable Environment. Toxics, 10(8). https://doi.org/10.3390/toxics10080484

Bandowe, B. A. M., Leimer, S. Meusel, H., Velescu, A., Dassen, S., Eisenhauer, N., Hoffmann, T., Oelmann, Y., & Wilcke, W. (2019). Plant diversity enhances the natural attenuation of polycyclic aromatic compounds (PAHs and oxygenated PAHs) in grassland soils. Soil Biology and Biochemistry, 129, 60–70. https://doi.org/10.1016/j.soilbio.2018.10.017

Banerjee, S., & van der Heijden, M. G. A. (2023). Soil microbiomes and one health. Nature Reviews. Microbiology, 21(1), 6–20. https://doi.org/10.1038/s41579-022-00779-w

Barber, N. A., & Gorden, N. (2015). How do belowground organisms influence plant-pollinator interactions? Journal of Plant Ecology, 8(1), 1–11. https://doi.org/10.1093/jpe/rtu012

Belluco, S., Losasso, C., Maggioletti, M., Alonzi, C. C., Paoletti, Maurizio, G., & Ricci, A. (2013). Edible Insects in a Food Safety and Nutritional Perspective: A Critical Review. Comprehensive Reviews in Food Science and Food Safety, 12(3), 296–313. https://doi.org/10.1111/1541-4337.12014

Bender, S. F., & van der Heijden, M. G. A. (2015). Soil biota enhance agricultural sustainability by improving crop yield, nutrient uptake and reducing nitrogen leaching losses. Journal of Applied Ecology. https://doi.org/10.1111/1365-2664.12351

Bere, E., & Westersjø, J. H. (2013). Nature trips and traditional methods for food procurement in relation to weight status. Scandinavian Journal of Public Health, 41(2), 180–184. https://doi.org/10.1177/1403494812471446

Berkes, F., & Folke, C. (1998). Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience. Cambridge University Press.

Bethwell, C., Burkhard, B., Daedlow, K., Sattler, C., Reckling, M., & Zander, P. (2021). Towards an enhanced indication of provisioning ecosystem services in agro-ecosystems. Environmental Monitoring and Assessment, 193(Suppl 1), 269. https://doi.org/10.1007/s10661-020-08816-y

Beugnon, R., Zeiss, R., Bönisch, E., Phillips, H. R. P., & Jochum, M. (2024). Communicating soil biodiversity research to kids around the world. https://doi.org/10.25674/413

Blanchart, E., Alain, A., Alegre, J. C., & Duboisset, A. (Eds.). (1999). Effects of earthworms on soil structure and physical properties: In: P. Lavelle, L. Brussaard, P. Hendrix (Eds.): Earthworm management in tropical agroecosystems. CABI Publishing.

Blouin, M., Lavelle, P., & Laffray, D. (2007). Drought stress in rice (Oryza sativa L.) is enhanced in the presence of the compacting earthworm Millsonia anomala. Environmental and Experimental Botany, 60(3), 352–359. https://doi.org/10.1016/j.envexpbot.2006.12.017

Boag, B., & Yeates, G. W. (2001). THE POTENTIAL IMPACT OF THE NEW ZEALAND FLATWORM, A PREDATOR OF EARTHWORMS, IN WESTERN EUROPE. Ecological Applications, 11(5), 1276–1286. https://doi.org/10.1890/1051-0761(2001)011[1276:TPIOTN]2.0.CO;2

Boll, P. K., & Leal-Zanchet, A. M. (2015). Predation on invasive land gastropods by a Neotropical land planarian. Journal of Natural History, 49(17-18), 983–994. https://doi.org/10.1080/00222933.2014.981312

Booth, A., Sutton, A., Papaioannou, D. (2012). Systemativ Approaches to a Successful Literature Review. https://www.researchgate.net/publication/235930866_Systematic_Approaches_to_a_Successful_Literature_Review

Botschek, J., Krause, S., Abel, T., & Skowronek, A. (2002). Hydrological parameterization of piping in loess-rich soils in the Bergisches Land, Nordrhein-Westfalen, Germany. Journal of Plant Nutrition and Soil Science, 165(4), 506. https://doi.org/10.1002/1522-2624(200208)165:4<506::AID-JPLN506>3.0.CO;2-7

Brevik, E. C., & Burgess, L. C. (Eds.). (2013). Human contact with plants and soils for health and well-being. In: Heckman, J. R. (Eds.): Soils and Human Health. CRC Press. Boca Raton.

Brevik, E. C., Fenton, T. E., & Homburg, J. A. (2016). Historical highlights in American soil science — Prehistory to the 1970s. CATENA, 146, 111–127. https://doi.org/10.1016/j.catena.2015.10.003

Brevik, E. C., Pereg, L., Steffan, J. J., & Burgess, L. C. (2018). Soil ecosystem services and human health. Current Opinion in Environmental Science & Health, 5, 87–92. https://doi.org/10.1016/j.coesh.2018.07.003

Brevik, E. C., & Sauer, T. J. (2015). The past, present, and future of soils and human health studies. SOIL, 1(1), 35–46. https://doi.org/10.5194/soil-1-35-2015

Brooker, S., Clements, A. C. A., & Bundy, D. A. P. (Eds.). (2006). Global Epidemiology, Ecology and Control of Soil-Transmitted Helminth Infections: In: S. I. Hay, A. Graham, D. J. Rogers (Eds.): Advances in Parasitology. Global Mapping of Infectious Diseases: Methods, Examples and Emerging Applications. Academic Press.

Bundesverband Boden e.V. (2024). Bodenerlebnispfade. https://www.bvboden.de/links/bodenerlebnispfade

Burri, K., Gromke, C., & Graf, F. (2013). MYCORRHIZAL FUNGI PROTECT THE SOIL FROM WIND EROSION: A WIND TUNNEL STUDY. Land Degradation & Development, 24(4), 385–392. https://doi.org/10.1002/ldr.1136

BvBoden – Bundesverband Boden e. V. (2023). Bundesverband Boden e. V. https://www.bvboden.de/

Cahn, L. (2023). Volume 4. Anthropocenes – Human, Inhuman, Posthuman, 4(1). https://doi.org/10.16997/ahip.1435

Carvalheiro, L. G., Bartomeus, I., Rollin, O., Timóteo, S., & Tinoco, C. F. (2021). The role of soils on pollination and seed dispersal. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 376(1834), 20200171. https://doi.org/10.1098/rstb.2020.0171

Cesarz, S., Ciobanu, M., Wright, A. J., Ebeling, A., Vogel, A., Weisser, W. W., & Eisenhauer, N. (2017). Plant species richness sustains higher trophic levels of soil nematode communities after consecutive environmental perturbations. Oecologia, 184(3), 715–728. https://doi.org/10.1007/s00442-017-3893-5

Christmann, S. (2022). Regard and protect ground-nesting pollinators as part of soil biodiversity. Ecological Applications : A Publication of the Ecological Society of America, 32(3), e2564. https://doi.org/10.1002/eap.2564

Collins, G., Schneider, C., Boštjančić, L. L., Burkhardt, U., Christian, A., Decker, P., Ebersberger, I., Hohberg, K., Lecompte, O., Merges, D., Muelbaier, H., Romahn, J., Römbke, J., Rutz, C., Schmelz, R., Schmidt, A., Theissinger, K., Veres, R., Lehmitz, R., . . . Bálint, M. (2023). The MetaInvert soil invertebrate genome resource provides insights into below-ground biodiversity and evolution. Communications Biology, 6(1), 1241. https://doi.org/10.1038/s42003-023-05621-4

Comerford, N. B., Franzluebbers, A. J., Stromberger, M. E., Morris, L., Markewitz, D., & Moore, R. (2013). Assessment and evaluation of soil ecosystem services. Soil Horizons(54 (3)), 1–14. https://doi.org/10.2136/sh12-10-0028

Compant, S., Duffy, B., Nowak, J., Clément, C., & Barka, E. A. (2005). Use of plant growth-promoting bacteria for biocontrol of plant diseases: Principles, mechanisms of action, and future prospects. Applied and Environmental Microbiology, 71(9), 4951–4959. https://doi.org/10.1128/AEM.71.9.4951-4959.2005

Cooper, E. L., Balamurugan, M., Huang, C.-Y., Tsao, C. R., Heredia, J., Tommaseo-Ponzetta, M., & Paoletti, M. G. (2012). Earthworms dilong: Ancient, inexpensive, noncontroversial models may help clarify approaches to integrated medicine emphasizing neuroimmune systems. Evidence-Based Complementary and Alternative Medicine : ECAM, 2012, 164152. https://doi.org/10.1155/2012/164152

Corato, U. de (2020). Disease-suppressive compost enhances natural soil suppressiveness against soil-borne plant pathogens: A critical review. Rhizosphere, 13, 100192. https://doi.org/10.1016/j.rhisph.2020.100192

Cortois, R., Schröder-Georgi, T., Weigelt, A., van der Putten, W. H., & Deyn, G. B. de (2016). Plant–soil feedbacks: role of plant functional group and plant traits. Journal of Ecology, 104(6), 1608–1617. https://doi.org/10.1111/1365-2745.12643

Couradeau, E., Karaoz, U., Lim, H. C., Da Nunes Rocha, U., Northen, T., Brodie, E., & Garcia-Pichel, F. (2016). Bacteria increase arid-land soil surface temperature through the production of sunscreens. Nature Communications, 7, 10373. https://doi.org/10.1038/ncomms10373

Craig, J. M., Logan, A. C., & Prescott, S. L. (2016). Natural environments, nature relatedness and the ecological theater: Connecting satellites and sequencing to shinrin-yoku. Journal of Physiological Anthropology, 35, 1. https://doi.org/10.1186/s40101-016-0083-9

Creamer, R. E., Hannula, S. E., Leeuwen, J. P. V., Stone, D., Rutgers, M., Schmelz, R. M., Ruiter, P. C. de, Hendriksen, N. B., Bolger, T., Bouffaud, M. L., Buee, M., Carvalho, F., Costa, D., Dirilgen, T., Francisco, R., Griffiths, B. S., Griffiths, R., Martin, F., Da Silva, P. M., & … Lemanceau, P. (2016). Ecological network analysis reveals the inter-connection between soil biodiversity and ecosystem function as affected by land use across Europe. Applied Soil Ecology(97), 112–114. https://doi.org/10.1016/j.apsoil.2015.08.006

Crowder, D. W., & Jabbour, R. (2014). Relationships between biodiversity and biological control in agroecosystems: Current status and future challenges. Biological Control, 75, 8–17. https://doi.org/10.1016/j.biocontrol.2013.10.010

Crowther, T. W., van den Hoogen, J., Wan, J., Mayes, M. A., Keiser, A. D., Mo, L., Averill, C., & Maynard, D. S. (2019). The global soil community and its influence on biogeochemistry. Science, 365(6455). https://doi.org/10.1126/science.aav0550

Dangi, A. K., Sharma, B., Hill, R. T., & Shukla, P. (2019). Bioremediation through microbes: Systems biology and metabolic engineering approach. Critical Reviews in Biotechnology, 39(1), 79–98. https://doi.org/10.1080/07388551.2018.1500997

Davidson, D. A. (2002). Bioturbation in Old Arable Soils: Quantitative Evidence from Soil Micromorphology. Journal of Archaeological Science, 29(11), 1247–1253. https://doi.org/10.1006/jasc.2001.0755

Decaëns, T., Jiménez, J. J., Gioia, C., Measey, G. J., & Lavelle, P. (2006). The values of soil animals for conservation biology. European Journal of Soil Biology, 42, S23-S38. https://doi.org/10.1016/j.ejsobi.2006.07.001

Del Toro, I., Ribbons, R. R., & Pelini, S. L. (2012). The little things that run the world revisited: a review of ant-mediated ecosystem services and disservices (Hymenoptera: Formicidae). Myrmecological News(17), 133–146.

Delgado-Baquerizo, M., Maestre, F. T., Reich, P. B., Jeffries, T. C., Gaitan, J. J., Encinar, D., Berdugo, M., Campbell, C. D., & Singh, B. K. (2016). Microbial diversity drives multifunctionality in terrestrial ecosystems. Nature Communications, 7, 10541. https://doi.org/10.1038/ncomms10541

Dewitz, I., Wenz, K., Hüpperling, S., & Peters, J. (Eds.). (2023). Mooratlas. Daten und Fakten zu nassen Klimaschützern. Ein Kooperationsprojekt von Heinrich-Böll-Stiftung, Bund für Umwelt und Naturschutz Deutschland und der Michael Succow Stiftung, Partner im Greifswald Moor Centrum. Heinrich-Böll-Stiftung.

Dilly, O., Gnaß, A., & Pfeiffer, E.-M. (2005). Humus accumulation and microbial activities in calcari-epigleyic fluvisols under grassland and forest diked in for 30 years. Soil Biology and Biochemistry, 37(11), 2163–2166. https://doi.org/10.1016/j.soilbio.2005.03.014

Dlussky, G. M., & Wedmann, S. (2012). The poneromorph ants (Hymenoptera, Formicidae: Amblyoponinae, Ectatomminae, Ponerinae) of Grube Messel, Germany: high biodiversity in the Eocene. Journal of Systematic Palaeontology, 10(4), 725–753. https://doi.org/10.1080/14772019.2011.628341

Dominati, E., Patterson, M., & Mackay, A. (2010). A framework for classifying and quantifying the natural capital and ecosystem services of soils. Ecological Economics, 69(9), 1858–1868. https://doi.org/10.1016/j.ecolecon.2010.05.002

Don, A., Steinberg, B., Schöning, I., Pritsch, K., Joschko, M., Gleixner, G., & Schulze, E.-D. (2008). Organic carbon sequestration in earthworm burrows. Soil Biology and Biochemistry, 40(7), 1803–1812. https://doi.org/10.1016/j.soilbio.2008.03.003

Dörfelt, H., Ruske, E., & Kästner, A. (Eds.). (2022). Pilze heute und früher: In: H. Dörfelt, E. Ruske & A. Kästner (Eds.): Die Welt der Pilze. Springer.

Dugan, F. (2008). Fungi, folkways and fairy tales: mushrooms & mildews in stories, remedies & rituals, from Oberon to the Internet. North American Fungi, 23–72. https://doi.org/10.2509/naf2008.003.0074

Ehrmann, S., Ruyts, S. C., Scherer-Lorenzen, M., Bauhus, J., Brunet, J., Cousins, S. A. O., Deconchat, M., Decocq, G., Frenne, P. de, Smedt, P. de, Diekmann, M., Gallet-Moron, E., Gärtner, S., Hansen, K., Kolb, A., Lenoir, J., Lindgren, J., Naaf, T., Paal, T., . . . Liira, J. (2018). Habitat properties are key drivers of Borrelia burgdorferi (s.L.) prevalence in Ixodes ricinus populations of deciduous forest fragments. Parasites & Vectors, 11(1), 23. https://doi.org/10.1186/s13071-017-2590-x

Ehwald, E. (1964). Entwicklungslinien in der Geschichte der Bodenkunde: Berli (Ed.) 1964 – Albrecht-Thaer-Archiv Band 8. In D. A. d. L. z. Berli (Ed.), Albrecht-Thaer-Archiv Band 8, Heft 1-3 (pp. 5–36). De Gruyter. https://doi.org/10.1515/9783112653869-003

Eisenhauer, N. (2010). The action of an animal ecosystem engineer: Identification of the main mechanisms of earthworm impacts on soil microarthropods. Pedobiologia, 53(6), 343–352. https://doi.org/10.1016/j.pedobi.2010.04.003

Eisenhauer, N., Frank, K., Weigelt, A., Bartkowski, B., Beugnon, R., Liebal, K., Mahecha, M., Quaas, M., Al-Halbouni, D., Bastos, A., Bohn, F. J., Brito, M. M. de, Denzler, J., Feilhauer, H., Fischer, R., Fritsche, I., Guimaraes-Steinicke, C., Hänsel, M., Haun, D. B. M., . . . Quaas, J. (2024a). A belowground perspective on the nexus between biodiversity change, climate change, and human well-being. Journal of Sustainable Agriculture and Environment, 3(2), Article e212108. https://doi.org/10.1002/sae2.12108

Eisenhauer, N., Reich, P. B., & Isbell, F. (2012). Decomposer diversity and identity influence plant diversity effects on ecosystem functioning. Ecology, 93(10), 2227–2240. https://doi.org/10.1890/11-2266.1

Eisenhauer, N., Ristok, C., Guerra, C. A., Tebbe, C. C., Xylander, W., Babin, D., Bartkowski, B., Burkhard, B., Filser, J., Glante, F., Hohberg, K., Kleemann, J., Kolb, S., Lachmann, C., Lehmitz, R., Rillig, M., Römbke, J., Rueß, L., Scheu, S., . . . et al. (Eds.). (2024b). Bodenbiodiversität: In: Wirth, C.; Bruelheide, H.; Farwig, N.; Marx, J.; Settele, J. (Eds.); Faktencheck Artenvielfalt. Bestandsaufnahme und Perspektiven für den Erhalt der biologischen Vielfalt in Deutschland. Oekom.

Eisenhauer, N., & Scheu, S. (2008). Invasibility of experimental grassland communities: The role of earthworms, plant functional group identity and seed size. Oikos, 117(7), 1026–1036. https://doi.org/10.1111/j.0030-1299.2008.16812.x

European Commission (2006). Communication: Thematic strategy for soil protection. https://eur-lex.europa.eu/EN/legal-content/summary/thematic-strategy-for-soil-protection.html

European Parliament. (2024). REGULATION (EU) 2024/1991 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 24 June 2024 on nature restoration and amending Regulation (EU) 2022/869. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202401991

Falandysz, J., & Borovička, J. (2013). Macro and trace mineral constituents and radionuclides in mushrooms: Health benefits and risks. Applied Microbiology and Biotechnology, 97(2), 477–501. https://doi.org/10.1007/s00253-012-4552-8

FAO (2020). State of Knowledge of Soil Biodiversity. Status, challenges and potentialities. Report 2020. https://doi.org/10.4060/cb1928en

FAO. (2024). World Soil Day, 5 December. https://www.fao.org/world-soil-day/en/

Feller, C., Landa, E. R., Toland, A., & Wessolek, G. (2015). Case studies of soil in art. SOIL, 1(2), 543–559. https://doi.org/10.5194/soil-1-543-2015

Ferlian, O., Eisenhauer, N., Aguirrebengoa, M., Camara, M., Ramirez-Rojas, I., Santos, F., Tanalgo, K., & Thakur, M. P. (2018). Invasive earthworms erode soil biodiversity: A meta-analysis. The Journal of Animal Ecology, 87(1), 162–172. https://doi.org/10.1111/1365-2656.12746

Fisher, M. C., Henk, D. A., Briggs, C. J., Brownstein, J. S., Madoff, L. C., McCraw, S. L., & Gurr, S. J. (2012). Emerging fungal threats to animal, plant and ecosystem health. Nature, 484(7393), 186–194. https://doi.org/10.1038/nature10947

Fonte, S. J., Hsieh, M., & Mueller, N. D. (2023). Earthworms contribute significantly to global food production. Nature Communications, 14(1), 5713. https://doi.org/10.1038/s41467-023-41286-7

Forey, E., Barot, S., Decaëns, T., Langlois, E., Laossi, K.-R., Margerie, P., Scheu, S., & Eisenhauer, N. (2011). Importance of earthworm–seed interactions for the composition and structure of plant communities: A review. Acta Oecologica, 37(6), 594–603. https://doi.org/10.1016/j.actao.2011.03.001

Frankenberger, W. T., & Arshad, M. (2001). Bioremediation of selenium-contaminated sediments and water. BioFactors (Oxford, England), 14(1-4), 241–254. https://doi.org/10.1002/biof.5520140130

Fu, B.-J., Su, C.-H., Wei, Y.-P., Willett, I. R., Lü, Y.-H., & Liu, G.-H. (2011). Double counting in ecosystem services valuation: causes and countermeasures. Ecological Research, 26(1), 1–14. https://doi.org/10.1007/s11284-010-0766-3

Gebhard, U. (2020). Angst und Ekel vor Tieren.: Gebhard, U. (Ed.): Kind und Natur. Die Bedeutung der Natur für die psychische Entwicklung. Springer.

Gelbrecht, J., Zak, D., & Augustin, J. (2008). PHOSPHOR- UND KOHLENSTOFF-DYNAMIK UND VEGETATIONSENTWICKLUNG IN WIEDERVERNÄSSTEN MOOREN DES PEENETALS IN MECKLENBURG VORPOMMERN. https://www.igb-berlin.de/sites/default/files/media-files/download-files/IGB-Bericht-26.pdf

Graaff, M.-A. de, Adkins, J., Kardol, P., & Throop, H. L. (2015). A meta-analysis of soil biodiversity impacts on the carbon cycle. SOIL, 1(1), 257–271. https://doi.org/10.5194/soil-1-257-2015

Grant, M. J., & Booth, A. (2009). A typology of reviews: An analysis of 14 review types and associated methodologies. Health Information and Libraries Journal, 26(2), 91–108. https://doi.org/10.1111/j.1471-1842.2009.00848.x

Grenni, P., Gibello, A., Barra Caracciolo, A., Fajardo, C., Nande, M., Vargas, R., Saccà, M. L., Martinez-Iñigo, M. J., Ciccoli, R., & Martín, M. (2009). A new fluorescent oligonucleotide probe for in situ detection of s-triazine-degrading Rhodococcus wratislaviensis in contaminated groundwater and soil samples. Water Research, 43(12), 2999–3008. https://doi.org/10.1016/j.watres.2009.04.022

Haines-Young, R., & Potschin, M. B. (2018). Common International Classification of Ecosystem Services (CICES) V5.1. Guidance on the Application of the Revised Structure. https://cices.eu/content/uploads/sites/8/2018/01/Guidance-V51-01012018.pdf

Hanski, I., Hertzen, L. von, Fyhrquist, N., Koskinen, K., Torppa, K., Laatikainen, T., Karisola, P., Auvinen, P., Paulin, L., Mäkelä, M. J., Vartiainen, E., Kosunen, T. U., Alenius, H., & Haahtela, T. (2012). Environmental biodiversity, human microbiota, and allergy are interrelated. Proceedings of the National Academy of Sciences of the United States of America, 109(21), 8334–8339. https://doi.org/10.1073/pnas.1205624109

Hanyu, K., Tamura, K., & Mori, H. (2014). Changes in Heart Rate Variability and Effects on POMS by Whether or Not Soil Observation Was Performed. Open Journal of Soil Science, 04(01), 36–41. https://doi.org/10.4236/ojss.2014.41005

Hausmann, S. L., Petermann, J. S., & Rolff, J. (2016). Wild bees as pollinators of city trees. Insect Conservation and Diversity, 9(2), 97–107. https://doi.org/10.1111/icad.12145

Huang, Y., Stein, G., Kolle, O., Kübler, K., Schulze, E.-D., Dong, H., Eichenberg, D., Gleixner, G., Hildebrandt, A., Lange, M., Roscher, C., Schielzeth, H., Schmid, B., Weigelt, A., Weisser, W. W., Shadaydeh, M., Denzler, J., Ebeling, A., & Eisenhauer, N. (2024). Enhanced stability of grassland soil temperature by plant diversity. Nature Geoscience, 17(1), 44–50. https://doi.org/10.1038/s41561-023-01338-5

Hugh-Jones, M., & Blackburn, J. (2009). The ecology of Bacillus anthracis. Molecular Aspects of Medicine, 30(6), 356–367. https://doi.org/10.1016/j.mam.2009.08.003

Hyman, P. (2019). Phages for Phage Therapy: Isolation, Characterization, and Host Range Breadth. Pharmaceuticals, 12(1). https://doi.org/10.3390/ph12010035

ICBA. (2025). Emirates Soil Museum. International Center for Biosaline Agriculture (ICBA). https://www.emiratessoilmuseum.org/digital-exhibition

ISRIC. (2025). World Soil Museum. World Soil Information (ISRIC). https://wsm.isric.org/

Jochum, M., & Eisenhauer, N. (2022). Out of the dark: Using energy flux to connect above- and belowground communities and ecosystem functioning. European Journal of Soil Science, 73(1), Article e13154. https://doi.org/10.1111/ejss.13154

Jónsson, J., Davíðsdóttir, B., & Nikolaidis, N. P. (2017). Valuation of Soil Ecosystem Services. In Advances in Agronomy. Quantifying and Managing Soil Functions in Earth's Critical Zone - Combining Experimentation and Mathematical Modelling (Vol. 142, pp. 353–384). Elsevier. https://doi.org/10.1016/bs.agron.2016.10.011

Jourdan, P. M., Lamberton, P. H. L., Fenwick, A., & Addiss, D. G. (2018). Soil-transmitted helminth infections. Lancet, 391(10117), 252–265. https://doi.org/10.1016/S0140-6736(17)31930-X

Karsten, G. R., & Drake, H. L. (1997). Denitrifying Bacteria in the Earthworm Gastrointestinal Tract and In Vivo Emission of Nitrous Oxide (N(inf2)O) by Earthworms. Applied and Environmental Microbiology, 63(5), 1878–1882. https://doi.org/10.1128/aem.63.5.1878-1882.1997

Kayalvizhi, K., & Kathiresan, K. (2019). Microbes from wastewater treated mangrove soil and their heavy metal accumulation and Zn solubilization. Biocatalysis and Agricultural Biotechnology, 22, 101379. https://doi.org/10.1016/j.bcab.2019.101379

Kecinski, M., Keisner, D. K., Messer, K. D., & Schulze, W. D. (2018). Measuring Stigma: The Behavioral Implications of Disgust. Environmental and Resource Economics, 70(1), 131–146. https://doi.org/10.1007/s10640-017-0113-z

Keesstra, S., Sannigrahi, S., López-Vicente, M., Pulido, M., Novara, A., Visser, S., & Kalantari, Z. (2021). The role of soils in regulation and provision of blue and green water. Philosophical Transactions of the Royal Society B, 376(1834), 20200175

Klein, A.-M., Vaissière, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C., & Tscharntke, T. (2007). Importance of pollinators in changing landscapes for world crops. Proceedings. Biological Sciences, 274(1608), 303–313. https://doi.org/10.1098/rspb.2006.3721

Koenig, R., & Huth, W. (2003). Natural Infection of Wheat by the Type Strain of Soil-borne Wheat Mosaic Virus in a Field in Southern Germany. European Journal of Plant Pathology, 109(2), 191–193. https://doi.org/10.1023/A:1022517522813

Köhler, J. M., Beetz, N., Günther, P. M., Möller, F., Schüler, T., & Cao, J. (2020). Microbial community types and signature-like soil bacterial patterns from fortified prehistoric hills of Thuringia (Germany). Community Ecology, 21(2), 107–120. https://doi.org/10.1007/s42974-020-00017-4

Köhler, J. M., Kalensee, F., Cao, J., & Günther, P. M. (2019). Hadesarchaea and other extremophile bacteria from ancient mining areas of the East Harz region (Germany) suggest an ecological long-term memory of soil. SN Applied Science. https://link.springer.com/content/pdf/10.1007/s42452-019-0874-9.pdf

Köhler, J. M., Kalensee, F., Günther, P. M., Schüler, T., & Cao, J. (2018). The Local Ecological Memory of Soil: Majority and Minority Components of Bacterial Communities in Prehistorical Urns from Schöps (Germany). International Journal of Environmental Research, 12(5), 575–584. https://doi.org/10.1007/s41742-018-0116-9

Kucharzyk, K. (Ed.). (2022). Bodenschutz als Bildungsaufgabe zum Erhalt der Lebensgrundlage.: In: K. Kucharzyk (Ed.): Boden, Schülervorstellungen, Unterricht. Effekte unterschiedlich gestalteter Lernumgebungen auf die Veränderlichkeit. Springer.

Lahiri, A., Kneisel, J., Kloster, I., Kamal, E., & Lewin, A. (2014). Abundance of Mycobacterium avium ssp. Hominissuis in soil and dust in Germany - implications for the infection route. Letters in Applied Microbiology, 59(1), 65–70. https://doi.org/10.1111/lam.12243

Landa, E. R., & Feller, Christian (Eds.). (2009). Soil and Culture. Springer Netherlands. https://doi.org/10.1007/978-90-481-2960-7

Lang, F., & Luster, J. (2022). Waldökosystemernährung und Klimawandel: Schmilzt mit der Humusauflage auch die Nährstoffverfügbarkeit? Forum Für Wissen, 19–25. https://doi.org/10.55419/wsl:32002

Lange, M., Eisenhauer, N., Sierra, C. A., Bessler, H., Engels, C., Griffiths, R. I., Mellado-Vázquez, P. G., Malik, A. A., Roy, J., Scheu, S., Steinbeiss, S., Thomson, B. C., Trumbore, S. E., & Gleixner, G. (2015). Plant diversity increases soil microbial activity and soil carbon storage. Nature Communications, 6, 6707. https://doi.org/10.1038/ncomms7707

Lavorel, S., Locatelli, B., Colloff, M. J., & Bruley, E. (2020). Co-producing ecosystem services for adapting to climate change. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 375(1794), 20190119. https://doi.org/10.1098/rstb.2019.0119

Le Bayon, R.-C., & Binet, F. (2001). Earthworm surface casts affect soil erosion by runoff water and phosphorus transfer in a temperate maize crop. Pedobiologia, 45(5), 430–442. https://doi.org/10.1078/0031-4056-00097

Leimer, S., Oelmann, Y., Eisenhauer, N., Milcu, A., Roscher, C., Scheu, S., Weigelt, A., Wirth, C., & Wilcke, W. (2016). Mechanisms behind plant diversity effects on inorganic and organic N leaching from temperate grassland. Biogeochemistry, 131(3), 339–353. https://doi.org/10.1007/s10533-016-0283-8

Lengyel, S., Gove, A. D., Latimer, A. M., Majer, J. D., & Dunn, R. R. (2010). Convergent evolution of seed dispersal by ants, and phylogeny and biogeography in flowering plants: A global survey. Perspectives in Plant Ecology, Evolution and Systematics, 12(1), 43–55. https://doi.org/10.1016/j.ppees.2009.08.001

Leroch, M., Plesken, C., Weber, R. W. S., Kauff, F., Scalliet, G., & Hahn, M. (2013). Gray mold populations in german strawberry fields are resistant to multiple fungicides and dominated by a novel clade closely related to Botrytis cinerea. Applied and Environmental Microbiology, 79(1), 159–167. https://doi.org/10.1128/AEM.02655-12

Leroux, P., Fritz, R., Debieu, D., Albertini, C., Lanen, C., Bach, J., Gredt, M., & Chapeland, F. (2002).

Mechanisms of resistance to fungicides in field strains of Botrytis cinerea. Pest Management Science, 58(9), 876–888. https://doi.org/10.1002/ps.566

Letourneau, D. K., Jedlicka, J. A., Bothwell, S. G., & Moreno, C. R. (2009). Effects of Natural Enemy Biodiversity on the Suppression of Arthropod Herbivores in Terrestrial Ecosystems. Annual Review of Ecology, Evolution, and Systematics, 40(1), 573–592. https://doi.org/10.1146/annurev.ecolsys.110308.120320

Ling, L. L., Schneider, T., Peoples, A. J., Spoering, A. L., Engels, I., Conlon, B. P., Mueller, A., Schäberle, T. F., Hughes, D. E., Epstein, S., Jones, M., Lazarides, L., Steadman, V. A., Cohen, D. R., Felix, C. R., Fetterman, K. A., Millett, W. P., Nitti, A. G., Zullo, A. M., . . . Lewis, K. (2015). A new antibiotic kills pathogens without detectable resistance. Nature, 517(7535), 455–459. https://doi.org/10.1038/nature14098

Lubbers, I. M., van Groenigen, K. J., Fonte, S. J., Six, J., Brussaard, L., & van Groenigen, J. W. (2013). Greenhouse-gas emissions from soils increased by earthworms. Nature Climate Change, 3(3), 187–194. https://doi.org/10.1038/nclimate1692

Manici, L. M., Kelderer, M., Franke-Whittle, I. H., Rühmer, T., Baab, G., Nicoletti, F., Caputo, F., Topp, A., Insam, H., & Naef, A. (2013). Relationship between root-endophytic microbial communities and replant disease in specialized apple growing areas in Europe. Applied Soil Ecology, 72, 207–214. https://doi.org/10.1016/j.apsoil.2013.07.011

Mao, J., Nierop, K. G. J., Dekker, S. C., Dekker, L. W., & Chen, B. (2019). Understanding the mechanisms of soil water repellency from nanoscale to ecosystem scale: a review. Journal of Soils and Sediments, 19(1), 171–185. https://doi.org/10.1007/s11368-018-2195-9

Matthews, A. J., & Wilson, C. J. (2005). The Management of Problems Involving Badgers (Meles meles): Protection of Badgers Act 1992, lincensing cases 1997 – 1999.

Maxwell, E. E., Alexander, S., Bechly, G., Eck, K., Frey, E., Grimm, K., Kovar-Eder, J., Mayr, G., Micklich, N., Rasser, M., Roth-Nebelsick, A., Salvador, R. B., Schoch, R. R., Schweigert, G., Stinnesbeck, W., Wolf-Schwenninger, K., & Ziegler, R. (2016). The Rauenberg fossil Lagerstätte (Baden-Württemberg, Germany): A window into early Oligocene marine and coastal ecosystems of Central Europe. Palaeogeography, Palaeoclimatology, Palaeoecology, 463, 238–260. https://doi.org/10.1016/j.palaeo.2016.10.002

Menta, C., & Pinto, S. (2016). Biodiversity and Ecology of Soil Fauna in Relation to Truffle: In: Zambonelli, Iotti et al. (Hg.) 2016 – True Truffle Tuber spp. In A. Zambonelli, M. Iotti, & C. Murat (Eds.), Soil Biology. True Truffle (Tuber spp.) in the World (Vol. 47, pp. 319–331). Springer International Publishing. https://doi.org/10.1007/978-3-319-31436-5_19

Mergeay, M., Monchy, S., Vallaeys, T., Auquier, V., Benotmane, A., Bertin, P., Taghavi, S., Dunn, J., van der Lelie, D., & Wattiez, R. (2003). Ralstonia metallidurans, a bacterium specifically adapted to toxic metals: Towards a catalogue of metal-responsive genes. FEMS Microbiology Reviews, 27(2-3), 385–410. https://doi.org/10.1016/S0168-6445(03)00045-7

Meyer-Wolfarth, F., Schrader, S., Oldenburg, E., Weinert, J., & Brunotte, J. (2017). Biocontrol of the toxigenic plant pathogen Fusarium culmorum by soil fauna in an agroecosystem. Mycotoxin Research, 33(3), 237–244. https://doi.org/10.1007/s12550-017-0282-1

Milbert, G. (2024). Boden des Jahres. https://boden-des-jahres.de/

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., Das, B. S., Field, D. J., Gimona, A., Hedley, C. B., Hong, S. Y., Mandal, B., Marchant, B. P., Martin, M., McConkey, B. G., Mulder, V. L., . . . Winowiecki, L. (2017). Soil carbon 4 per mille. Geoderma, 292, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002

Moine, O., Antoine, P., Hatté, C., Landais, A., Mathieu, J., Prud'homme, C., & Rousseau, D. D. (2017). The impact of Last Glacial climate variability in west-European loess revealed by radiocarbon dating of fossil earthworm granules (Proceedings of the National Academy of Sciences of the United States of America), 114, pp. 6209–6214.

Morel, J. L., Chenu, C., & Lorenz, K. (2015). Ecosystem services provided by soils of urban, industrial, traffic, mining, and military areas (SUITMAs). Journal of Soils and Sediments, 15(8), 1659–1666. https://doi.org/10.1007/s11368-014-0926-0

Motiejūnaitė, J., Børja, I., Ostonen, I., Bakker, M. R., Bjarnadottir, B., Brunner, I., Iršėnaitė, R., Mrak, T., Oddsdóttir, E. S., & Lehto, T. (2019). Cultural ecosystem services provided by the biodiversity of forest soils: A European review. Geoderma, 343, 19–30. https://doi.org/10.1016/j.geoderma.2019.02.025

Mumtaz, R., Bashir, S., Numan, M., Shinwari, Z. K., & Ali, M. (2019). Pigments from Soil Bacteria and Their Therapeutic Properties: A Mini Review. Current Microbiology, 76(6), 783–790. https://doi.org/10.1007/s00284-018-1557-2

NABU, n.d. Laut werden für den Feldhamster! https://www.nabu.de/natur-und-landschaft/landnutzung/landwirtschaft/artenvielfalt/lebensraum/27829.html

Northfield, T. D., Crowder, D. W., Jabbour, R., & Snyder, W. E. (2013). Natural enemy functional identity, trait-mediated interactions and biological control. In T. Ohgushi, O. Schmitz, & R. D. Holt (Eds.), Trait-Mediated Indirect Interactions (pp. 450–465). Cambridge University Press. https://doi.org/10.1017/CBO9780511736551.029

Oberreich, M., Steinhoff-Knopp, B., Burkhard, B., & Kleemann, J. (2024). The Research Gap between Soil Biodiversity and Soil-Related Cultural Ecosystem Services. Soil Systems, 8(3), 97. https://doi.org/10.3390/soilsystems8030097

O'Riordan, R., Davies, J., Stevens, C., Quinton, J. N., & Boyko, C. (2021). The ecosystem services of urban soils: A review. Geoderma, 395, 115076. https://doi.org/10.1016/j.geoderma.2021.115076

Overholt, W. A., Trumbore, S., Xu, X., Bornemann, T. L. V., Probst, A. J., Krüger, M., Herrmann, M., Thamdrup, B., Bristow, L. A., Taubert, M., Schwab, V. F., Hölzer, M., Marz, M., & Küsel, K. (2022). Carbon fixation rates in groundwater similar to those in oligotrophic marine systems. Nature Geoscience, 15(7), 561–567. https://doi.org/10.1038/s41561-022-00968-5

Paoletti, M. G., Buscardo, E., & Dufour, D. L. (2000). Edible Invertebrates Among Amazonian Indians: A Critical Review of Disappearing Knowledge. Environment, Development and Sustainability, 2(3/4), 195–225. https://doi.org/10.1023/A:1011461907591

Pascual, U., Termansen, M., Hedlund, K., Brussaard, L., Faber, J. H., Foudi, S., Lemanceau, P., & Jørgensen, S. L. (2015). On the value of soil biodiversity and ecosystem services. Ecosystem Services, 15, 11–18. https://doi.org/10.1016/j.ecoser.2015.06.002

Paul, C., Kuhn, K., Steinhoff-Knopp, B., Weißhuhn, P., & Helming, K. (2021). Towards a standardization of soil-related ecosystem service assessments. European Journal of Soil Science, 72(4), 1543–1558. https://doi.org/10.1111/ejss.13022

Pepper, I. L., Gerba, C. P., Newby, D. T., & Rice, C. W. (2009). Soil: A Public Health Threat or Savior? Critical Reviews in Environmental Science and Technology, 39(5), 416–432. https://doi.org/10.1080/10643380701664748

Pérès, G., Cluzeau, D., Menasseri, S., Soussana, J. F., Bessler, H., Engels, C., Habekost, M., Gleixner, G., Weigelt, A., Weisser, W. W., Scheu, S., & Eisenhauer, N. (2013). Mechanisms linking plant community properties to soil aggregate stability in an experimental grassland plant diversity gradient. Plant Soil, 373(1-2), 285–299. https://doi.org/10.1007/s11104-013-1791-0

Pérez-Moreno, J. (2021). Global perspectives on the ecological, cultural and socioeconomic relevance of wild edible fungi. Studies in Fungi, 6(1), 408–424. https://doi.org/10.5943/sif/6/1/31

Persson, H. (2016). Mushrooms. Medicine, 44(2), 116–119. https://doi.org/10.1016/j.mpmed.2015.11.011

Peters, F. S., Busskamp, J., Prospero, S., Rigling, D., & Metzler, B. (2014). Genetic diversification of the chestnut blight fungus Cryphonectria parasitica and its associated hypovirus in Germany. Fungal Biology, 118(2), 193–210. https://doi.org/10.1016/j.funbio.2013.11.009

Phillips, H. R. P., Beaumelle, L., Eisenhauer, N., Hines, J., & Smith, L. C. (2020). Lessons from the WBF2020: Extrinsic and intrinsic value of soil organisms. Soil Organisms, 92(2), 121–127. https://doi.org/10.25674/so92iss2pp121

Plaas, E., Meyer-Wolfarth, F., Banse, M., Bengtsson, J., Bergmann, H., Faber, J., Potthoff, M., Runge, T., Schrader, S., & Taylor, A. (2019). Towards valuation of biodiversity in agricultural soils: A case for earthworms. Ecological Economics, 159, 291–300. https://doi.org/10.1016/j.ecolecon.2019.02.003

Polák, J., Rádlová, S., Janovcová, M., Flegr, J., Landová, E., & Frynta, D. (2020). Scary and nasty beasts: Self-reported fear and disgust of common phobic animals. British Journal of Psychology (London, England : 1953), 111(2), 297–321. https://doi.org/10.1111/bjop.12409

Potschin, M. B., & Haines-Young, R. H. (2011). Ecosystem services. Progress in Physical Geography: Earth and Environment, 35(5), 575–594. https://doi.org/10.1177/0309133311423172

Prud'homme, C., Antoine, P., Moine, O., Turpin, E., Huguenard, L., Robert, V., & Degeai, J. P. (2015). Earthworm calcite granules: a new tracker of millennial-timescale environmental changes in Last Glacial loess deposits. Journal of Quaternary Science(30), 529–536.

Prud'homme, C., Lécuyer, C., Antoine, P., Moine, O., Hatté, C., Fourel, F., Amiot, R., Martineau, F., & Rousseau, D. D. (2018). d13C signal of earthworm calcite granules: a new proxy for palaeoprecipitation reconstructions during the Last Glacial in Western Europe. Quaternary Science Reviews(179), 158–166.

Prud'homme, C., Lécuyer, C., Antoine, P., Moine, O., Hatté, C., Fourel, F., Martineau, F., & Rousseau, D. D. (2016). Palaeotemperature reconstruction during the Last Glacial from d18O of earthworm calcite granules from Nussloch loess sequence, Germany. Earth and Planetary Science Letters(422), 13–20.

Prud'homme, C., Moine, O., Mathieu, J., Saulnier-Copard, S., & Antoine, P. (2019). High-resolution quantification of earthworm calcite granules from western European loess sequences reveals stadial–interstadial climatic variability during the Last Glacial. Boreas, 48(1), 257–268. https://doi.org/10.1111/bor.12359

Randler, C., Hummel, E., & Wüst-Ackermann, P. (2013). The Influence of Perceived Disgust on Students' Motivation and Achievement. International Journal of Science Education, 35(17), 2839–2856. https://doi.org/10.1080/09500693.2012.654518

Reichman, O. J., & Seabloom, E. W. (2002). The role of pocket gophers as subterranean ecosystem engineers. Trends in Ecology & Evolution, 17(1), 44–49. https://doi.org/10.1016/S0169-5347(01)02329-1

Riesenfeld, C. S., Goodman, R. M., & Handelsman, J. (2004). Uncultured soil bacteria are a reservoir of new antibiotic resistance genes. Environmental Microbiology, 6(9), 981–989. https://doi.org/10.1111/j.1462-2920.2004.00664.x

Rillig, M. C. (2004). Arbuscular mycorrhizae and terrestrial ecosystem processes. Ecology Letters, 7(8), 740–754. https://doi.org/10.1111/j.1461-0248.2004.00620.x

Roscher, C., Schumacher, J., Baade, J., Wilcke, W., Gleixner, G., Weisser, W. W. , Schmid, B., Schulze, E.-D. (2004). The role of biodiversity for element cycling and trophic interactions: An experimental approach in a grassland community. Basic and Applied Ecology 5, 107–121. https://doi.org/10.1078/1439-1791-00216

Rostás, M., & Tautz, J. (Eds.) (2011). Ants as Pollinators of Plants and the Role of Floral Scents: In: Z. Dubinsky, J. Seckbach (Eds.): All Flesh Is Grass: Plant-Animal Interrelationships. Cellular Origin, Life in Extreme Habitats and Astrobiology. Springer.

Sánchez-Moreno, S., & Ferris, H. (2007). Suppressive service of the soil food web: Effects of environmental management. Agriculture, Ecosystems & Environment, 119(1-2), 75–87. https://doi.org/10.1016/j.agee.2006.06.012

Schädel, C., Bader, M. K.-F., Schuur, E. A. G., Biasi, C., Bracho, R., Čapek, P., Baets, S. de, Diáková, K., Ernakovich, J., Estop-Aragones, C., Graham, D. E., Hartley, I. P., Iversen, C. M., Kane, E., Knoblauch, C., Lupascu, M., Martikainen, P. J., Natali, S. M., Norby, R. J., . . . Wickland, K. P. (2016). Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils. Nature Climate Change, 6(10), 950–953. https://doi.org/10.1038/nclimate3054

Schaefer, M., & Filser, J. (2007). The influence of earthworms and organic additives on the biodegradation of oil contaminated soil. Applied Soil Ecology, 36(1), 53–62. https://doi.org/10.1016/j.apsoil.2006.11.002

Scherzinger, F., Schädler, M., Reitz, T., Yin, R., Auge, H., Merbach, I., Roscher, C., Harpole, W. S., Blagodatskaya, E., Siebert, J., Ciobanu, M., Marder, F., Eisenhauer, N., & Quaas, M. (2024). Sustainable land management enhances ecological and economic multifunctionality under ambient and future climate. Nature Communications, 15(1), 4930. https://doi.org/10.1038/s41467-024-48830-z

Scheu, S. (2002). The soil food web: structure and perspectives. European Journal of Soil Biology, 38(1), 11–20. https://doi.org/10.1016/S1164-5563(01)01117-7

Schierstaedt, J., Jechalke, S., Nesme, J., Neuhaus, K., Sørensen, S. J., Grosch, R., Smalla, K., & Schikora, A. (2020). Salmonella persistence in soil depends on reciprocal interactions with indigenous microorganisms. Environmental Microbiology, 22(7), 2639–2652. https://doi.org/10.1111/1462-2920.14972

Schrader, S., van Capelle, C., & Meyer-Wolfarth, F. (2020). Regenwürmer als Partner bei der Bodennutzung. Biologie in Unserer Zeit, 50(3), 192–198. https://doi.org/10.1002/biuz.202010706

Senckenberg Museum für Naturkunde Görlitz. (2024). Die dünne Haut der Erde – Unsere Böden. Touring exhibition. https://museumgoerlitz.senckenberg.de/de/ausstellung/wanderausstellungen/die-duenne-haut-der-erde-unsere-boeden/

Shuster, W., McDonald, L., McCartney, D., Parmelee, R., Studer, N., & Stinner, B. (2002). Nitrogen source and earthworm abundance affected runoff volume and nutrient loss in a tilled-corn agroecosystem. Biology and Fertility of Soils, 35(5), 320–327. https://doi.org/10.1007/s00374-002-0474-4

Singh, B. K., Yan, Z.-Z., Whittaker, M., Vargas, R., & Abdelfattah, A. (2023). Soil microbiomes must be explicitly included in One Health policy. Nature Microbiology, 8(8), 1367–1372. https://doi.org/10.1038/s41564-023-01386-y

Sofo, A., Mininni, A. N., & Ricciuti, P. (2020). Soil Macrofauna: A key Factor for Increasing Soil Fertility and Promoting Sustainable Soil Use in Fruit Orchard Agrosystems. Agronomy, 10(4), 456. https://doi.org/10.3390/agronomy10040456

StMLU. (2006). Produzenten und Konsumenten, Zersetzer und Aasfresser, Räuber und Parasiten. Der Boden als Lebensraum.: In: Handreichung "Lernort Boden". Sachinformationen. Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz (StMUGV), Staatsinstitut für Schulqualität und Bildungsforschung (ISB)

Swift, M. J., Izac, A.-M., & van Noordwijk, M. (2004). Biodiversity and ecosystem services in agricultural landscapes—are we asking the right questions? Agriculture, Ecosystems & Environment, 104(1), 113–134. https://doi.org/10.1016/j.agee.2004.01.013

Toland, A., & Wessolek, G.. (2009). Merging Horizons - Soil Science and Soil Art: In E. R. Landa & Feller, Christian (Eds.), Soil and Culture (pp. 45–66). Springer Netherlands. https://doi.org/10.1007/978-90-481-2960-7_4

Tryon, C. A. (2006). The Destructive Potential of Earthworms on the Archaeobotanical Record. Journal of Field Archaeology, 31(2), 199–202. http://www.jstor.org/stable/40024958

Ullrich, J. (2021). Schwarmästhetik - Insekten in der Kunst. https://www.kulturrat.de/themen/nachhaltigkeit-kultur/insekten-kultur/schwarmaesthetik/

UNESCO. (2024). UNESCO Global Geoparks. https://www.unesco.org/en/iggp/geoparks/about

Uprety, Y., Poudel, R. C., Shrestha, K. K., Rajbhandary, S., Tiwari, N. N., Shrestha, U. B., & Asselin, H. (2012). Diversity of use and local knowledge of wild edible plant resources in Nepal. Journal of Ethnobiology and Ethnomedicine, 8, 16. https://doi.org/10.1186/1746-4269-8-16

van der Heijden, M. G. A., Bardgett, R. D., & van Straalen, N. M. (2008). The unseen majority: Soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. Ecology Letters, 11(3), 296–310. https://doi.org/10.1111/j.1461-0248.2007.01139.x

van der Heijden, M. G. A., & Wagg, C. (2013). Soil microbial diversity and agro-ecosystem functioning. Plant Soil, 363(1-2), 1–5. https://doi.org/10.1007/s11104-012-1545-4

van Huis, A. (2003). Insects as Food in sub-Saharan Africa. International Journal of Tropical Insect Science, 23(03), 163–185. https://doi.org/10.1017/S1742758400023572

Vries, F. T. de, & Wallenstein, M. D. (2017). Below-ground connections underlying above-ground food production: a framework for optimising ecological connections in the rhizosphere. Journal of Ecology, 105(4), 913–920. https://doi.org/10.1111/1365-2745.12783

Wagner, H. (n.d.) Mythologisches und Kulturgeschichtliches von Pilzen. „Heimat-Pfalz - Das Wissensportal der gesamten Pfalz“ ist ein kostenfreies Bildungsprojekt der Geomart UG. https://www.heimat-pfalz.de/pfalz-kolumne/hans-wagners-naturseite/902-mythologisches-und-kulturgeschichtliches-von-pilzen.html

Walimbe, S. (2021). Formation Processess of the Human Skeletal Record in Archaeology. Man and Environment, XLV, Article 2.

Wall, D. H., Nielsen, U. N., & Six, J. (2015). Soil biodiversity and human health. Nature, 528(7580), 69–76. https://doi.org/10.1038/nature15744

Walther, J. (Ed.). (1935). Einführung in die deutsche Bodenkunde. Julius Springer Verlag.

Wardle, D. A., Bardgett, R. D., Klironomos, J. N., Setälä, H., van der Putten, W. H., & Wall, D. H. (2004). Ecological linkages between aboveground and belowground biota. Science (New York, N.Y.), 304(5677), 1629–1633. https://doi.org/10.1126/science.1094875

Wesenberg, J., Baber, K., Westermann, L., & Xylander, W. E. R. (2019). Adventure Soil Life“ – A virtual journey through a hidden world. VIMM Virtual Multimodal Museum. https://www.vi-mm.eu/project/adventure-soil-life-a-virtual-journey-through-an-unknown-world/

Westermann, L., Baber, K., Wesenberg, J., & Xylander, W. E. R. (2018) “Abenteuer Bodenleben” -Virtual Reality (VR) zur digitalen Wissenschaftsvermittlung im Museum. In: Bienert, A., A. Börner, E. Emenlauer-Blömers & J. Hemsley (Eds.): Proceedings EVA, Berlin, 27-33.

Wijnhoven, S., Thonon, I., van der Velde, G., Leuven, R., Zorn, M., Eijsackers, H., & Smits, T. (2006). The Impact of Bioturbation by Small Mammals on Heavy Metal Redistribution in an Embanked Floodplain of the River Rhine. Water, Air, and Soil Pollution, 177(1-4), 183–210. https://doi.org/10.1007/s11270-006-9148-4

Wirth, C., Bruelheide, H., Farwig, N., Marx, J. M., & Settele, J. (2024a). Faktencheck Artenvielfalt. oekom verlag. https://doi.org/10.14512/9783987263361

Wirth, C., Bruelheide, H., Farwig, N., Marx, J. M. & Settele, J. (2024b). Faktencheck Artenvielfalt. Zusammenfassung für die gesellschaftliche Entscheidungsfindung. oekom verlag. https://doi.org/10.14512/9783987263378

Xylander, W. E. R. (2019) Reflexionen zu Kriterien zum Einsatz von Virtual Reality in Naturkundemuseen. Museumskunde (83), 148–155.

Xylander, W. E. R. (2020). Society´s awareness for protection of soils, its biodiversity and function in 2030 – We need a more intrinsic approach. SOIL ORGANISMS 92(3), 202-213. https://doi.org/10.25674/so92iss3pp203

Xylander, W. E. R. (2024). Mehr Bewusstsein für Bodenbiodiversität - Defizite, Bedarfe, Transferansätze und -formate. Natur und Landschaft 99 (9/10), 445–451.

Xylander, W. E. R., & Zumkowski-Xylander, H. (2018). Increasing awareness for soil biodiversity and protection The international touring exhibition “The Thin Skin of the Earth”. SOIL ORGANISMS 90(2), 79–94. https://doi.org/10.25674/KKY5-A011

Yamaki, M., Miwa, M., Ishiguro, K., & Takagi, S. (1994). Antimicrobial activity of naturally occurring and synthetic phloroglucinols against Staphylococcus aureus. Phytotherapy Research, 8(2), 112–114. https://doi.org/10.1002/ptr.2650080214

Yamin-Pasternak, S. (2008). A MEANS OF SURVIVAL, A MARKER OF FEASTS: MUSHROOMS IN

THE RUSSIAN FAR EAST. Ethnology, 47(2/3), 95–107. http://www.jstor.org/stable/25651552

Yun, W., & Hall, I. R. (2004). Edible ectomycorrhizal mushrooms: challenges and achievements. Canadian Journal of Botany, 82(8), 1063–1073. https://doi.org/10.1139/b04-051

Zaller, J. G. (2004). Ecology and non-chemical control of Rumex crispus and R. obtusifolius (Polygonaceae): a review. Weed Research, 44(6), 414–432. https://doi.org/10.1111/j.1365-3180.2004.00416.x

Zaller, J. G., Saxler, N. (2007). Selective vertical seed transport by earthworms: Implications for the diversity of grassland ecosystems. European Journal of Soil Biology, 43, S86-S91. https://doi.org/10.1016/j.ejsobi.2007.08.010

Zanella, A., Ponge, J.-F., Briones, M. J. (2018). Humusica 1, article 8: Terrestrial humus systems and forms – Biological activity and soil aggregates, space-time dynamics. Applied Soil Ecology, 122, 103–137. https://doi.org/10.1016/j.apsoil.2017.07.020

Zucconi, L., Canini, F., Isola, D., Caneva, G. (2022). Fungi Affecting Wall Paintings of Historical Value: A Worldwide Meta-Analysis of Their Detected Diversity. Applied Sciences, 12(6), 2988. https://doi.org/10.3390/app12062988