Perspective

Microbes as conservation targets

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Abstract

A world without microorganisms would lack essential processes that support life. The degradation or loss of microbiomes will lead to severe disruptions in ecosystems, nutrient cycling, and the climate; failures in food production; and crises in animal and human health. Yet, microbes remain largely excluded from nature conservation efforts. Current microbial management predominantly relies on the use of antibiotics and other destructive practices, while anthropogenic perturbations additionally accelerate the decline of microbial diversity. In this perspective, we argue that traditional conservation goals benefit from the inclusion of microbes and propose adaptations to existing conservation frameworks that account for the unique characteristics of microbial life. Achieving successful microbial conservation requires closing critical research gaps, implementing supportive legislation at national and international levels, and conducting risk assessments. This perspective serves as a call to action to establish a framework for microbial conservation, set measurable and effective goals, and foster public support through education and outreach.

Introduction

Microorganisms are fundamental to life on earth, playing crucial and irreplaceable roles in biogeochemical cycles, climate, ecosystem services, and human health. Yet their diversity and functionality are threatened by anthropogenic global change. Nevertheless, microbes are considered neither in conservation biology, legal and policy frameworks, nor in practical implementation of conservation concepts. In this perspective, we advocate for microbial conservation, discuss how traditional conservation goals can be advanced through the inclusion of microbes, and propose necessary adaptations to conservation concepts that account for the unique characteristics of microorganisms. Arguments in favor of the conservation of microbes can be separated into their instrumental values and the microorganisms’ own rights (Redford 2023). While the conservation of microbes in their own rights is centered around debatable ethical questions about the intrinsic value of microorganisms (Cockell and Jones 2009), their crucial importance for life on Earth is undisputable (Cavicchioli et al. 2019, Voolstra et al. 2024). Beyond their contributions to biogeochemical cycles and ecosystem processes, microorganisms hold substantial economic value (Han et al. 2023), are essential in food production (Singh et al. 2016), play and will continue to play a crucial role in mitigating negative effects of climate warming (Banerjee et al. 2020, Silverstein et al. 2023, Peixoto et al. 2024) and further global change effects (Berg and Cernava 2022). In fact, despite not being explicitly mentioned, microbes are integral to achieving most of the UN Sustainable Development Goals (Rappuoli et al. 2023) with strong positive impacts on human health (Robinson et al. 2024).

The planet is on an alarming trajectory towards a sixth mass extinction event (Ceballos et al. 2015, Cowie et al. 2022) and microbes are no exception in being under threat due to human activities (Berg and Cernava 2022). While some losses in microbial diversity may be offset by rapid evolution and diversification (Thaler 2021), evidence is accumulating that microbial alpha- and beta-diversity is declining. The drivers of microbiological diversity loss overlap with those for the decline in ‘macrobiological’ diversity (IPBES 2019) and include habitat loss (Peixoto et al. 2022), direct effects of global change factors such as pollution, drought and climate warming (Rillig et al. 2019, Rocca et al. 2019), as well as cascading effects from declines in macrobiological diversity (Junker et al. 2021, Baldrian et al. 2023) such as co-extinctions with hosts (Averill et al. 2022). Loss of and decline in microbial diversity causes the homogenization of microbial communities across larger scales, reduced host-specificity, increased prevalence of pathogens with higher antimicrobial resistance, and consequently, dysbioses (Guerra et al. 2021, Berg and Cernava 2022). Despite the critical functions and services provided by microorganisms, current microbial management predominantly involves destructive practices such as the use of disinfectants, antibiotics, or fungicides, which further threatens microbial diversity (Peixoto et al. 2022, Rappuoli et al. 2023). Accordingly, we urge for the inclusion of microorganisms as explicit targets in conservation efforts (Fig. 1).

A microbial perspective on conservation practices

In the nineteenth century, the loss of landscape elements and species with high aesthetic value led to the first efforts to protect nature, which resulted in today’s strategies and concepts of conservation biology (Table 1, Muir 1901, Primack 1995). Since the designation of the world's first national park in 1872 (Yellowstone, US), the share of protected areas has increased globally (Watson et al. 2014). The protection and conservation of landscapes and species has been enshrined in international agreements, constitutions and national laws with e.g. the International Convention for the Protection of Plants agreed in 1929, the Convention on the regulation of Whaling in 1946, the foundation of the International Union for Conservation of

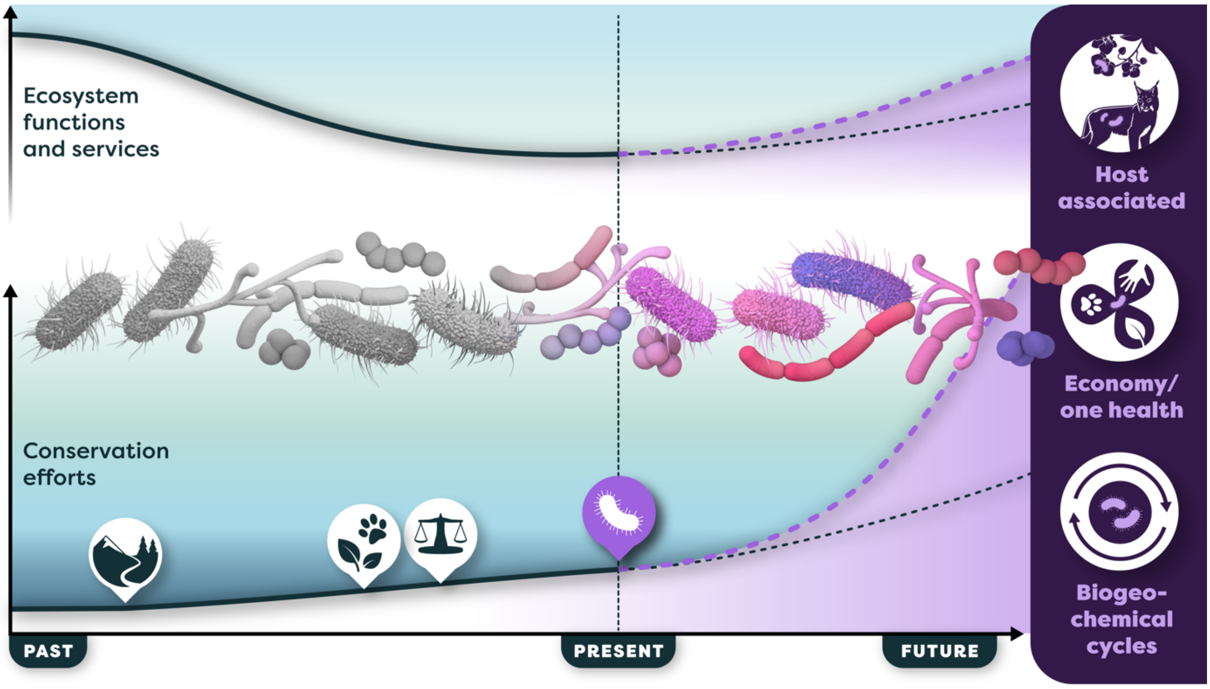

Fig. 1 Microbes must be defined as explicit conservation targets to complement traditional approaches and thereby accelerate the protection and restoration of ecosystem functions and services (dashed purple lines). Anthropogenic activities led to degraded ecosystem functions and services (upper black curve). Consequently, conservation practices such as habitat and species protection (since ~1872 and ~1929, respectively) as well as national and international policies (since ~1948) were implemented to protect and restore ecological processes (lower black curve). These and further conservation measures increased over time and led to a recovery or the maintenance of (near-) natural ecosystems. Microbes are essential for any processes that support life and a livable environment. Associated to hosts (plants, animals, humans) or free-living in the environment, microbes are irreplaceable in their contributions to biogeochemical cycles, the climate, ecosystem services, and human economy and health (illustrated in the purple bar at the right side). Accumulating evidence suggests that anthropogenic perturbations result in a decline of microbial diversity and degradation of microbiomes, but our knowledge on their full impact as well as on diversity baselines remains limited. Consequently, research on microbiological diversity as well as microbial conservation may be key in protecting and restoring nature and crucial processes fundamental for live on earth. Credits for illustration: Daniela Leitner.

Nature in 1948, the International Convention for the Protection of Birds signed in 1950 and the Antarctic treaty being firstly in force since 1961 (Gillespie 2013, Tab. 1). To successfully protect wild living plants and animals as well as their habitats, systematic surveys of the population situation of species and status of habitats were indispensable, which led in 1964 to the publication of the first Red Lists (www.IUCN.org; "Red Data Book"). As protected areas have been generally shown to effectively improve the state of biodiversity, i.e. ecosystems and species under consideration (Langhammer et al. 2024), the proposition to protect 30% of land and marine areas by 2030 (Dinerstein et al. 2019) has been agreed by the Conference of the Parties in the Kunming–Montreal Global Biodiversity Framework (CBD, 2022). Despite these global targets to tackle the ongoing biodiversity loss, there is still a lack of comprehensive data on the distribution of biodiversity on Earth to set evidence-based conservation priorities (Karimi et al. 2018, Guerra et al. 2022, Jetz et al. 2022, Pinkert et al. 2024). Technological developments in the recording and processing of biodiversity data (Besson et al. 2022) offer, along with an increasing interest and participation of citizen scientists in the recording of biodiversity (Bonney 2021), the opportunity to aggregate a wealth of data for evidence-based decisions and to increase public awareness for the necessity of nature conservation for human health and well-being.

The unique characteristics of microbes do require adaptations of these concepts prior to their effective application in microbial conservation. At the same time, microbes may assist in reaching the ‘macrobiological’ goals of the conservation concepts, which represents another strong argument for the inclusion of microbes in conservation biology and practice. To initiate discussions and lay the groundwork for microbial conservation, we reviewed common nature conservation strategies (Tab. 1, habitat protection, species protection, legal and policy frameworks, and public awareness, education, and citizen science). For each of the strategies, we highlighted how microbes will support existing efforts. For instance, microbes serve important functions in maintaining the health of terrestrial and marine species as well as the functioning of habitats, and are thus crucial for their protection (Soliveres et al. 2016, Trevelline et al. 2019, Voolstra et al. 2024). Additionally, and most importantly, we propose necessary adaptations to conservation concepts that account for the unique characteristics of microorganisms and discuss potential challenges in the implementation. We demonstrate that traditional conservation concepts provide a useful framework for microbial conservation. However, for an effective conservation of microorganisms and their functions, these concepts require an update to conserve microbes and their habitats and thereby reaching integrated approaches that protect whole ecosystem with all their interacting constituents. As a next important step, microbial conservation needs to be implemented in national and international legislations and conventions and should become a familiar concept in the public.

Tab. 1 Nature conservation concepts and their adaptation to microorganisms. The table lists and defines common nature conservation concepts, and discusses how the traditional goals are supported by microorganisms and how these concepts need to be adapted to microbial conservation.

Conservation concept	Definition of traditional approach	Microbial assistance to 'macrobiological' goals	Adaptation to and challenges in microbial conservation
A Habitat protection	• Habitat protection refers to protecting the quality, diversity, abundance, and natural resources of habitats. • Protected areas differ in their conservation purpose ranging from strict nature reserves and wilderness areas (Category I) to protected area with sustainable use of natural resources (category VI, IUCN).	• Ecosystem functioning depends on microbes (Soliveres et al. 2016) calling for the consideration of microbial diversity and community composition in habitat protection.	*Adaptations* • Minimal use of antibiotics and other chemical agents will protect microbial habitats including hosts and soil (Rappuoli et al. 2023). *Challenges* • Total microbial diversity depends on environmental conditions and the availability of heterogenous niches (Seabloom et al. 2023). Definition of further and accurate determinants of microbial diversity is required for the designation of protected areas.
	• Biodiversity hotspots are areas containing a high level of species of selected taxonomic groups, particularly endemic and threatened species or both (Myers 1990). So far, global hotspots are selected based on vertebrates and vascular plants.		*Adaptations* • The protection of microbial hotspots may act at different scales than 'macrobiological' conservation. Scales need to be defined. *Challenges* • Global hotspots of soil microbial diversity are currently not protected (Guerra et al. 2022). Microbial diversity hotspots may thus not overlap with 'macrobiological' hotspots.
	• Ecosystem restoration refers to assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed (Jordan et al. 1990).	• Microbes may serve, with some limitations, as indicators for disturbed environments and restoration success (Ribas et al. 2023). • Microbes may support restoration success (Singh et al. 2019). • Nature based solutions in restoration ecology often include microbes (Ohler et al. 2023).	*Adaptations* • Engineering of habitats that promote bacterial diversity (Peixoto et al. 2022) is required, e.g. by increasing the number of micro-niches for various microbial communities. Scales need to be defined! *Challenges* • Microbiomes often do not recover to the same diversity, composition or functionality after restoration (Hart et al. 2020) calling for specific restoration practices for the recovery of microbiomes and their functions.
B Species protection	• Selected wild species are protected by law, meaning that it is illegal to kill, injure, capture or damage these plants and animals. • Red Lists serve as vital monitoring tool for population trends of species with categories ranging from being extinct to being of least concern. Vulnerable, endangered and critically endangered species are considered	• Plants' and animals' microbiomes are crucial for host health and survival. Species protection will thus benefit from including species-specific microbiomes (Trevelline et al. 2019). • Bioaugmentation *via* microbiome transplantation or probiotic treatments can increase survival rates of hosts (Peixoto et al. 2022).	*Adaptations* • Apart from *ex situ* conservation (see below), the protection of individual species or strains is impractical in natural environments (Cockell and Jones 2009). • The protection of microbial functions and communities should have highest priority (Cockell and Jones 2009). *Challenges* • Difficulties in the microbial species concept may prevent a targeted protection (Redford 2023).

	to be threatened with extinction. (IUCN Red List).		
	• Keystone species such as ecosystem engineers fulfil a central function in a habitat and/or enable the presence of other species through their existence. • Umbrella species are representatives for an ecosystem whose protection and promotion ensures the survival of numerous other species. • Indicator species are organisms whose presence, absence or abundance reflects a specific environmental condition. • Flagship species are attractive species that have a high prestige or publicity value. • Conflict generating species are species with polarized perception on impact and benefit among stakeholders (Nyhus 2016).		*Adaptations* • Microbial functions are key for ecosystem functioning and must thus be protected. Practical definitions of core microbiomes may facilitate the protection of functional modules. • Knowledge on the distribution of individual bacterial genera has been shown to predict the biogeographical distribution of their phylum (Karimi et al. 2018). These genera may represent umbrella species. • Some microbes with recognition values may serve as flagship species, such as edible mushrooms, lichens, fairy rings formed by fungi, or stromatolites (Rillig 2024). • Pathogens (Seidel et al. 2024) or microorganisms that inhibit important ecosystem functions (D'Andrea et al. 2024) may create conflicts in conservation goals if associated with otherwise beneficial microbial consortia. Risk assessments thus need to be essential parts of microbial conservation.
	• *Ex Situ* conservation programs are necessary for some species before reintroduction of a viable population into its original or restored habitat is possible. • Zoos, herbaria, seed storages and natural history collections contribute to *ex situ* conservation programs by preserving (genetic) diversity of species aiming at minimizing selection and improving the adaptability.	• The availability of host microbiomes along with viable individuals of the hosts will facilitate reintroductions. • The 'extended specimen concept', suggesting to include information on the host-associated microbiome, increases the value of samples in natural history collections (Miller et al. 2020).	*Adaptations* • In natural history collections, microbes (except for macro-fungi and lichen) are usually not considered but deserve receiving the same attention as plants and animals (Johnson et al. 2023). • Additional to *ex situ* conservation of individual strains, whole microbial communities, their genetic diversity, and their functions should be conserved for future use.
C Legal and policy frameworks	• International conventions and treaties on specific taxa (plants, birds) or areas (Antarctic, Wetlands) provide the legislation for the protection of species and habitat with the most comprehensive being the Convention of Biodiversity (Gillespie 2013). These frameworks have been transferred into continental (e.g. Nature Restoration Law as key element of EU Biodiversity Strategy for 2030) and national frameworks i.e. the National Biodiversity Strategies and Action Plans (Perino et al. 2022, Affinito et al. 2024).		*Adaptations* • Legislation currently does not include the protection of microbes or their habitats (Labouyrie et al. 2023), which, however, seems to be inappropriate given the essential microbial functions. • EU Biodiversity Strategy for 2030 and EU Soil Strategy for 2030 include proposals for the protection of soil (Labouyrie et al. 2023), which mainly addresses microbial functions. Thus, more explicit frameworks are needed. • Activities that harm microbial diversity such as pollution and intensive land use should be reduced. • The risk of resistances against antibiotics reinforces legislation to reduce the use of antibiotics to a minimum.

D Public awareness, education, and citizen science	• As the urgency to counteract the loss of biodiversity has probably never been greater (Diaz et al. 2019), it has become a political focus (CBD) leading to public awareness, education and citizen science projects (Bonney 2021).	• The 'One Health' approach requires knowledge on healthy microbiomes (Ma et al. 2023).	*Adaptations* • The public is often unaware of the beneficial effects of microbes and overestimates individual risks associated with microorganisms (Jones et al. 2013). Accordingly, more emphasis on the beneficial aspects of microbes in the public perception is required. Additionally, a more realistic individual risk assessment about the exposure to pathogens and zoonoses should be aided. • Microbes must be accessible in nature experience and non-academic experts must be involved (e.g. mycologists). • Inclusion of the value of healthy microbiomes into school curricula (Fatton et al. 2021). • Citizen science projects that include microorganisms need to be pushed. • Microbes must be more often displayed in natural history collections and museums.

Towards microbial conservation

Profound knowledge on the ecology of microbial species and communities is required to identify the most urgent microbial conservation targets and to prevent the degradation of microbial habitats and the loss of crucial microbial functions and their genetic diversity. In the following we are addressing research gaps and propose actions to place microbes into the framework of nature conservation concepts as listed in Tab. 1.

A Habitat protection:

Microbial (a)biotic niches and responses to global change: In order to define global hotspots of microbial diversity, knowledge on the distribution of species, genes and functions within and across ecosystems is required (Karimi et al. 2018, Labouyrie et al. 2023). However, microbial biogeography on the species/strain level is still underdeveloped (Weinbauer and Rassoulzadegan 2007). Accordingly, microbial abiotic niches are poorly defined (Baldrian et al. 2023) and information on responses of microbial strains, species and communities to global change components (including but not limited to climate change, Banerjee et al. 2020) is scattered (Cavicchioli et al. 2019). On a smaller scale, the multiple micro-niches that exist on a single host (e.g. Junker and Keller 2015) or within an ecosystem are often unexplored but would provide valuable information on the overall microbial diversity an ecosystem harbors. Often, we even lack a robust baseline of microbial diversity (Thaler 2021, Ribas et al. 2023), which hampers evaluations on whether microbial diversity is declining or shifting in taxonomic and functional composition. Furthermore, the mobility of microorganisms within and between ecosystem constituents deserves attention as dynamic modulations of hosts' microbiome may enable the hosts to quickly adapt to changing biotic and abiotic conditions by adding novel functions to the holobiont (Sessitsch et al. 2023). Monitoring programs should be complemented by field and lab experiments (Hanusch et al. 2024, He et al. 2024) to shed light on the effects of global change on microbial diversity and the functional redundancy in microbial communities, which is essential for their resistance, resilience and thus stability.

Overlap of microbial and 'macrobiological' conservation: It is unknown whether current conservation efforts that not explicitly target microbes also protect and promote microbial diversity. Unfortunately, plant and animal diversity is often poorly or not correlated to microbial diversity (Hanusch et al. 2022) and a global survey on the soil microbiome revealed that most hotspots of microbial diversity are currently not protected (Guerra et al. 2021). In general, hotspots are usually identified based on vertebrate and vascular plant diversity; whether and how these taxa are well suited indicators for other taxa including microbes and many other understudied taxa is still poorly understood (Kass et al. 2022, Pinkert et al. 2024) or remains unknown (Han et al. 2023). In this context, the scales need to be defined. Plant and animal diversity assessment are meaningful on larger scales, whereas microbial diversity may vary even within centimeters. Moreover, functional and phylogenetic facets of biodiversity are rarely considered (Pollock et al. 2017, Voskamp et al. 2023), which would be particularly helpful in defining microbial hotspots. Considering only host-associated microbes, the pronounced host-specificity may suggest correlations between host and microbe diversities. However, reduced host-specificity and homogenization due to global change (Berg and Cernava 2022) may strongly weaken these relationships. Thus, knowledge on the spatiotemporal distribution of microbial species and functions is required for a thorough understanding of the determinants of microbial diversity.

Retaining and restoring healthy microbiomes: Restoration projects often fail in recovering microbial diversity, composition and functionality despite specific management practices such as soil amendments and inoculations (Hart et al. 2020). Likewise, microbial transplants or probiotic treatments often fail in supporting the desired function (Peixoto et al. 2022). Partly, the pronounced stochasticity in microbial community assembly is responsible for unpredictable results of such treatments (De Vrieze et al. 2020). Accordingly, a mechanistic understanding of microbial community assembly is required that also takes functional consequences of different assembly trajectories into consideration. It may turn out that inoculations with individual strains are not sufficient to provide all functions required in specific contexts and thus applications of consortia or whole communities may be a way towards effective treatments (Azarbad and Junker 2024).

B Species protection:

Ex situ conservation: Most microorganisms are notoriously hard to culture under standard laboratory conditions as they have specific requirements on their environment or are “viable but nonculturable“ (VBNC), i.e. in deep dormancy (Bodor et al. 2020). VBNCs may, however, be key for ecosystem functions and their absence in *ex situ* collections would prevent a successful reintroduction of microbial communities in original or restored habitats. Accordingly, *ex situ* conservation of many microorganisms is hampered by these limitation and research is needed to increase the taxonomic range of culturable microbes. Alternatively, the isolation and long-term storing of VBNCs without cultivation or preserving whole microbial communities on stock may allow for successful reintroductions.

Consequences of microbial diversity loss on ecosystems and human wellbeing: Microbial communities are essential for ecosystem functioning and crucial for human wellbeing and economy (Cavicchioli et al. 2019). The ‘One Health’ concept refers to the link between human and environmental health often mediated by microbes (Banerjee and Van Der Heijden 2023) and thereby emphasizes the requirement to consider microbial functions (as opposed to species or strains) in comprehensive assessments on ecosystem functions and services as well as in conservation efforts. Often, research on the interplay between ecosystem functioning and microbial communities is presenting correlational findings (e.g. Soliveres et al. 2016), which provides valuable insights but does not allow a clear separation of causes from effects

(He et al. 2024). Therefore, detailed (experimental) studies on the effect of the decline in microbial diversity on ecosystems, human health and economy (Han et al. 2023, Redford 2023) are crucial for predicting consequences and identifying conservation priorities to attenuate or avoid global change effects.

Risks associated to microbial conservation: The minority of microbes is pathogenic or has negative impacts on the environment or human health (Rappuoli et al. 2023). Nonetheless, microbial diversity bears the danger of diseases, which is even increased due to global change (Seidel et al. 2024), as exemplified by the endured COVID 19 crises (Lawler et al. 2021). Furthermore, probiotic treatments and microbiome transplantation may have undesired side-effects to hosts and non-hosts (Peixoto et al. 2022), that must be excluded prior to exhaustive applications. Microbial conservation thus needs to be accompanied by comprehensive risk assessments in order not to jeopardize environmental and public health.

Ethical considerations: One justification for nature conservation is the ethical status of plants and animals that should be protected in their own rights. Whether and how an ethical status for microbes should be defined is centered around debatable questions about the intrinsic worth of microorganisms (Cockell and Jones 2009). According to Cockell (2004), it may be unethical to use bleach or disinfectants as it kills an enormous diversity of microbes. This deliberately exaggerated example demonstrates that a balanced discussion about intrinsic values of microbes is required to put forward legitimate arguments in favor of microbial conservation without losing acceptance in the scientific community and the general public.

C Legal and Policy frameworks

Currently international and national frameworks are focusing on ‘macrobiological’ facets, yet as outlined above the microbiological perspective is inherently linked to successful conservation of the macrobiological facet. Therefore, legal and policy frameworks need to include also microbes and their vital role in ecosystems, for which the Kunming-Montreal Global Biodiversity Framework (GBF) could serve as a starting point to expand the conservation focus to the microbial world (Redford 2023). GBF target seven aims at reducing the use of pollution to levels that are not harmful to biodiversity and thus includes microbes already. The integration of the global hotspots for soil microbial diversity (Guerra et al. 2022) into GBF could serve as a starting point for prioritizing most promising areas for conservation and restoration of the microbial world. Still such international agreed frameworks need to be implemented into national targets necessary to achieve the 2050 targets (Xu et al. 2021). This requires a significant increase in financial resources for conservation in general, including payments for vital ecosystem services provided not only by ‘macrobiological’ but also by microbiological diversity. Transparent science-policy interfaces involving stakeholders from different sectors are needed for informed decision-making and a monitoring framework is required for tracking progress of implementing these targets.

D Public awareness, education, and citizen science:

Despite the importance of microbes, the general public is still persuaded that ‘killing 99.9% of all microbes’ is advisable in many situations. In fact, allergies, asthma, and autoimmune disorders can be prevented by microbial exposure (Van den Bosch and Sang 2017, Robinson and Jorgensen 2020). Therefore, an increased awareness of the beneficial effects and a realistic assessment of potential risks of microbial diversity may foster management decisions facilitating habitats hosting health-promoting microbiomes that provide benefits across social groups (Robinson et al. 2022). Such transformations in public perception of environmental concerns can successfully be initiated in schools, where school students are educated in and made aware of unfamiliar concepts (McGenity et al. 2020). Respective educational programs may also include citizen science projects that emphasize the advantages of diverse microbiomes in natural and anthropogenetic environments (Dunn et al. 2019). Conservation biology is deeply rooted in the experience of nature. Microbes are mostly not part of the human perception of nature (Cockell and Jones 2009) apart from e.g. edible mushrooms and lichens. Awareness may be increased by training a new generation of nature educators that appreciate and teach microbial contributions to how nature is perceived. In fact, an important part of the olfactory perception of nature stems from microbial activity such as the emission of geosmin, a terpenoid that is responsible for the earthy smell in forests after rains (Garbeva et al. 2023). Dyer (2003) published a ‘field guide to bacteria’, which is a wonderful example on how to make microbes accessible to interested citizens and to engage non-academic experts into microbial conservation.

Conclusion

Twenty years ago, Cockell (2004) stated: ‘without lions there is life, but without microorganisms there can be no higher life forms,’ thereby expressing his astonishment that microbes are not part of conservation efforts. Nothing changed since then; microbes are still ignored in conservation biology and policy, despite the increasing threat of global change. Therefore, it seems mandatory to take action and conserve microbial diversity. So far, there are neither formal concepts for microbial conservation nor are clear goals defined. We argue that current conservation concepts can benefit from microbes and must be adapted to address microbes as explicit conservation targets. Ultimately, nature conservation must become an integrated approach that protects entire ecosystems with all their interacting constituents as well as the abiotic environment. Thus, this perspective is a call to action to build the framework for microbial conservation, set measurable and effective goals in microbial conservation, closely monitor the risks, and seek broad public support through education and outreach.

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