COMMENTARY

The economics of microbiodiversity

Kwi Young Han, Lennard Kröger, Florian Buchholz, Ian Dewan, Martin Quaas, Hinrich Schultenburg, Thorsten B.H. Reusch

ABSTRACT

The economics of biodiversity is gaining traction and with it the economic valuation of ecosystem services (ESS). Most current developments neglect microbial diversity, although microbial communities provide ecosystem services of great importance. Here we argue that microbial biodiversity translates into considerable economic value which is usually not explicitly included in quantitative valuation of ecological functions to date. This omission may result in inaccurate values, potentially entailing substantial economic losses, both in private and in public decision-making, due to external effects that arise as microbiodiversity is horizontally and vertically transferred between hosts and natural environments. Microbiodiversity, an important part of biodiversity in general, occupies an irreplaceable position as a natural resource in ecosystems, because of its additional insurance value within changing environments. We illustrate our arguments with specific examples (microbiomes associated with humans, soil, and corals), all of which are jeopardized through anthropogenic pressure. We conclude that the consideration of microbiodiversity in economic valuation will help to find essential assets and guide decision-makers to conserve and protect the economic value of highly diverse microbial communities for future generations.

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1. Introduction

Biodiversity is a key attribute of the biosphere that is essential for the functioning of ecosystems and biogeochemical cycles (Naeem et al., 2009) (See Box 1.1). In economic terms, it is hence a vital asset, as it is an essential enabling part of many natural capital stocks (Bateman and Mace, 2020; Dasgupta, 2021; Guerry et al., 2015). As the inaccurate and incomplete valuation of biodiversity eventually leads to loss of biodiversity and incorrect decision-making (e.g., Barber, 2007; Swallow, 1994), it is a declared goal of many countries within the Convention on Biological Diversity (Secretariat of the Convention on Biological Diversity, 2005) to mainstream the valuation of biodiversity and natural capital in decision-making at all levels. (See Table 1 for definitions of key terms).

Although models of biodiversity valuation have been improved in recent years (Dasgupta, 2021, Bartkowski, 2017, Paul et al., 2020), one specific component of biodiversity is still mostly neglected, namely microbial biodiversity (microbiodiversity from now on. See Box 1.2). The microbiodiversity of both environmental communities and host-associated microbiomes is increasingly recognized to be central for every living organism, and hence, to all ecosystem function and services (ESS). Host-associated microbiomes contribute to almost all host functions, including digestion, immunity, and even behavior (Box 1.3; Gibbons and Gilbert, 2015, McFall-Ngai et al., 2013, Onen et al., 2020, Vibha and Neelam, 2012). A similarly central role of microbes in conservation biology is being discussed Mishra et al., 2020, Trevelline et al., 2019). As microbiodevity is essential for ecosystem functioning, its value is implicitly included in standard economic valuation of biodiversity and ecosystem services. Here we argue for an explicit and context-specific valuation of microbiodiversity, where values should be

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drawn by understanding specific roles and functions of microbiodiversity in the ecosystems. This is possibly most important for host-associated microbiomes, for which microbiodiversity is nested within host individuals and transmissible both vertically and horizontally—two aspects that are not necessarily captured by standard measures of biodiversity usually assessed at the level of host species. These particular microbiodiversity values can subsequently inform economic decision making both at the individual level—most evidently in cases of human-associated microbiomes—and at the public level. We propose to use the term “microbiodiversity” for microbial biodiversity in both settings to emphasize its significance for the process of economic valuation. Microbiodiversity collectively describes the biodiversity of microbial communities, encompassing the genetic and taxonomic diversity of microorganisms (bacteria, archaea, protists, and viruses) in the environment and also in association with a host, thus including microbiome ecosystems in so-called holobionts (Box 1). We start by explaining how economic decision-making affects microbial biodiversity and thus have repercussions on its values. We thereby illustrate how current approaches to the economic valuation of biodiversity ignore the role of microbiodiversity. We subsequently discuss specific economic values of microbiodiversity, and in particular, how the evolutionary perspective on microbiodiversity reveals its option- and insurance values. Then, we present three examples of host-associated microbiomes where the diversity is impacted by economic decisions to illustrate how human perturbations affect microbiodiversity.

### 2. Economic values of microbiodiversity

The economics of microbiodiversity has to deal with a moving target. While the exact importance of microbiodiversity and especially its apparent role for both ecosystem services and host organisms is still being researched (with increasing intensity), microbiodiversity itself is already under threat at many levels. For example, land-use changes and contamination of the environment are threatening the diversity of host-associated microbiomes across different taxa, e.g. gut and skin microbiome of mammals and amphibians (Trevelline et al., 2019), while a modern lifestyle and certain medical and nutritional practices may threaten microbiodiversity in humans (Tochitani, 2021, Goff et al., 2020, Asnicar et al., 2017), the best studied example of host-microbe associations. More specific examples will be listed and discussed in detail in section 3.

#### 2.1. Current economic valuation of biodiversity and the missing link to microbiodiversity

Valuation of biodiversity has been a topic in economic research since long (Heal, 2000; Kumar, 2012, Pearce and Moran, 2013), and in recent years the academic interest in the economic value of biodiversity has been growing (Seddon et al., 2016, Bartkowski, 2017, Paul et al., 2020). Seddon et al. (2016) strongly emphasized the diversity aspect in the context of economic value of ecosystems and concluded: “Although much of the diversity of microbes, pathogens, insects, birds and mammals in the forest system is not directly generating services to humanity, it is supplying something more fundamental by allowing the ecosystem to regenerate in perpetuity, and to withstand and recover from disease and environmental change.” Here we expand these considerations by taking a more specific focus and argue that the value of microbiodiversity deserves a particular attention.

Several initiatives have been striving for economic valuation of biodiversity in its broad-sense definition, covering all living organisms, although usually treated as referring to eukaryotic species diversity. For example, the UN SEEA-Ecosystem Accounting (UN SEEA-EA) framework has recently been advanced, and in part accepted, by the United Nations Statistical Commission as a statistical standard (52nd session, March 2021). While the UN SEEA-EA is based on market transactions, the Dasgupta Review (Dasgupta, 2021) proposes a valuation based on shadow prices that reflect the contribution of biodiversity and natural capital to human welfare in a broader sense.

Despite these methodological accomplishments in biodiversity valuation, the ecosystem services (ESS) connected to microbiodiversity are usually ignored. This contrasts with the biological and ecological insights currently obtained at an accelerating rate on the diverse contributions of microbes to ecosystem functions (Box 1; references therein). However, none of the recent studies specifically mention or attempt to quantify the values provided by a microbial community. Dasgupta (2021) mentions microbial biodiversity with some case studies but without positing specific exclusive values and in Bateman and Mace (2020) genetic and medicinal resources from microbes are mentioned, but without a precise connection to microbiodiversity.

We identify three reasons why a specific look at microbiodiversity is missing in current valuations. Firstly, the consequences of microbiodiversity rather than single microbes on ecosystem functions and/or host phenotypes have been only recently uncovered and quantified, and are still being intensively researched. This knowledge has yet to be properly transferred and applied to the fields of ecosystem service research and the economic valuation of biodiversity. Secondly, microbial communities are usually considered to be shaped by a high degree of species redundancy. In the case of local extinctions, the traditional consensus view posits that unlimited dispersal could replace the missing microbial functions (Galad et al., 2018). Although this might be true for some microbial communities, it is not always possible to recover lost functions through dispersal. For example, replacement by dispersal is not possible in the case of lost diversity of host-associated microbiomes, because source populations or reservoirs of the lost taxa are usually missing (Venkataraman et al., 2015). A third misconception is that a macroscopic description of biodiversity is already accounting for the associated microbiodiversity as the latter is tightly correlated to the former, and a “double-counting” should be avoided. We argue that often the correlation between microbiodiversity and species diversity is weak in the case of host-associated microbiodiversity under environmental

### Table 1

<table>
<thead>
<tr>
<th>Term/Concept</th>
<th>Definition and context</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Biodiversity</td>
<td>Box 1.1</td>
<td>Daily (1997)</td>
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<tr>
<td>Microbiodiversity</td>
<td>Box 1.2</td>
<td>Daily (1997)</td>
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<tr>
<td>Ecosystem services</td>
<td>Ecosystem services are ecological functions that sustain and improve human life</td>
<td>De Groot (1992)</td>
</tr>
<tr>
<td>Ecosystem function</td>
<td>The capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly. If ecosystem functions are to the benefit of human well-being they are ecosystem services (ESS).</td>
<td>Kremen et al. (2008)</td>
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<tr>
<td>Ecosystem resilience</td>
<td>Ecosystem resilience is an ecosystem’s ability to maintain its basic functions and controls under disturbances.</td>
<td>Baumgartner and Strunz (2014)</td>
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<td>Insurance value</td>
<td>Decrease of the probability of future drops in the provision of ecosystem services due to a (marginal) change in the level of (micro) biodiversity. This resilience insures risk-averse ecosystem users against potential welfare losses.</td>
<td>Baumgartner (2007), Baugartner and Strunz (2014), Paul et al. (2020), Quans et al. (2019)</td>
</tr>
<tr>
<td>Option value</td>
<td>Value of postponing an irreversible action (depleting microbiodiversity) in the face of uncertainty about future benefits.</td>
<td>Spanenberg and Settele (2010), Traeger (2014)</td>
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2.2. Direct and indirect value of microbiodiversity

Most of our current knowledge on the economic value of microbiodiversity comes from free-living microbes (Box 1.2 reviews the distinction between free-living microbes and those in host-associated microbiomes). Some use values from the diversity of free-living microbes have been partly accounted for, as they are already industrialized and are vital components in different branches of industry. For example, microbial cultures are used in the agricultural industry as biofertilizers, biopesticides, and bioinsecticides; in the food industry for the production of yogurt, cheese, bread, and alcohol products; and in the pharmaceutical industry for the production of vaccines, antibiotics, probiotics, and enzymes (Simpson et al., 1996, Torino et al., 2015, Naughton et al., 2019, Kalsoom et al., 2020). As products exist that are based on microbial cultures, their market price partially captures the value of microbiodiversity, yet such products are only a tiny fraction of the benefits that humans derive from microbiodiversity.

Free-living microbes are involved in diverse ecosystem functioning processes, in both microscopic and macroscopic scales, for example in nutrient cycling and biodegradation, or the production of oxygen and capture of CO₂ (Ceci et al., 2019, Fester et al., 2014, Louise et al., 2008). Even though they are not explicitly listed, their indirect use values are
implicitly and indirectly accounted for in current ecological valuation frameworks.

We here argue that microbiodiversity plays a large and indirect role of significant economic impacts in host-associated microbiomes across all life forms, including plants, animals, and humans. Microbiomes play key roles at all levels of biological organization, from the cell to organisms (including humans) and populations, and hence they also contribute centrally to ecosystem functioning (Box 1). Ecosystem services (ESS) provided by host-associated microbiomes include provision of energy and enhanced defense against pathogens of the host organisms (Cho and Blaser, 2012; McFall-Ngai et al., 2013; Kohl and Carey, 2016; McKenney et al., 2018; Mishra et al., 2020). Although further basic research is needed to fully understand the value of complex ESS networks derived from microbiodiversity, the indirect value can be approximated by the costs of restoring the diversity. In agriculture, bacteria, fungi, and viruses are already used to restore microbiodiversity of crop-associated microbiomes and thereby provide ecosystem services that can influence crop yields (Trivedi et al., 2020). The global agricultural market was estimated to be worth 6 billion USD in 2020 (Markets and Markets 2021). Additionally, different microbiome therapies are being developed to treat human gut diseases and, for these applications, the human microbiome market is estimated to reach 1598 million by 2028 (Markets and Markets 2021). These examples highlight that an indirect value of microbiodiversity is already economically acknowledged, but thus far this is limited to particular fields and lacks conceptualization.

2.3. Evolutionary perspective on the value of microbiodiversity: insurance and option values

The use values of microbiodiversity, as exemplified above, only make up a small proportion of its overall economic value. The key aspect of microbiodiversity is its relevance for humans and ecosystems in a variable and uncertain environment. This is because diverse host-associated microbiome provides insurance values, which arise if microbiodiversity reduces the risk premium associated to the value of a volatile ecosystem service (Baumgärtner, 2007; Quaas et al., 2019).

Microbiodiversity also provides an insurance value by increasing ecosystem resilience buffering thus reducing the adverse effects of perturbations to humans and ecosystems (Baumgärtner and Strunz, 2014, Primmer and Paavola, 2021, Dallimer et al., 2020). The insurance value is achieved by a decrease of the probability of future drops in the provision of ecosystem services due to a (marginal) change in the level of microbiodiversity. This resilience insures risk-averse ecosystem users against potential welfare losses (Baumgärtner and Strunz, 2014; Paul et al., 2020).

The hosts’ ability to survive under environmental fluctuations can depend on the functions of their microbiome (van Oppen and Blackall, 2019). For example, microbiomes can help the host to adapt to rises in temperature and CO2 levels in the course of climate change, through phenotypic plasticity covered by the associated microbiome (see the example of coral holobionts in the following section). Microbiodiversity can ensure that species and their microbiomes can adapt to changing environments, as increased diversity enables more effective plastic and evolutionary responses to novel environmental stresses (Kolodny and Schulpenburg, 2020; Webster and Reusch, 2017).

The finding that microbiodiversity enhances resilience in a changing environment implies a very important evolutionary aspect to the ecosystem that is related to its insurance value. A species’ ability to cope with a changing or new environment increases with its ability to evolve. By buffering the host’s reaction to the new environment, the associated microbiome provides time or functional margins so that the host can either genetically evolve or undergo phenotypic adaptation (Henry et al., 2021, Kolodny and Schulpenburg, 2020). The latter may be driven by either a frequency shift in the composition of the microbiome or genetic evolution of the existing taxa within the microbiome (Webster and Reusch, 2017).

While these arguments show that there are insurance values associated to microbiodiversity, and we hypothesize that these values may be large, the postulated values have not been assessed for real-world systems to date. Importantly, these insurance values specifically depend on the biodiversity of the microbial community and, consequently, they cannot be captured by assessing biodiversity of the host organisms alone, as usually done, but they require the explicit analysis of microbiodiversity itself.

2.4. Transmission of microbiodiversity and external effects

Any value of microbiodiversity goes beyond an immediate value of the host. This is because the associated microbiome itself can be inherited to the next generation of the host population and contributes to the adaptability of the ecosystem (Kolodny and Schulpenburg, 2020; Wein et al., 2019). In the longer time scale, this is supported by coevolving hosts and microbial species and macroscopic level of species evolution (Grousset et al., 2017) and horizontally transferred antibiotic resistance genes among human and animal gut and human pathogens (Hu et al., 2016). For the shorter time scale, vertical transfer of the human microbiome can occur through birth and breastfeeding (Tocchini, 2021, Cioffi et al., 2020, Asnicar et al., 2017), which signifies direct transfer of functionalities among generations of hosts. There is evidence of horizontal transfer of microbiomes among hosts, for example, the transfer of oral microbiome in mice (Abusleme et al., 2020), of microbial communities in a fly species, which is an important pest and vector for plant viruses (Paredes-Montero et al., 2020), and transfer of plant associated microbiome through bulk soil microbiome (Zarraonaindia et al., 2015; de Souza et al., 2016). Thus, host-associated microbiomes provide “evolvability” to the hosts that is transferable and will eventually impact ecosystem functioning, with an increased probability of sustainability.

It follows that, maintaining microbiodiversity has an option value by keeping the option of a benefit from microbial communities open in the future. This value is largely analogous to the option value of genetic diversity, which has been extensively discussed in current literature (Jump et al., 2009, Hein and Gatzweiler, 2006, Bartkowski, 2017, Paul et al., 2020). However, microbiodiversity occupies distinct albeit overlapping space in extracting economic value by providing transmissibility among different hosts and ecosystems. Especially, in cases where associated microbes are both beneficial and are at least to some extent transmitted vertically from parent to offspring, the inheritance of microbial associated “genomes” is somewhat analogous to the attribute of genetic diversity of the host genome itself as pre-requisite of adaptive evolution. In addition to the host genomes, the microbes themselves can evolve, sometimes more rapidly, as for example shown in recent experiments that strive to enhance the heat tolerance of symbiotic Symbiodinium algae ex hospite in reef-building corals (Buerger et al., 2020).

3. Examples of the economic significance of host-associated microbiomes

Our central tenet is that acknowledging the value of microbiodiversity as part of all biodiversity is essential, in particular as human interventions regularly impact microbiodiversity and possibly disrupt fragile ESS – without necessarily compromising biodiversity of the larger multicellular organisms. Consequences from human economic decisions such as land-use change, climate change, contamination, and captivity of livestock directly change microbial communities both quantitatively and qualitatively and in both regional and global scales (Trevelline et al., 2019). We selected three representative examples where host-associated microbiomes are of economic significance while threatened by human activity: (i) human-associated microbiomes, (ii) coral-associated microbiomes, and (iii) soil-associated microbiomes. In these examples, specific members of microbiodiversity are essential for
provision of ecosystem services, and further research directions greatly benefit conservation policy guidelines.

3.1. Human microbiome

The human microbiome is a special case as it is an ecosystem inside human individuals and environmental valuation studies mostly deal with ecosystems external to human body. Nonetheless, it is an essential environment that we are surrounded by and that as an ecosystem provides ESS which create economic value. Moreover, the human case is the best studied example of a host-associated microbiome and the possible economic values – an example, which can be used for similar valuations of microbiodiversity in other host organisms. The microbiome associated with all organs and tissues of the human body and its importance in human health and disease has been studied extensively in the last decades (e.g., Human Microbiome Project and MetaHIT, Cho and Blaser, 2012, Gilbert et al., 2016, Turnbaugh et al., 2007, Ehrlich, 2011).

Humans and their gut microbiome have co-adapted to certain diets (Moeller and Sanders, 2020). Moreover, the human gut microbiome is associated with many conditions and diseases, such as obesity, asthma, inflammatory bowel disease, and certain cancers (Stokholm et al., 2016; Berbó et al., 2019; Menni et al., 2017; Cavadas et al., 2020; Wu et al., 2009; Halfwarson et al., 2017). Importantly, human microbiome diversity is generally negatively associated with the occurrence of disease (Andersson et al., 2008, Atherton and Blaser, 2009). Therefore, the loss of microbiome diversity in human results in a loss of resilience and thus insurance value through an increase in disease susceptibility and risk. The general economic burden has been established for several of these conditions or diseases and amounts to billions of dollars in the US; e.g., 80 billion USD for Asthma (Nurnagambetov et al., 2018), 190 billion USD for obesity, and 14.1 billion USD for colorectal cancer (Centers for Disease Control and Prevention). Anthropogenic perturbations can worsen these conditions because a modern lifestyle and certain medical and nutritional practices affect microbiome composition and eventually reduce its diversity. In particular, antibiotic abuse and misuse, especially in early ages, have effects on obesity and other diseases through loss of microbiodiversity. In particular, antibiotic abuse and misuse, especially in early ages, have effects on obesity and other diseases through loss of microbiodiversity (e.g., Human Microbiome Project and MetaHIT, Cho and Blaser, 2012, Gilbert et al., 2016, Turnbaugh et al., 2007, Ehrlich, 2011).

Unintentional alteration of microbiodiversity has been shown for different reproductive practices and include reduced gut microbiodiversity in infants after cesarean sections compared to vaginal delivery (Jakobsson et al., 2014). Additionally, urbanization is related to lower microbiodiversity in more industrialized populations (Vangay et al., 2018; Lokmer et al., 2020). In these examples, it is clear that the human microbiome provides important services and flows of those services for particular human beings, which makes it natural capital stock of that person.

These distinct examples of microbiodiversity losses cannot be directly recovered from studying human biodiversity, but require direct analysis of microorganisms. Moreover, microbiodiversity loss in humans cannot be easily replaced (Rees and Gilman, 2018), and thus require specific preventive measures. Personal lifestyle can affect microbiome composition and alleviate the impact of perturbations on the microbiome. Individual decision-makers will actively change their behavior in order to preserve the benefits of microbiome diversity. Additionally, appropriate policies that would influence such lifestyle decisions can be made by acknowledging the true costs. Yet, this is only the case if they have accurate information about status and role of their microorganisms and of the likely consequences of individual behavioral change. In addition, decisions of parents, for example, will influence their progeny through vertical transmission, as in the case of breastfeeding or mode of child delivery (Jakobsson et al., 2014, Tochitani, 2021), but also potentially horizontal, as in the case of transfer of gut microbiota among social groups (Turnbaugh et al., 2006). For this reason, on the one hand, the depletion of the microbiome needs to be prevented to maintain its insurance value. On the other hand, the interdisciplinary information flow from biology to social sciences has to be strengthened such that information of high information value reaches decision-makers before such a depletion occurs unintentionally.

3.2. Coral-associated microbiome

Coral reefs are complex ecosystems harboring 25–38% of all marine species, and they host up to 2.5% of the world’s prokaryotic (bacterial and archaeal) diversity on their surfaces (Chiarello et al., 2020, Fisher et al., 2015). The ecosystem services provided by coral reefs have been well studied and include: (i) supporting services, by providing a habitat and supporting biodiversity benefits, (ii) provisioning services, by providing materials and fish, (iii) regulating services, by providing coastal protection, improved water quality, and biogeochemical cycling, and (iv) cultural services, as they are used for recreation and tourism (Woodhead et al., 2019). All of these services combined were estimated in 2003 to generate a value of 29.9 billion US Dollars (USD) per year (Cesar et al., 2003). The true value would likely be even higher, as reef-adjacent and on-reef tourism alone was estimated in 2017 to be worth around 36 billion USD in the world’s coral reef countries (Spalding et al., 2017). What has so far been rarely considered for economic valuation is that corals are meta-organisms and form complex host-symbiont interactions with microorganisms that play an essential role in regulating coral physiology, including energy provision (Boilard et al., 2020). The endosymbionts living inside coral cells are involved in host defense and survival. More importantly, which specific endosymbionts (both bacteria and unicellular algae) are associated with the coral host is directly impinging upon their heat tolerance, which is vital to adaptation and acclimatization to global warming (van Oppen and Blackall, 2019; Webster and Reusch, 2017; Ziegler et al., 2016). The importance of microbiodiversity is again not captured by studying host biodiversity alone, but its economic valuation requires the explicit analysis of the microbial communities.

Of major concern are the recurring widespread bleaching events and subsequent coral mortality (Glynn, 1983, Douglas, 2003) with increasing frequency throughout the world (Hughes et al., 2017), triggered by ocean heat waves, but also locally by short term water quality changes from sunscreen and human waste (Douglas, 2003; Harriott, 2002; Smith, 1976; Corinaldesi et al., 2018; Hawkins and Roberts, 1992). Coral bleaching can be described as microbial dysbiosis, in which bleaching resistance is determined by the composition of the microbiome community (Boilard et al., 2020; Bieri et al., 2016). More importantly, coral associated microbes that confer heat tolerance, for example, seem to be rare (Matsuda et al., 2022), and are often specific to certain locations or particular populations (Doering et al., 2021; Savary et al., 2021). Thus, loss of host diversity is not always equal to loss of general microbiodiversity. The cost of loss of the specific microbiobiodiversity has to be added to the cost of hypothetical reintroduction, where resilience and adaptation to the resulting changes critically depend on high microbiodiversity (Spalding and Brown, 2015). Natural and engineered marine probiotics are promising treatment options where natural probiotics have already been shown to protect from bleaching events in vitro (Levin et al., 2017, Rosado et al., 2019, Dungan et al., 2022). Overall, the microbiodiversity of corals explicitly provides direct use values via market values of natural probiotics, indirect values by providing ESS to the corals and thus to humans, and option and insurance value by mitigating against environmental challenges in the future.

3.3. Soil-associated microbiome

Terrestrial soils contain extensive microbiodiversity in a variety of microscopic environments and ecosystems, which are a vital component of soil health and the ability of soil to support functioning of both natural and agro-ecosystems (Doran, 2002). Particularly important to humans is
the microbiome associated with plant roots, called the rhizobial microbiome (Jackson et al., 2008). It plays an important role in plant health and in agriculture can be an important determinant of crop yields (Trivedi et al., 2020), which therefore promises an important indirect use value. In addition, the general soil microbiome also provides insurance value through services to plants (Lugtenberg and Kamilova, 2009), including nutrient acquisition, such as by nitrogen-fixing bacteria (Mahmoud et al., 2020); disease and pathogen resistance, as certain soil microbial communities produce “disease suppressive soils” (Schlatter et al., 2017; Ellis, 2017; Jettyanond and Kloeper, 2002; Van Oosten et al., 2008; Raaijmakers and Mazzola, 2016; van Loon et al., 1998); and increased stress tolerance, e.g. to water depletion, salinization (Qin et al., 2016), and heavy metal contamination (Bellarbbara et al., 2019). Evidence for the effects of pesticides on the microbial communities of soil suggests that the community composition is affected (Dai et al., 2016; Jacobsen and Hjelms, 2014; Newman et al., 2016). Climate change, and the stressors it will bring, such as drought, will also harm the soil microbiome (Manzoni et al., 2012; de Vries et al., 2012). However, whether the impact on microbiodiversity inhibits the provision of ESS is not yet clear. Some work is now being done on economic valuation of soil health and diversity (Mikhailova et al., 2021; Pascual et al., 2015). More detailed studies are thus required that focus on quantification and measurement of microbiodiversity’s contribution to ecosystem services, which is an important area of research to connect to the valuation of the ecosystem services.

4. Conclusions

The economics of microbiodiversity urgently needs further development to guide private and public economic decisions, especially by providing thorough and careful assessments of the economic value of microbiodiversity and the related ecosystem services. Despite considerable advances in methods of valuation of biodiversity in general, this field at the interface of ecology and economics is still far from being mature, with the associated risk that wrong decisions may be economically very costly. As microbiodiversity is transferred vertically and horizontally between hosts and environments, external effects arise of so far largely unknown values. For example, in the case of methane emission of cattle, it can be seen that negative externalities arise when the blindly connecting the role of microbiodiversity to the role of the hosts. However, specific composition of microbe matter in terms of methane emissions for cattle (Tapio et al., 2017) and for sheep (Kamke et al., 2016). Thus, a better understanding of microbiodiversity would lead to a better management of the externalities that might be brought by microbiodiversity.

Direct and indirect use values of the diversity of environmental microbes and host-associated microbiome obviously exist, but are currently omitted in valuation models. One potential concern is that valuation of diversity will “double-count” economic value (Turner et al., 2010): if microbial biodiversity contributes to a certain direct use-value through multiple (redundant or incompatible) causal routes, then assigning value to the ecosystem services may count the same value multiple times. But this risk can be mitigated by a well-designed approach to valuation, that precisely distinguishes indirect and direct use values. Especially, the option and insurance values of resilience and evolvability have been hitherto not well measured, thus are less subject to concerns of double counting. For example, it is now becoming established that unique sets of microbes confer heat tolerance in corals or the loss of specific microbial taxa in the human microbiome contribute to disease. Both are key examples that not just diversity per se, but the precise taxonomic affiliation of associated microbes that need to be identified and that are the biological entities associated with option and insurance values.

In particular, under at least some form of vertical transmission (i.e. from parent to offspring) microbiodiversity maintains evolvability, and thus often encompasses long-term insurance along with option values, especially in a variable and uncertain environment. As climatic and economic change makes the world ever more variable and uncertain, this is a particularly important perspective we should consider in order to prepare against predictable and unpredictable future threats. Here we have shown that insurance and option values appear in a wide variety of contexts, from human health, to agriculture, and biogeochemical cycling, and heavily suffer from human perturbations at the moment. By presenting examples of the currently often ignored values of microbiodiversity, we suggested novel areas of research, including the quantification of biological effects of microbiodiversity to ESS. Indeed, this practice should be expanded to other components of ecosystems and their services. We are confident that acknowledging the values of microbiodiversity and the links to ecosystem services will guide a better understanding of biodiversity and improve policymaking that ensures use, option as well as insurance values associated with microbial communities.

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Declaration of Competing Interest

The authors declare no competing interest.

Data availability

No data was used for the research described in the article.

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