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PRACTICE AND POLICY

Challenges of and opportunities for protecting European soil biodiversity

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Abstract

Soil biodiversity and related ecosystem functions are neglected in most biodiversity assessments and nature conservation actions. We examined how society, and particularly policy makers, have addressed these factors worldwide with a focus on Europe and explored the role of soils in nature conservation in Germany as an example. We reviewed past and current global and European policies, compared soil ecosystem functioning in- and outside protected areas, and examined the role of soils in nature conservation management via text analyses. Protection and conservation of soil biodiversity and soil ecosystem functioning have been insufficient. Soil-related policies are unenforceable and lack soil biodiversity conservation goals, focusing instead on other environmental objectives. We found no evidence of positive effects of current nature conservation measures in multiple soil ecosystem functions in Europe. In German conservation management, soils are considered only from a limited perspective (e.g., as physicochemical part of the environment and as habitat for aboveground organisms). By exploring policy, evidence, and management as it relates to soil ecosystems, we suggest an integrative perspective to move nature conservation toward targeting soil ecosystems directly (e.g., by setting baselines, monitoring soil threats, and establishing a soil indicator system).

KEYWORDS
belowground, Europe, Germany, nature conservation, protected areas, soil biodiversity, soil ecosystem functioning, soil policy

Resumen

La biodiversidad del suelo y las funciones ambientales relacionadas se dejan de lado en la mayoría de las evaluaciones de la biodiversidad y de las acciones de conservación de la naturaleza. Analizamos cómo la sociedad, y particularmente los formuladores de políticas, han abordado estos factores a nivel mundial con un enfoque en Europa y exploramos como ejemplo el papel de los suelos en la conservación de la naturaleza en Alemania. Revisamos las políticas mundiales y europeas en el pasado y en la actualidad, comparamos el funcionamiento ambiental del suelo dentro y fuera de las áreas protegidas y examinamos el papel de los suelos en la gestión de la conservación por medio del análisis de textos. La protección y la conservación de la biodiversidad y el funcionamiento ambiental del suelo han sido insuficientes. Las políticas relacionadas con el suelo son inaplicables y carecen de objetivos de conservación para su biodiversidad, pues se enfocan más bien en otros objetivos ambientales. No descubrimos evidencias de los efectos positivos de las medidas actuales de conservación en múltiples funciones ambientales del suelo en Europa. En la gestión alemana de la conservación, los suelos sólo se consideran desde una perspectiva limitada (p. ej.: como una parte físico química del ambiente y como hábitat para los organismos que habitan por encima de él). Mediante la exploración de la política, evidencias y gestión conforme se relaciona con los ecosistemas del suelo, sugerimos una perspectiva integrada para dirigir a la conservación hacia el enfoque directo sobre los ecosistemas del suelo (p. ej.: al establecer líneas base, monitorear las amenazas para el suelo y establecer un sistema indicador del suelo).

PALABRAS CLAVE
Alemania, áreas protegidas, biodiversidad del suelo, conservación de la naturaleza, Europa, funcionamiento ambiental del suelo, política del suelo, subterráneo

欧洲土壤生物多样性保护的挑战和机遇

【摘要】大多数生物多样性评估和自然保护行动都忽视了土壤生物多样性及相关生态系统功能。我们研究了社会, 特别是政策制定者, 如何在以欧洲为重点的全世界范围内应对这些问题, 并以德国为例探讨了土壤在自然保护中的作用。本研究综述了过去与现在全球及欧洲的政策, 比较了保护区内外的土壤生态系统功能, 并通过文本分析研究了土壤在自然保护管理中的作用。我们发现, 对土壤生物多样性和土壤生态系统功能的保护仍有欠缺。与土壤有关的政策难以实施, 且缺少土壤生物多样性保护目标, 已有的保护目标更多地集中在其他环境目标上。我们没有发现欧洲目前的自然保护措施对多种土壤生态系统功能产生积极影响的证据。德国的保护管理仅从有限的角度考虑土壤因素(如作为环境的物理化学部分和地上生物的栖息地)。通过探讨与土壤生态系统有关的政策、证据和管理, 我们提出了一个综合性观点, 以促进自然保护朝着直接针对土壤生态系统的方向发展, 如通过设定基线、监测土壤威胁, 以及建立土壤指标体系。**【翻译:胡怡思;审校:聂永刚】**

关键词: >地下, 土壤生物多样性, 土壤生态系统功能, 自然保护, 保护区, 土壤政策, 欧洲, 德国

INTRODUCTION

Biodiversity plays an important role in nature's contributions to people (Cardinale et al., 2012; Bardgett & van der Putten, 2014; Díaz et al., 2018). However, biodiversity changes are affecting ecosystem status and altering how humans relate to nature (Díaz et al., 2019; IPBES, 2019). Failure to achieve, for example, the Aichi Biodiversity Targets (Buchanan et al., 2020; CBD, 2020a) and UN Sustainable Development Goals (UN, 2020; UN Economic & Social Council, 2019) requires new ambitious targets (Visconti et al., 2019; Díaz et al., 2020; Leclère et al., 2020). Although the 2030 agendas begin to reflect these ambitions (e.g., UN Agenda 2030, European Biodiversity Strategy for 2030), most assessments that underpin the establishment of nature conservation policies are based on marine or aboveground terrestrial biodiversity and ecosystem processes (Guerra et al., 2021; Jung et al., 2021). Although nearly 25% of all terrestrial species are estimated to be soil organisms (Decaëns et al., 2006; Orgiazzi et al., 2016), they are rarely considered in conservation policy and in most global biodiversity assessments and conservation actions (Kraemer et al., 2004; Cameron et al., 2019; Eisenhauer & Guerra, 2019).

Soil represents a complex ecosystem with a wide variety of organisms and communities (Bardgett & van der Putten, 2014; Delgado-Baquerizo et al., 2020; FAO et al., 2020). Belowground biodiversity is linked to many ecosystem functions and services related to human health and well-being (Bardgett & van der Putten, 2014; Soliveres et al., 2016; Crowther et al., 2019; Delgado-Baquerizo et al., 2020); thus, soil is considered an ecosystem service supplier and is included in land-degradation policies (e.g., IPCC, 2019). Nevertheless, for soil biodiversity to be central to conservation, as birds or mammals are, its intrinsic value (i.e., value unrelated to its usefulness) needs further consideration (Hågvar, 1998; Decaëns et al., 2006; Phillips et al., 2020). Addressing soil ecosystem functions and the intrinsic value of soil biodiversity would allow conservation policies, including establishment of new protected areas, to put more emphasis on conservation of soil biodiversity and soil ecosystem functioning. Currently, protected areas appear to insufficiently preserve soil biodiversity (e.g., Ciobanu et al., 2019; Le Provost et al., 2021). However, this finding requires evaluation at larger scales and for a range of soil functions to allow understanding of the inherent causes and ways forward, particularly to make soil biodiversity protection a central piece of nature conservation.

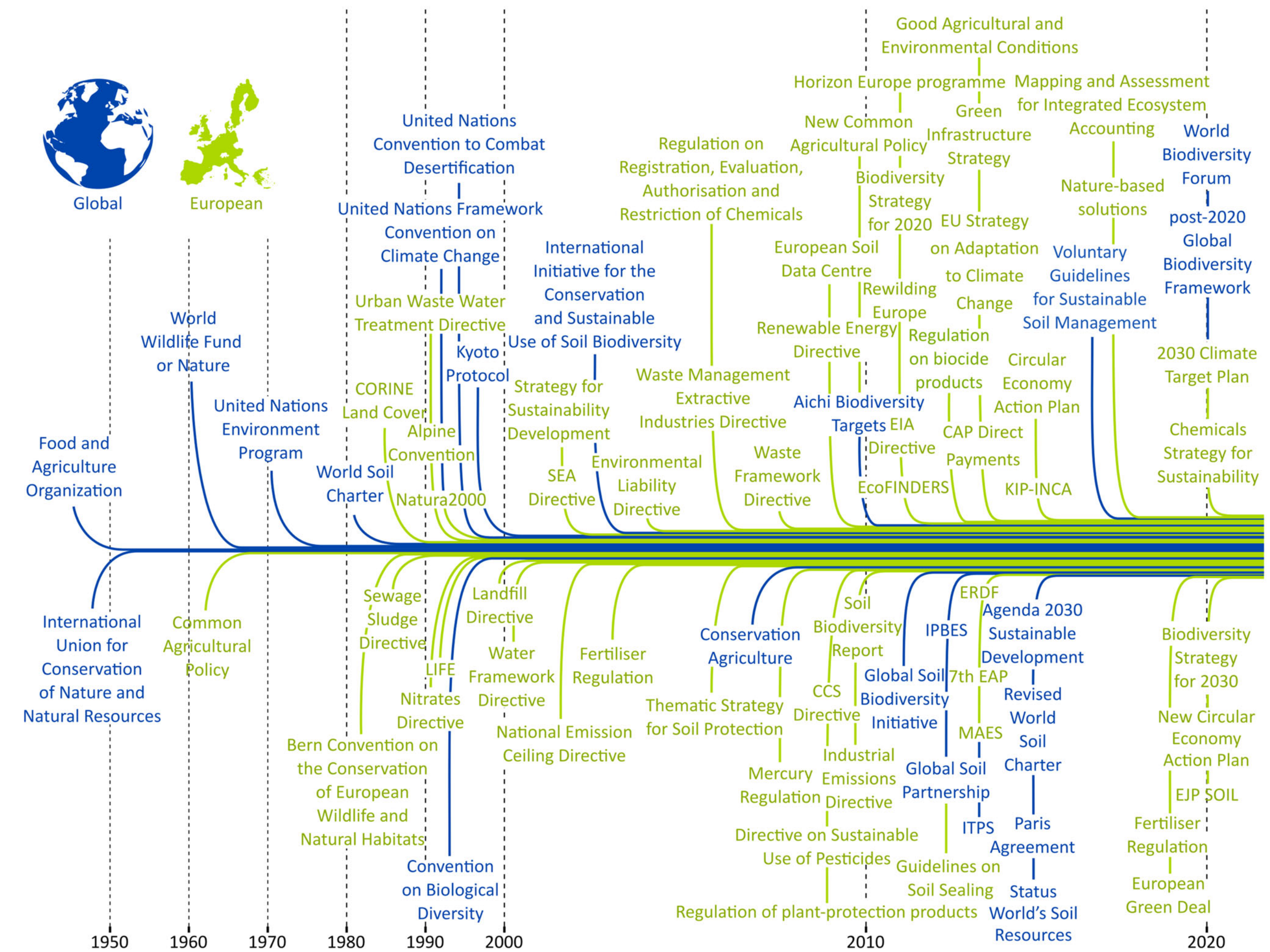

FIGURE 1 Policy timeline of soil-related milestones categorized according to their global (blue) or European scope (green). A comprehensive, chronological list of soil-related policies is in the Appendix S2. See Kraemer et al. (2004), Frelih-Larsen et al. (2016), Paleari (2017), and Ronchi et al. (2019) for further reading

POLICIES ON SOIL BIODIVERSITY AND ECOSYSTEM FUNCTIONING

Soil biodiversity and related ecosystem functions have been politically neglected for many years, even though awareness of its values has risen recently (Phillips et al., 2017; Ciobanu et al., 2019; FAO et al., 2020; Guerra et al., 2021; Köninger et al., 2022). Globally, general agreements on conservation and agricultural practices (e.g., within the scope of the United Nations [UN]) have existed for decades, in part initiated by international organizations (e.g., Convention on Biological Diversity [CBD]) (Figure 1; Appendix S1). These global agreements built the foundation for many of the positive effects of conservation seen today. However, they disconnect soil biodiversity and related ecosystem functions from mainstream nature conservation, framing it almost exclusively as the vector for positive or negative consequences for food production (Vrebos et al., 2017; Ronchi et al., 2019). This is reflected in other policy scopes. For example, until 2010, the European Union focused almost exclusively on soil contamination in the broadest sense, especially in agricultural systems. Arrangements that consider soils and are still in force include directives on industrial emissions (Directive 2010/75/EU), environmental liability (Directive 2004/35/CE), and waste (Directive 2008/98/EC) and regulations on chemicals (EC 1907/2006) and agricultural practices (e.g., EC 2003/2003 on fertilizers). Past EU soil protection policy, mainly targeting soil erosion and pollution, was also represented in the Soil Framework Directive (COM[2006] 232), proposed as part of the Thematic Strategy of Soil Protection (COM[2006] 231). This directive would have been an important step for soil preservation in Europe, but it was consistently blocked by the member states and withdrawn in 2014 (EC, 2014; Chen, 2019).

As climate change has become more apparent, soil has been noticed due to its importance in mitigating climate change effects (e.g., Crowther et al., 2019; IPCC, 2019). Over time, global environmental targets considering land degradation or the role of soils in the greenhouse effect—specifically the improvement of soil health, fertility, and carbon sequestration—have been defined and monitored under several conventions (e.g., UN Convention to Combat Desertification or Climate Framework Convention [UN, 2018]). Similar targets have been set by acts emanating from the CBD (2010; Bouma et al., 2019). In addition, within the 7th Environmental Action Programme for 2014–2020, the EU agreed on 5 goals that focus on effects detrimental to soil and human interventions (Decision 1600/2002/EC). Unfortunately, many of the international targets were not reached (EC, 2019a; Buchanan et al., 2020; CBD, 2020a), and effective, transformative change is still needed (IPBES, 2019). Global assessments of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES, 2019) and the European Green Deal (COM[2019] 640 final) consider soil a part of nature especially threatened by pollution, but do not specifically target soil biodiversity and its ecosystem functions for conservation.

The International Initiative for the Conservation and Sustainable Use of Soil Biodiversity, Global Soil Biodiversity Initiative, and Global Soil Partnership have attempted to address the limited recognition of soil biodiversity and related ecosystem functions. With the increased acknowledgement of the importance of soils, international events have aimed to raise awareness and exchange knowledge among sectors (e.g., UN International Year of Soil, Global Soil Week, and World Soil Day). European initiatives have been established to improve data availability, such as the European Soil Data Centre, which maintains a comprehensive, soil-related database that includes soil biodiversity and functional data (Orgiazzi et al., 2018).

The recent EU Biodiversity Strategy explicitly considers soils in establishment of large networks of protected areas, ecosystem restorations, and enactment of transformative change. The strategy is accompanied by the Mission on Soil Health and Food that aims to restore 75% of all European soils by 2030 (EC, 2020b). But despite the attention and discussions for the post-2020 biodiversity conservation goals (CBD, 2020b), global and European soil-related policies have reduced their overall impact because they are fragmented and unenforceable, focus on soil contamination in agricultural systems, and lack concrete actions, indicators and conservation priorities to preserve soil biodiversity and related ecosystem functions (Kraemer et al., 2004; Paleari, 2017; Ronchi et al., 2019). Soil is the only environmental medium without its own European directive to comprehensively and coherently regulate its protection (BfN, 2021). The updated EU Strategy on Soil (EC, 2021; European Parliament, 2021) may represent a critical step forward, but it requires new instruments that allow integration of soils across several other policies and development of targets and indicators of soil biodiversity and related ecosystem functions. Policies must move beyond assessing chemical soil function toward monitoring biological and physical functions (Leeuwen et al., 2017). Although polices aimed at soils exist at global and European levels, the absence of a specific targeting of soil biodiversity and related ecosystem functions makes their protection a coincidental by-product of other environmental objectives.

EFFECTS OF PROTECTED AREAS ON SOIL ECOSYSTEM FUNCTIONS ACROSS EUROPE

Protection of soil organisms needs to be incorporated in nature conservation. For example, potential positive effects of protected areas on ecosystem functioning (Allan et al., 2015; Eastwood et al., 2016) are thought to spill over to other nontargeted ecosystems and biodiversity groups (Ament & Cumming, 2016). However, it is unclear to what degree this is true for soil biodiversity and soil ecosystem functioning. Protected areas in Europe, such as those in the Natura 2000 network (Habitats Directive [Council Directive 92/43/EEC] and Birds Directive [Directive 2009/147/EC]), do not sufficiently cover many organism groups (Watson et al., 2014; Geldmann et al., 2015; Barnes et al., 2018; Ciobanu et al., 2019; Visconti et al., 2019). To increase coverage of protected areas, policy makers consider the quality of respective sites secondarily (including size, policy enforcement, and biological representativeness) and fail to prioritize establishment of protected areas and conservation objectives over the goals of particular stakeholders (e.g., industry and agriculture) (Watson et al., 2014; Barnes et al., 2018; Visconti et al., 2019; Jung et al., 2021). Decisions for protecting species and their habitats should be based on extinction risks and ecology rather than popularity (Mammola et al., 2020).

We extended assessments of conservation effects on soil biodiversity (e.g., Ciobanu et al., 2019; Le Provost et al., 2021) to include effects on soil ecosystem functions directly connected to soil biodiversity and key ecosystem services, such as nutrient cycling and carbon sequestration. Investigated soil ecosystem functions (i.e., enzyme activity, microbial respiration and biomass, mean weight diameter, and water-stable aggregates) are components of several indicators (e.g., Soil Health, Soil Biodiversity, or Nutrient Cycling and Fertility) (Guerra et al., 2021). We compared European soil samples from conservation areas (Natura 2000 sites; EEA, 2019) with samples from unprotected areas. We used a subset of the soil samples collected by the LUCAS (Land Use and Cover Area frame Survey) Soil project in 2018 (Orgiazzi et al., 2018) (Figure 2a). To test the effects of protected areas on soil ecosystem functions, we randomly selected pairs of protected and unprotected sites. Paired sites were environmentally similar and generated 1000 times randomly without replacement (total 474, protected 87, unprotected 387). Environmental similarity was quantified as the lowest average Mahalanobis distance based on latitude and longitude, elevation, annual and monthly precipitation and temperature, and soil pH, organic carbon, and texture (Smith et al., 2021). The randomization process allowed us to account for multiple comparisons of the same protected site with different environmentally similar unprotected sites of the same land-cover type (Appendix S1). Effect size was calculated using Cohen's *d* (Cohen, 1988). We assumed soil ecosystem functions of all pairs differed significantly if *p* from a Welch 2-sample *t*-test

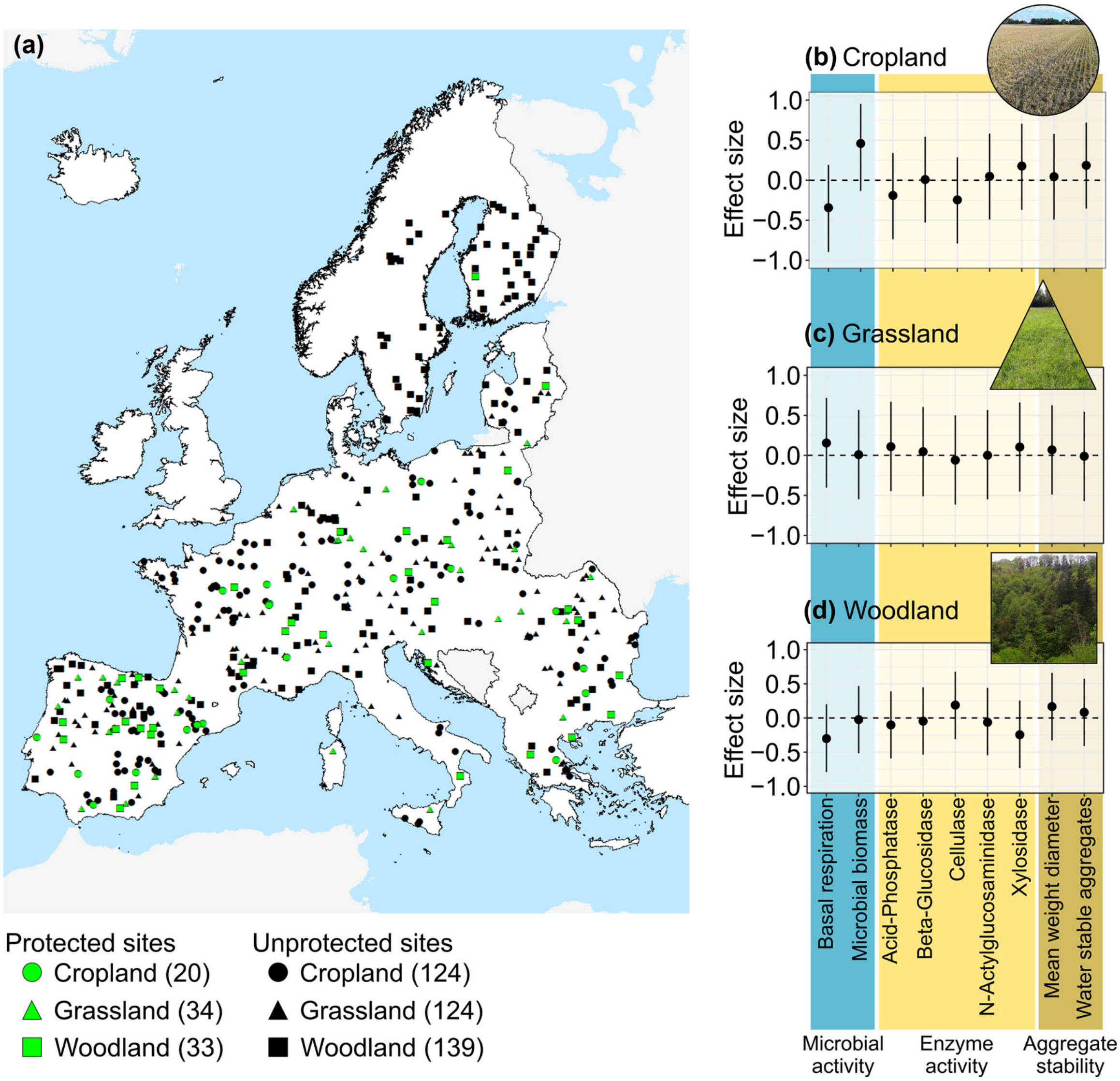

FIGURE 2 (a) Location of LUCAS (Land Use and Cover Area) soil sites ($n = 474$) in protected areas (green) ($n = 87$) and environmentally similar unprotected sites (black) ($n = 387$) (numbers in parentheses, observations per land-cover type). (b–d) Practical differences (i.e., Cohen's d effect size) in soil ecosystem functions in protected areas compared with environmentally similar unprotected sites (1000 semirandom pairing runs) (black dots, mean; pictures from LUCAS Soil Survey 2018; p-values in the Appendix S4)

was <0.05 in at least half of the randomized runs (i.e., mean of p values of all runs <0.05).

When comparing soils in protected and unprotected sites across Europe, we did not find a positive effect of protected areas on functional performance (Figure 2; Appendices S3 and S4). Thus, either all soils were equally threatened regardless of conservation measures or none of the soils were threatened. The latter is unlikely because several studies show the precarious status of soils worldwide (FAO & ITPS, 2015; Montanarella et al., 2016; FAO et al., 2020; Tibbett et al., 2020). Conceptually, this lack of effect from nature conservation has been highlighted in previous studies (Kraemer et al., 2004; Cameron et al., 2019; Eisenhauer & Guerra, 2019) but not demonstrated at such a large scale. Protected areas may not improve soil ecosystem functioning (Figure 2b) because of other factors, such as climate or land use, that overshadow the potential effect of nature conservation. Undetectable differences between soils in protected and unprotected areas—even at a wide sampling scope—demonstrate the need for more appropriate soil protection to overcome potential detrimental effects of global change (Veresoglou et al., 2015). In addition, data limitations (i.e., small sample size, potentially disturbed baseline) did not allow us to test the impact of different levels of human pressures on soil ecosystems. Based on previously demonstrated relationships between soil ecosystem functioning and soil biodiversity (Bardgett & van der Putten, 2014; Soliveres et al., 2016; Crowther et al., 2019; Delgado-Baquerizo et al., 2020), we would expect similar results for soil biodiversity.

ROLE OF SOIL SYSTEMS IN CONSERVATION MANAGEMENT

Considering the negligible effects of protected areas we found and results of previous studies pointing to similar effects on diversity (e.g., Ciobanu et al., 2019; Le Provost et al., 2021), it is important to understand why current protected areas do not contribute to soil biodiversity conservation yet. We used Germany as an example to explore how nature conservation management considers soil ecology and how this has evolved through time (see also Appendix S5). By screening management plans of German Natura 2000 areas, we evaluated the role of soil in conservation management. We focused on areas of the Flora-Fauna-Habitat Directive (92/43/EWG) and were able to collect 3505 management plans for these protected areas in all 16 Federal States (as of February 2021; Appendix S6). We separated the collected documents into 3 time intervals to examine temporal patterns: 2001–2010, 2011–2015, and 2016–2020. For each plan, we extracted and cleaned the text. We combined different text mining approaches (Bickel, 2017; Silge & Robinson, 2017; Brito et al., 2020) and built a list of ∼1,000 relevant terms that are directly or indirectly related to soils, soil threats, soil ecosystem functions, and soil drivers, based on available literature (Montanarella et al., 2016; FAO et al., 2020; Tibbett et al., 2020; BfN, 2021). Next, we classified all terms into 7 categories and 41 subcategories, representing distinct soil aspects (Table 1; Appendices S1 and S7). We summarized the number of occurrences per subcategory by taking the mean of the term frequencies (tf) over all documents and estimated the proportion of management plans in which the subcategories were mentioned (relative document frequency [df]). Finally, we calculated tf and df for the co-occurrence of subcategories within the extracted word groups (i.e., parts of the text around any soil terms; visualized as line thickness between term nodes) and examined how soils were represented in management plans over time.

Our results showed that current conservation management considers soils from a limited perspective (Figure 3; Appendices S8 and S9). Although soils were mentioned in most management plans (93%, $n = 3505$), most soil-related terms were considered in a minority of documents (df < 0.4 on average) only, particularly terms related to soil biodiversity and its protection. In general, soils were mostly regarded as a static part of the environment (e.g., for site description) and in their role as habitat for aboveground organisms (Appendices S8 and S9). This was reflected by the fact that terms belonging to the subcategories environment, aboveground biodiversity, and habitat appear systematically associated with soil terms and therefore showed comparably high frequencies (tf = 15.5, 10.9, and 5.3; df = 0.86, 0.60, and 0.63, respectively). Frequently used terms describing environmental soil conditions (cf. category feature), such as chemical and physical soil properties and specific soil types (tf > 6.5, df ≥ 0.7), were in line with this habitat perspective. Similarly to the above-reviewed policies, soil threats—particularly erosion and land use—were addressed more frequently (even if unequally, see also Tibbett et al., 2020) in German nature conservation management plans (Appendices S8 and S9), whereas soil biodiversity and the intrinsic value of the belowground ecosystem was not (tf = 1.8). In line with previous findings, land managers seem to consider the intrinsic ecological value of soils less, while incorporating their context-specific knowledge (Vanermen et al., 2020), that is, considering soil aspects site-specifically. The limited view of soils does not provide conservation managers with the tools to effectively address soil ecological conservation.

Over time, we detected only a few changes in term frequencies (Figure 3a; Appendix S8 for statistics), whereas the number of links between distinct soil aspects increased (i.e., higher co-occurrence of subcategories; line thickness in Figure 3b). Large decreases in certain term frequencies from 2010 to 2015 become slightly less large in 2020 (e.g., aboveground biodiversity, environment, research, soil type, and erosion) (Figure 3a). Terms belonging to the category protection, such as soil-friendly practices and soil policies, became notably more frequent and more strongly associated with other aspects over time compared with 2010 (e.g., higher tf and df of co-occurrence with chemical and physical properties and habitat; positive effect size in Figure 3a, thick lines in Figure 3b; Appendix S8). The overall low occurrence and co-occurrence of soil-related terms demonstrates the lack of common soil concepts and their communication, leading to the neglect of well-known links between soil biodiversity and ecosystem services or between soils and management practices, among others. We are aware of management practices with possible side effects on soil biodiversity that were not covered by our text analysis. Examples include mowing, grazing, and dead wood management, which may not be directly related to soil biodiversity and thus did not co-occur with our soil terms despite their potentially positive effects on the soil community (Minnich et al., 2021). Similarly, other management practices might have side effects on soil biodiversity that are less obvious and have not even been investigated so far. Indeed, general definitions for soil and related terms or threshold values for pollution and other soil threats are still missing in conservation and many soil-related policies (Paleari, 2017; FAO et al., 2020; BfN, 2021); important relationships are not sufficiently recognized (e.g., ecological, economic, and social aspects of soil impacting human well-being).

TARGETING NATURE CONSERVATION OF SOIL BIODIVERSITY AND SOIL ECOSYSTEM FUNCTIONS

In light of the recent declaration of the European Parliament on soil protection (EC, 2021) and our findings, it is clear that problems resulting from knowledge gaps and inefficient conservation actions aimed at soil biodiversity and soil ecosystem functions need to be overcome (Guerra et al., 2021). We suggest an integrative path that considers multiple actions to target the conservation of soil biodiversity and soil ecosystem functions (Figure 4). We acknowledge that initially the focus of such an approach should revise existing conservation

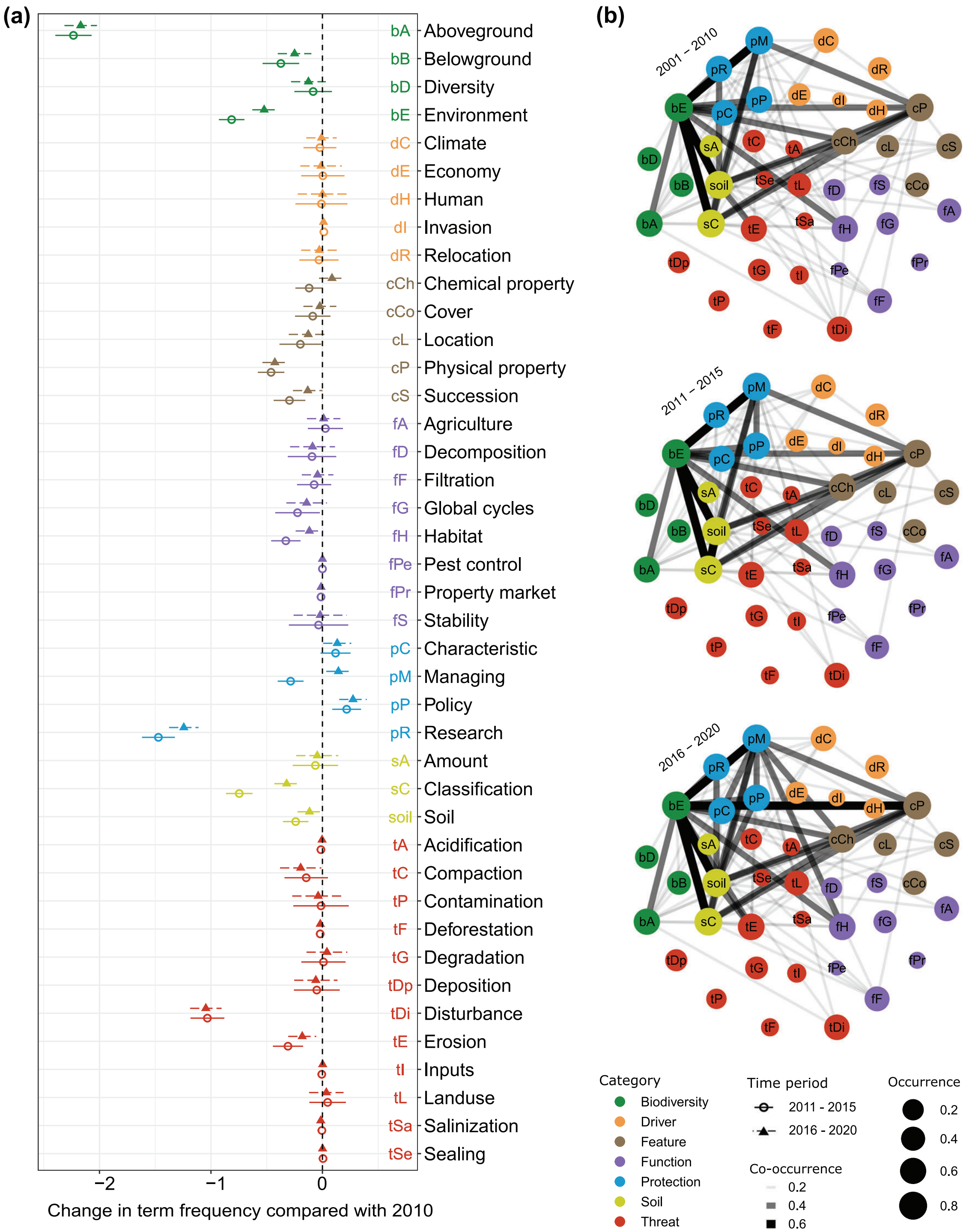

FIGURE 3 Role of soil in current management of German protected areas. (a) Difference (Cohen's *d* effect size) in mean frequency of terms in management plans of German protected areas between 2011 to 2015 (circles, $n = 1175$) and 2001 to 2010 (vertical line, $n = 539$), and between 2016 to 2020 (triangles, $n = 1791$) and 2001 to 2010. Mean term frequency for each period is in Appendices S8 and S9. The 95% confidence intervals (horizontal bars) are not calculated for terms occurring in <10% of documents ($n = 3505$). (b) Term association networks showing co-occurrence of terms at the 3 time intervals (edge width and color darkness, categorical relative document frequency of co-occurrence per period [e.g., 0.2 = co-occurring in 20% to 40% of the documents published in that period]; node size, relative document frequency in period; color, term category; letter labels, correspond to abbreviations in [a] and defined in Table 1). For visibility, only word co-occurrences present in at least 20% of documents are plotted

TABLE 1 Classification and definitions of soil-related terms

Category	Meaning	Abbreviation	Subcategories
Biodiversity	Aboveground- and belowground-living organisms and environments (e.g., *forests*); synonym for *diversity* (e.g., German equivalents to terms like *species number*, *diverse*, *species rich*)	bA bB bD bE	Aboveground Belowground Diversity Environment
Driver	Drivers of soil biodiversity, including transport and excavation of soils (i.e., *relocation*)	dC dE dH dI dR	Climate Economy Human Invasion Relocation
Feature	Physicochemical soil properties, vegetation cover, successional stages, and synonyms for site (i.e., *location*)	cCh cCo cL cP cS	Chemical property Cover Location Physical property Succession
Function	Related to ecosystem functions and services provided by soils or to its economic value in the property market	fA fD fF fG fH fPe fPr fS	Agriculture Decomposition Filtration Global cycles Habitat Pest control Property market Stability
Protection	Associated with protection of soils, including specific characteristics that make soils deserve special protection (e.g., *age*, *heterogeneity*, *rarity*), practices beneficial to soil (i.e., *managing*), name of soil policies, and technical research terms (e.g., *observation*, *assessment*)	pC pM pP pR	Characteristic Managing Policy Research
Soil	Soil types (i.e., *classification*), terms describing amount of soil (e.g., *volume*, *mass*, *material*), subcategories of the term *soil* comprise synonyms for *soil* and terms that do not fit in other categories	sA sC soil	Amount Classification Soil
Threat	Factors that detrimentally affect soil biodiversity, ecosystem functioning, or both; including *pollution* (i.e., contamination)	tA tC tP tF tG tDp tDi tE tI tL tSa tSe	Acidification Compaction Contamination Deforestation Degradation Deposition Disturbance Erosion Inputs Land use Salinization Sealing

Note: To facilitate our analysis, we created a word list of soil-related terms and classified those into 1 of 7 categories and 41 subcategories, respectively. More information and the meaning of the individual subcategories are in Appendix S1.

management activities to effectively embrace the belowground ecosystem. Specifically, the effects of activities—such as grazing and mowing in grasslands (Allan et al., 2015; Byrnes et al., 2018; Gilmullina et al., 2020) and deadwood management in forests—on soil biodiversity should be recognized and included in current decision-making. Leaving standing dead biomass in protected areas, for example, can preserve above- and belowground biodiversity and restore degraded land (Minnich et al., 2021). In a similar way, implementing an ecosystem approach to conservation will amplify the recognition of the ecological contribution of soils and soil-living species (Byrnes et al., 2014; Soliveres et al., 2016; Manning et al., 2018; Seibold et al., 2018; Eisenhauer et al., 2019) and avoid focusing on a few popular species (Mammola et al., 2020).

Although the first 2 steps take advantage of existing structures, baselines for the status of soil biodiversity and related ecosystem functions will move conservation toward targeting soil ecosystems directly (i.e., entering the cycle of soil ecosystem conservation). Indeed, information on the status quo of soil communities that could be used to compare existing and future climate or management scenarios is very limited (FAO & ITPS, 2015). Baselines serving as references, especially for temporal studies, need to be defined immediately, for example, by taking the latest LUCAS soil biodiversity data for Europe (Orgiazzi et al., 2018) as status quo. They allow one to investigate future changes in extinction patterns and in the provision of soil ecosystem functions, to assess drivers of soil biodiversity and related ecosystem functions, and subsequently to estimate

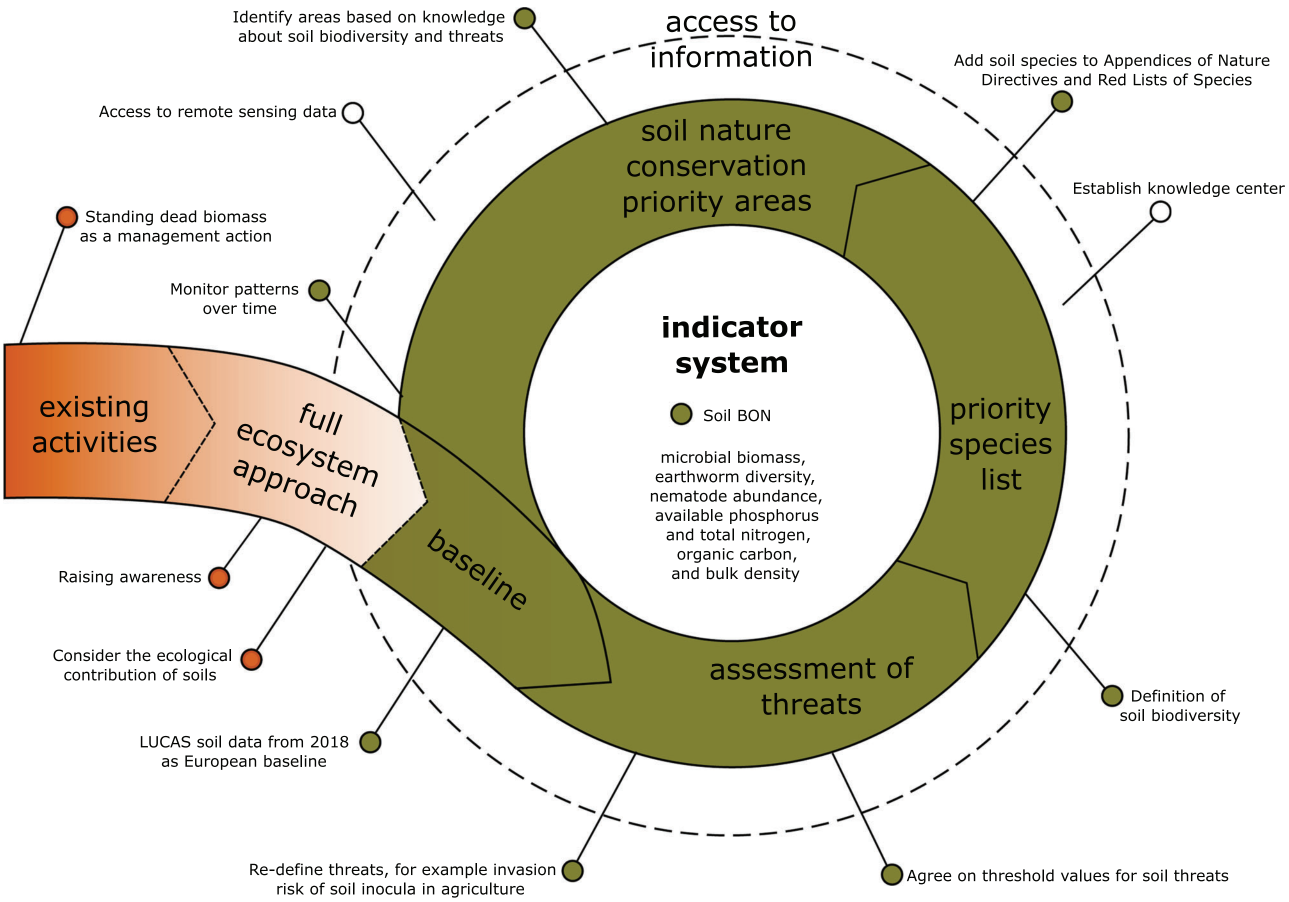

FIGURE 4 The cycle of targeting soil ecosystem conservation from an integrative perspective (pins, specific examples; color, gradient from use of existing tools to targeting soil biodiversity), starting with existing management actions, which go hand in hand with a full ecosystem approach in conservation. Baselines serve as reference for temporal studies that improve investigation and monitoring of threats. Soil organisms are included in species lists, from which priority areas for soil biodiversity can be identified and managed

extinction risks for soil biota, among others. Thereby, baselines will also promote the investigation and monitoring of threats to soil biodiversity and ecosystem functions. Such threats need to be redefined (e.g., species invasions that are often unconsidered when using soil inocula in agricultural systems [Ambrosini et al., 2016]) and thresholds for threat levels that cause detrimental or irreversible changes in soil communities need to be estimated (Beaumelle et al., 2021). It is also important to agree on a common definition of *soil biodiversity* (Orgiazzi, 2022), which is necessary to create soil-specific species lists for nature conservation; recent soil biodiversity reports (e.g., Orgiazzi et al., 2016; FAO et al., 2020) can serve as a basis. In Europe protected areas are established and managed based on a predefined set of species, which are listed in the appendices of the Habitats Directive (and Birds Directive). However, those lists account for only a minority of soil organisms, partly due to challenges in their identification to species level and to scarce information on their population dynamics (Phillips et al., 2017). Creating species lists that include soil organisms may be not as straightforward as for aboveground taxa (e.g., plants and animals) due to missing data at population or species level (Cameron et al., 2018; FAO et al., 2020), but it will help to set priority areas for soil biodiversity and critical functions. Such priority areas, that is, areas with the main purpose of protecting soil biodiversity and functions, are missing. To identify and manage priority areas for soil ecosystems, one needs to rely on knowledge of soil biodiversity, functional properties, and their threats and on a transparent soil indicator system that allows assessment of soil ecosystem status and conservation vulnerability (e.g., SoilBON; Guerra et al., 2021). Appropriate indicators are soil attributes that provide substantial information on soil biodiversity and ecosystem functions, such as those presented above (e.g., microbial biomass), earthworm diversity, organic nutrient or carbon content, and bulk density (Huber et al., 2008; Bispo et al., 2009; Leeuwen et al., 2017; Vogel et al., 2019). This implies systematic soil monitoring (Guerra et al., 2021), which is a central part of the proposed cycle of soil ecosystem conservation. Once established, all the cycle's components will expand the originally defined baseline with newly available data. An updated baseline will again drive the cycle of soil ecosystem conservation and allow for a broader access to information needed for conservation managers and other stakeholders (Vanermen et al., 2020). This could include establishing knowledge structures (Kühl et al., 2020), such as a global soil information platform

(Ramirez et al., 2015), and promoting easily accessible remote sensing data. Finally, the concept of improving soil ecosystem conservation we developed can be applied not only to Europe, but also to other areas worldwide.

CONCLUSIONS

We found that soil—even if considered more often over time in global and European policies—is still ineffectively protected by current conservation networks. Nature conservation management did not show the high regard for protecting soil organisms and related services afforded to other groups (e.g., birds, plants). Otherwise, we would have seen an effect of current protected areas on soil ecosystem functioning or a greater number of management plans mentioning distinct soil terms and a stronger association between belowground biodiversity and protection, among others. Important aspects, uppermost the intrinsic value of soils (Phillips et al., 2020), remain underrepresented in management plans and are therefore not covered by protected areas. To overcome such issues in soil biodiversity conservation, we propose 8 steps for a more targeted perspective: expand existing activities, consider a full ecosystem approach, set baselines as references, monitor threats to soil biodiversity and ecosystem functioning, define species lists for nature conservation, establish a soil indicator system, improve access to information for all stakeholders, and identify priority areas for soil ecosystem.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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