Global extinction risk assessment of soil-dependent species: recent progress and recommendations

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Abstract Soil biodiversity is crucial to the maintenance of multiple critical ecosystem functions and services. However, remarkably little is known about the conservation status of most soil-dependent species. To better understand the current situation, we determined the number of soil-dependent species listed in the various categories of the IUCN Red List of Threatened Species. Firstly, a definition of soil-dependent species was developed for IUCN Red List purposes, and this definition facilitated the identification of 8,653 currently listed soil-dependent species. These species included 503 invertebrate and fungal species assessed during the current study; these species were chosen as they were based on priorities for the Red List Strategic Plan, and IUCN Species Survival Commission (SSC) Specialist Group interests. We discuss progress and constraints on the IUCN Red List assessment of soil-dependent species worldwide. Our recommendations for the IUCN SSC to improve the IUCN Red List as a source of information on conservation of soil-dependent species are: (1) scaling up of SSC assessment processes for soil-dependent invertebrates and fungi, including establishment of a Soil Biota Working Group, in line with the IUCN Red List Strategic Plan; (2) building closer connections with other organizations and agencies researching and monitoring soil biodiversity;

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and (3) broader engagement with and education of governments, landholders and the public as to the fundamental importance of the conservation of global soil biodiversity.

Keywords IUCN Red List of Threatened Species, soil biodiversity, soil-dependent, species conservation, Species Survival Commission, symbiosis, threatened species, undescribed species

Introduction

Soils are estimated to be home to 59% of Earth's species (Anthony et al., 2023) and they contribute to multiple ecosystem functions and services, including climate regulation, soil formation and decomposition (Pascual et al., 2015; Orgiazzi et al., 2016; FAO et al., 2020; Larbodière et al., 2020). Reported options for improving knowledge of the status of soil biodiversity conservation include mapping potential levels of soil biodiversity and associated threats (Orgiazzi et al., 2016; Averill et al., 2022), uncovering global hotspots for soil species conservation (Guerra et al., 2022), and linking this to important ecosystem services (Guo, 2022; Venturini et al., 2023). Although these global reviews are beneficial for showing where soil biota is most imperilled, the risk of extinction for individual soil-dependent species is in most cases unknown. Without knowledge of the conservation status of individual species, we cannot ensure that measures that prevent serious population declines and extinction events are correctly identified and can be effectively implemented. However, these are precisely the requirements prescribed in the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity (CBD, 2022).

The IUCN Red List of Threatened Species (hereafter the IUCN Red List) is the primary source of information concerning the global extinction risk of species (Rodrigues et al., 2006). The IUCN Red List Categories and Criteria system (IUCN, 2012a) has been used to evaluate the conservation status of c. 163,040 species from all biomes and ecosystems (IUCN, 2024) and can be applied to determine the conservation status of all species, apart from micro-organisms such as bacteria, protists and viruses (IUCN Standards and Petitions Committee, 2024).

It is generally recognized that soil biodiversity is currently grossly under-represented on the IUCN Red List (Phillips et al., 2017; Fisher, 2019; Sullivan & Ozman-Sullivan, 2021). This is most likely an overall reflection of the relatively small proportion of species assessed to date: only 0.18% (12,484 species) of the world's estimated 7 million terrestrial arthropods (Stork, 2018), and only 0.04% (794 species) of the estimated 2 million fungi species (Niskanen et al., 2023), have had their global conservation status assessed (Stuart et al., 2010; Hochkirch et al., 2021; IUCN, 2024).

To gain a better baseline perspective on this substantial knowledge gap, we interrogated the IUCN Red List to determine how many soil-dependent species were listed and their respective conservation status. We also applied the Red List Categories and Criteria to hundreds more fungi and invertebrates. To complement these results, we then discuss the status of soil-dependent species and provide recommendations to increase knowledge of them and support sustainable management for them.

Methods

A review of the IUCN Red List (IUCN, 2024) was undertaken in June 2024 to establish the extent to which soil-dependent species had already been evaluated. However, prior to that, preliminary steps were required, because an official, globally adopted, standard definition of soil biodiversity was lacking. Although some definitions of soil biodiversity have been developed (FAO et al., 2020; Larbodière et al., 2020), it was first necessary to establish a working definition for which species meet the criterion 'soil-dependent', for specific use with respect to the IUCN Red List.

In the broadest sense, most terrestrial and many freshwater and marine species can be connected to soil ecosystems (van Straalen, 2021). This can be through a variety of associations, including burrowing, feeding and reproducing in soils, and/or contributing to the ongoing formation of soils.

To narrow the definition of soil-dependent species so as to facilitate the identification of those species on the IUCN Red List, a draft working definition was developed by the IUCN Biodiversity Assessment and Knowledge Team and circulated to key experts, especially for invertebrate and fungal species, from the IUCN Species Survival Commission (SSC) community and associated researchers. Subsequent revision and finalization of the definition occurred through further correspondence with experts from the SSC Invertebrate Conservation Committee and the SSC Fungal Conservation Committee.

In the second step, which was undertaken to gain a better understanding of any unknown constraints in applying the IUCN Red List Categories and Criteria to species typically regarded as soil-dependent, 503 terrestrial, soil-dependent invertebrate and fungal species were newly

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assessed for extinction risk (and 38 were additionally reassessed). These species were chosen based on priorities for the Red List Strategic Plan and on IUCN SSC Specialist Group interests. This assessment included standardized details of the global distribution of the individual species; population abundance and trends; habitat and ecological requirements; past, current and potential near future threats; and conservation measures in place, underway or needed. With these data compiled, the IUCN Red List Categories and Criteria system was applied to initially identify the global extinction risk to these species. A further review of the application of the IUCN Red List Categories and Criteria was then undertaken by the relevant IUCN Red List Authorities of the SSC before the completed species accounts with maps and IUCN Red List status were submitted for final publication on the IUCN Red List.

The third step was an IUCN online workshop of experts on soil-dependent species, convened in October 2023, to discuss the results of our application of the IUCN Red List Categories and Criteria for the identification of soil-dependent species and to develop recommendations for addressing remaining knowledge gaps in soil biota conservation. Expert contributions were predominantly from members of the SSC Specialist Groups, with additional input from experts from other relevant networks (e.g. the Soil Biodiversity Observation Network; Guerra et al., 2021). Fundamental uncertainties about the use of the IUCN Red List Categories and Criteria to assess the extinction risk for individual species were discussed, as well as opportunities for improving global knowledge of the conservation status of soil-dependent species via the IUCN Red List.

Results

Based on the consultative review process involving IUCN group members in 2023 and 2024, the following working definition for soil biota was adopted:

> Soil-dependent species are here defined for The IUCN Red List of Threatened Species as those organisms that spend a key part of their life cycle within a soil profile or predominantly inhabit the soil-litter interface. This includes soil megafauna, macrofauna, mesofauna, microfauna, microflora, fungi and microorganisms. Although we recognize that most plants play an important role in maintaining soil fertility, structure, drainage and aeration of soil, they are not tagged as soil species on the IUCN Red List.

Applying this definition, the extinction risks of all soil-dependent species published on the IUCN Red List (IUCN, 2024) were compiled. In total, 8,653 soil-dependent species, including the 503 species newly assessed for this study, were tagged (Table 1): 5,010 terrestrial vertebrates (14.3% of the 35,139 terrestrial vertebrates evaluated), 3,133 invertebrates (mostly arthropods and molluscs), and 510 fungi. Of the tagged soil-dependent species, 1,758 (20.3%) are globally threatened (Critically Endangered, Endangered or Vulnerable) and 1,722 (19.9%) species are Data Deficient (i.e. there is not yet enough information to determine whether the species is globally threatened). A further 5,138 soil-dependent species are not globally threatened (Near Threatened or Least Concern), but 35 soil-dependent species are believed to be globally Extinct (IUCN, 2024).

Of the 8,653 tagged soil-dependent species, 245 were identified as being globally threatened through meeting the IUCN Red List criterion A (a rapid and significant reduction in global population size); 1,136 through criterion B (a small and decreasing geographical range size); 130 through criterion C (small number of mature individuals); 335 through criterion D (population very small or restricted in distribution); two soil-dependent tortoise species were listed through the use of a quantitative analysis (criterion E); and 109 of the species met more than one criterion.

The main threats to the threatened species on the IUCN Red List were from agriculture (1,046 species), residential and commercial development (578 species), logging activities (530 species), impacts of invasive species (523 species), climate change and severe weather events (409 species), and fire and fire suppression (311 species), with more than one threatening process often applying to individual species.

Discussion

As soil-dependent species and their associated ecosystem functions and services tend to be neglected in most biodiversity assessments and nature conservation efforts, an improved understanding of their conservation status is essential for any efforts towards preventing extinctions and maintaining or improving soil health (Zeiss et al., 2022). There are still vast gaps in our knowledge of the conservation status of soil-dependent species, especially for soil invertebrates and fungi, whose fundamental roles in soil functioning should not be overlooked (Noriega et al., 2018).

Expert-driven assessments have now evaluated, at least once, the global conservation status of the majority of described terrestrial and freshwater vertebrates for the IUCN Red List (IUCN, 2024), and most described marine vertebrates have been evaluated. Gathering and publishing data and scientifically objective global conservation status information for vertebrates alone has been an immense task. Moreover, conservation status is not fixed and needs consistent, regular, global monitoring, at least of key/indicator species in representative groups. Therefore, gathering a complete global conservation picture for several hyper-diverse (e.g. soil insects and mites) or economically relevant (e.g. soil nematodes) groups, where most species remain undescribed, is another immense task, and one that the IUCN is unlikely to be able to tackle soon.

TABLE 1 Number (and per cent) of terrestrial vertebrate, invertebrate and fungal species assessed for the IUCN Red List (IUCN, 2024). Threatened includes species that are categorized as Critically Endangered, Endangered or Vulnerable. For the 'all species' groups, a further two vertebrates and three invertebrates are categorized as Lower Risk/conservation dependent, a category that is now discontinued.

	Terrestrial vertebrates		Terrestrial invertebrates		Terrestrial fungi		Total	
Category	Soil-dependent	All species	Soil-dependent	All species	Soil-dependent	All species	Soil-dependent	All species
Extinct or Extinct in the Wild	25 (0.5)	307 (0.9)	10 (0.3)	264 (1.6)	0 (0)	0 (0)	35 (0.4)	571 (1.1)
Threatened	869 (17.3)	7,288 (20.7)	715 (22.8)	3,898 (23.6)	174 (34.1)	327 (41.2)	1,758 (20.3)	11,513 (22.0)
Near Threatened	242 (4.8)	2,315 (6.6)	318 (10.2)	1,309 (7.9)	48 (9.4)	66 (8.3)	608 (7.0)	3,690 (7.0)
Least Concern	3,132 (62.5)	22,001 (62.6)	1,221 (39.0)	7,341 (44.5)	177 (34.7)	240 (30.3)	4,530 (52.4)	29,582 (56.4)
Data Deficient	742 (14.8)	3,226 (9.2)	869 (27.7)	3,690 (22.4)	111 (21.8)	160 (20.2)	1,722 (19.9)	7,076 (13.5)
Total	5,010	35,137	3,133	16,502	510	793	8,653	52,432

Within IUCN, there is a widely recognized need to expand Red List assessments for invertebrate and fungal species. However, although these groups are prioritized for investment in the IUCN Red List Strategic Plan 2021–2030 (IUCN, 2019), overall funding constraints for the IUCN Red List, and the lack of taxonomic experts, limits progress towards meeting the ambitious assessment targets. Although organisms can now be identified by molecular means, reduction in global soil taxonomic capacity diminishes the possibility of the rapid development and implementation of Red List assessments of soil organisms. With respect to single-celled soil-dependent microorganisms, however, although they cannot be assessed using the IUCN Red List Categories and Criteria (IUCN, 2024), the means to better understand their conservation status, for instance through sequencing tools, are available (Delgado-Baquerizo et al., 2020).

Most of the biodiversity in soil and the associated ecosystem functioning and services are driven by single-celled microorganisms (Anthony et al., 2023). However, the IUCN framework was developed primarily for multicellular eukaryotes and is not yet applicable to single-celled organisms (IUCN, 2024). Microbial taxa often lack clearly defined species definitions as a result of high genetic variability and ongoing debates surrounding microbial species concepts. Most microbes are recognized solely through environmental DNA or amplicon sequence variants, which do not meet IUCN criteria for valid species-level assessment (Hibbett et al., 2011). In addition, biogeographical metrics are difficult to define for microbes, which are often cosmopolitan, highly dispersive or occur at low abundance in a wide variety of habitats (Fenchel & Finlay, 2004). Their presence may go undetected, despite wide distribution, as a result of under-sampling, leading to the inability to establish microbial population baselines and trends (Dahlberg & Mueller, 2011). Similarly, demographic parameters such as generation length, age at maturity and reproductive rates are difficult to determine for microbes because of their rapid turnover rates, asexual reproduction and the difficulty of tracking populations over time (Delmas et al., 2019; Hochkirch et al., 2021). Conversely, the means to understand their conservation status, for instance through sequencing tools, are becoming more available (Delgado-Baquerizo et al., 2020) and taxonomic, ecological and methodological advances are ongoing.

The diversity of soil-dependent species already included in the IUCN Red List shows that it is possible to apply the IUCN Red List Categories and Criteria to evaluate the extinction risk of both global populations and national or regional populations (IUCN, 2012b) for many taxonomic groups. Examples of recent progress (2023–2024) are the inclusion on the IUCN Red List of 393 species (24 published so far) of dung beetles from southern Africa, 130 earthworms from Brazil, and selected North American mushrooms and fungi relatives. Contrary to some concerns

about the applicability of the IUCN Red List Categories and Criteria to soil-dependent taxa, no difficulties should be experienced in applying these criteria for the determination of the conservation status of these species.

One of the arguments for not using the IUCN Red List Categories and Criteria to evaluate conservation status is that there may be insufficient information to apply the criteria (although when this is the case, the even the categorization of Data Deficient is of potential value as it may encourage research on such taxa). This perception exists not just for poorly known soil-dependent species' groups, but often for comparatively well-known taxa. Detailed data are currently unavailable for many soil-dependent taxa, but consideration should be given to using surrogate or proxy information and spatially explicit modelling (Chaudhary et al., 2018; Salako et al., 2023), based on existing soil biodiversity databases (Burkhardt et al., 2014) and environmental data, to assess conservation status using the IUCN Red List Categories and Criteria.

The IUCN Red List Guidelines (IUCN Standards and Petitions Committee, 2024) provide a range of analytical approaches to infer conservation status. For example, where a species is limited to a specialized habitat (with knowledge preferably including information on the species' soil habitat), the amount of loss of that habitat type could be used as surrogate data to calculate any population reduction based on criterion A (IUCN, 2012b). Similarly, knowing that a species is confined to a small geographical area that is undergoing severe fragmentation can indicate that the species could qualify for listing under criterion B. However, criteria C and D (both concerning small population sizes) are difficult to apply to most soil-dependent invertebrates and fungal species. Progress in creating species-level databases and global distribution maps for soil biota can help address this limitation (Phillips et al., 2019; Potapov et al., 2023).

There is also a misconception that a species needs to meet each of the IUCN Red List criteria to be considered at risk of extinction. Although a species should be assessed against each of the criteria, it needs to meet only one criterion under the Critically Endangered, Endangered or Vulnerable category to be considered threatened (and one species can meet multiple criteria under multiple categories, with the highest category of threat met being used to determine the extinction risk to the species; IUCN, 2012b).

Certain taxa crucial for the functioning of soil ecosystems, such as arbuscular mycorrhizal fungi, are not currently included in the IUCN Red List. Discussions are ongoing as to the suitability of allowing typification of species from DNA sequence evidence alone, an approach that would have a profound impact on describing and assessing the many taxa that make up soil biodiversity (Nilsson et al., 2023). When framed in the context of a specific conservation strategy for soil biota, evaluating the conservation status of a representative selection of soil biota as indicator species for a specific geography, biome, ecosystem or habitat would facilitate better understanding and management of soil biodiversity and the benefits these species provide (Lavelle et al., 2022; Zeiss et al., 2022). By using the IUCN Red List Index methodology (Butchart et al., 2004), including investigating a diverse sample from the Red List Index (Henriques et al., 2020), it would be possible to monitor trends in overall extinction risk for soil-dependent species and ecosystems, and to track progress towards targets for halting biodiversity loss, including Target 4 (Halt species extinction, protect genetic diversity, and manage human–wildlife conflicts) of the Kunming–Montreal Global Biodiversity Framework (CBD, 2024).

Based on the consultative process and deliberations of this review, we here provide a situation report and then propose three recommendations for the implementation of improved assessment of the status of soil-dependent species globally, and for their conservation.

There is an urgent need to expand the coverage of soil biodiversity within the IUCN Red List to ensure better representation of soil biota; this statement echoes earlier calls (Dahlberg & Mueller, 2011; Gerlach et al., 2014; Hochkirch et al., 2021; Niskanen et al., 2023). Most of the acknowledged soil-dependent species on the IUCN Red List were vertebrates (5,010 species), which form only a small and unrepresentative proportion of the soil biota (Decaëns, 2010). Therefore, to effectively complement the comprehensive IPBES (2018) thematic assessment on soil biodiversity, which consolidated policy-relevant insights into soil biota functions, distributions and threats, there is an urgent need to better resource the IUCN Red List Strategic Plan objectives and expand the extinction risk assessment of the many underrepresented groups of soil invertebrates and fungi. The IUCN SSC has multiple Specialist Groups that provide expert guidance on the conservation status and needs of soil-dependent biota; for instance, there are existing volunteer networks that provide information on (among others) the conservation status of the dung beetles, mites and ants, along with several groups specializing in fungi, many species of which are soil-dependent. However, there remain many gaps in the coverage of soil-dependent species in the SSC Specialist Group networks, for which groups should be established and resourced (such as the recent formation of SSC Specialist Groups for earthworms and woodlice).

Based on the current situation, our first recommendation is to establish an IUCN SSC Soil Biota Task Force/Working Group that would bring together experts from SSC Specialist Groups to share data, knowledge and experiences on conservation of soil biota, including expansion of IUCN Red List assessment coverage to many additional soil-dependent species, in line with the IUCN Red List Strategic Plan. To enable the building of these

expert networks, and subsequent inclusion of more soil-dependent species on the IUCN Red List, there is a need to mobilize additional resources. Progress made, and reporting on expanding coverage of IUCN Red List soil-dependent taxa, should be tracked with annual species assessment targets across multiple groups of taxa. Funding primarily for species assessment is increasingly difficult to obtain, and more innovative means of raising support for this process that ensure there are connections among taxonomic expertise, species assessments and conservation planning and biodiversity monitoring, are more likely to be successful.

Our second recommendation is for the IUCN SSC to build closer connections to other organizations and agencies involved in the promotion and maintenance of soil biodiversity, both regionally and globally. Examples of these organizations include the Food and Agriculture Organization International Network on Soil Biodiversity, which focuses on measuring, assessing, monitoring and conserving soil biodiversity (FAO, 2024); the Soil Biodiversity Observation Network, a soil research community whose activities include evaluation and identification of protected areas for soil-dependent species (Guerra et al., 2021); the Society for the Protection of Underground Networks, which undertakes the mapping of global mycorrhizal fungal networks; the Global Soil Biodiversity Initiative, a global collaboration of soil scientists; the Global Soil Partnership, with a mission to position soils on the global agenda and to promote sustainable soil management; the Global Soil Biodiversity Observatory, a collaborative initiative led by FAO and the government of China; and the South American Mycorrhizal Research Network, a scientific community focused on mycorrhizal fungal species in South America, among other goals (Bueno et al., 2017).

Our third recommendation is to increase the transfer of knowledge to governments, landholders and the public regarding the fundamental global importance of the conservation of soil biodiversity, with the Red List serving as a baseline and reference.

Closing remarks

The value of conserving soil biodiversity is becoming increasingly recognized by landholders, government agencies and NGOs. However, there is a clear need to address the huge knowledge gaps that are limiting the scientifically planned management of soil ecosystems. Through the implementation of the recommendations of this study, the IUCN and its partner organizations will be able to support more informed decision-making by governments and communities globally to achieve more sustainable interactions with soil-dependent species and ecosystem functioning.

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Conflicts of interest None.

Ethical standards This research abided by the *Oryx* guidelines on ethical standards.

Data availability All data used for this study are available from the IUCN Biodiversity Assessment & Knowledge Team Red List Unit, IUCN UK Office, Cambridge, UK (redlist@iucn.org).

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