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Submission to the Nuffield Council on Bioethics 'Call for Evidence' – Considering future generations, the environment and the interests of non-human species in the analysis of emerging technologies, including solar radiation modification.

SUBMISSION TO THE NUFFIELD COUNCIL ON BIOETHICS 'CALL FOR EVIDENCE' – CONSIDERING FUTURE GENERATIONS, THE ENVIRONMENT AND THE INTERESTS OF NON-HUMAN SPECIES IN THE ANALYSIS OF EMERGING TECHNOLOGIES, INCLUDING SOLAR RADIATION MODIFICATION.

Contributors:

Dr. Luay Abu-Qatouseh
Head of Medical Analyses Department
Faculty of Pharmacy and Medical Sciences University of Petra
Amman-Jordan

Adeniyi Olarewaju Adeleye (BSc, MPH, MSc, PhD)
Department of Environmental Sciences, Faculty of Physical Sciences, Federal University Dutse, Nigeria.

Emmanuel Okyere Sakyi
National Public Health and Reference Laboratory, Ghana

Muhammed Duman
Bursa Uludag University, Faculty of Veterinary Medicine, Department of Aquatic Animal Diseases, Turkey

Contributions:

Dr. Luay Abu-Qatouseh
Head of Medical Analyses Department
Faculty of Pharmacy and Medical Sciences University of Petra
Amman-Jordan

1. Benefits and Complications in Considering Non-Human Species

The consideration of non-human species, particularly microorganisms, in policy and decision-making presents both significant opportunities and complex challenges. A primary benefit lies in the development of more holistic and effective environmental and health policies. The One Health framework, for instance, which recognizes the interconnectedness of human, animal, and environmental health, is greatly enhanced by a deeper understanding of microbial ecosystems [1]. By considering the full spectrum of microbial diversity—from pathogenic to beneficial—we can move beyond a purely anthropocentric view of microbes as threats and toward a model of microbial stewardship that promotes ecosystem resilience and sustainability [2]. This approach can unlock innovative solutions to global challenges, such as climate change and food security, by harnessing the power of microbial processes for bioremediation, carbon sequestration, and enhanced agricultural productivity [3]. However, incorporating microbes into policy frameworks also presents considerable complications. A fundamental challenge is the conceptual difficulty of defining the 'interests' of microorganisms. Unlike charismatic megafauna, the vast and diverse microbial world, often referred to as the 'invisible 99% of life,' does not lend itself to traditional ethical frameworks centred on individual organisms [4]. The sheer complexity and dynamic nature of microbial communities make it difficult to predict the consequences of interventions, raising the risk of unintended and potentially harmful ecological disruptions. Furthermore, there is a significant gap in public and policymaker understanding of the critical roles microbes play, which can hinder the development and implementation of effective policies. Existing legal and regulatory frameworks, designed with macroscopic life in mind, are often ill-equipped to address the unique challenges posed by the microbial world, from the regulation of synthetic organisms to the conservation of microbial biodiversity.

2. Methodologies and Experiments for Including Non-Human Species

Current methodologies for including non-human species, especially microbes, in policy and decision-making are still evolving, but several key approaches have emerged. The One Health framework is a cornerstone, promoting a transdisciplinary approach that recognizes the interconnectedness of human, animal, and environmental health [1]. This framework is increasingly being expanded to incorporate the full breadth of microbial diversity, moving beyond a focus on pathogens to encompass the entire microbiome [2]. Methodologically, this involves integrated surveillance systems that monitor microbial populations in different environments, and collaborative research projects that bring together experts from diverse fields, such as medicine, veterinary science, and environmental science.

In terms of experimental approaches, metagenomics, transcriptomics, proteomics, and metabolomics (collectively known as 'omics' technologies) have revolutionized our ability to study microbial communities. These high-throughput sequencing and analysis techniques allow us to identify the composition and functional potential of complex microbial ecosystems without the need for cultivation. This data is crucial for understanding the roles of microbes in everything from nutrient cycling to human health, and it provides the evidence base for developing policies related to microbial stewardship and conservation. For example, the Earth Microbiome Project has used these techniques to map global microbial diversity, revealing key patterns of microbial distribution and function that can inform environmental policy [5].

Microbial risk assessment is another critical methodology, particularly in the context of emerging technologies like synthetic biology and genetically modified organisms (GMOs). This involves a systematic process of identifying, characterizing, and evaluating the potential risks posed by microorganisms to human health and the environment. This methodology is essential for developing regulatory frameworks that can safely govern the development and release of new microbial technologies [6].

Finally, bioethics mediation is an emerging methodology that offers a structured process for resolving ethical conflicts and making decisions that involve multiple stakeholders with competing interests [7]. While traditionally used in clinical settings, its principles of neutrality, confidentiality, and structured dialogue can be applied to broader public health and environmental issues, including those involving non-human species. This approach can help to build consensus and ensure that the 'voices' of non-human species, as represented by scientific experts and other stakeholders, are heard and considered in the decision-making process.

3. Proposed Methodologies and Frameworks for Inclusion

To better incorporate non-human species, particularly microbes, into policy and decision-making, we propose a multi-faceted approach that integrates and expands upon existing frameworks. The cornerstone of this approach is the continued development and implementation of an ecologically expanded One Health framework [2]. This expanded framework would move beyond the traditional focus on zoonotic diseases and antimicrobial resistance to embrace the full spectrum of microbial life and its role in ecosystem health. This requires a conceptual shift from disease surveillance to microbial stewardship, which involves actively managing and protecting microbial ecosystems to enhance their resilience and the services they provide. We also propose the formal integration of bioethics mediation into environmental and public health governance [7]. This methodology, with its emphasis on structured dialogue, empathy, and shared problem-solving, can provide a valuable mechanism for navigating the complex ethical and social issues that arise when considering the interests of non-human species. By bringing together diverse stakeholders—including scientists, policymakers, industry representatives, and the public—bioethics mediation can help to build consensus and ensure that a wide range of values and perspectives are considered in the decision-making process.

For emerging technologies such as synthetic biology, we recommend the adoption of a precautionary and adaptive governance framework. This would involve a combination of robust risk assessment methodologies, transparent and inclusive public engagement, and ongoing monitoring to identify and mitigate potential harms. The development of a unified set of ethical principles for emerging technologies, such as those proposed by the Presidential Commission for the Study of Bioethical Issues, could provide a valuable foundation for such a framework [8]. These principles, which include public beneficence, responsible stewardship, intellectual freedom and responsibility, democratic deliberation, and justice and fairness, can help to guide the responsible development and deployment of new technologies that have the potential to impact microbial ecosystems. Finally, we recommend the development of microbial conservation strategies that are integrated into broader biodiversity conservation efforts. This would involve identifying and protecting key microbial habitats, establishing microbial culture collections and data repositories, and developing policies that promote the sustainable use of microbial resources. The recent inclusion of microbial diversity in the IUCN's global conservation policy is a significant step in this direction, but much more work is needed to translate this recognition into concrete action [4]

4. Examples of Well-Designed Legal, Regulatory, or Ethical Frameworks

Several existing frameworks, while not always explicitly designed for microbes, offer valuable models for the inclusion of non-human species in policy and decision-making. The Rights of Nature legal movement is a particularly compelling example. This framework challenges the legal status of nature as mere property and instead recognizes ecosystems as rights-bearing entities. Ecuador was the first country to enshrine the Rights of Nature in its constitution in 2008, granting ecosystems the right to exist, persist, maintain, and regenerate their vital cycles. Since then, similar legal frameworks have been adopted in other countries, such as Bolivia, and at the local level in the United States [9]. A specific and powerful example of this approach is the Te Urewera Act of 2014 in New Zealand. This legislation granted legal personhood to the Te Urewera National Park, a former national park that is the ancestral home of the Tūhoe people. The Act recognizes Te Urewera as a legal entity with "all the rights, powers, duties, and liabilities of a legal person." This innovative legal framework, rooted in Indigenous Māori cosmology, provides a powerful model for how to recognize and protect the intrinsic value of ecosystems in law [10].

The One Health framework, as previously discussed, is another excellent example of a framework that is well-designed to be inclusive of non-human species. By explicitly recognizing the interconnectedness of human, animal, and environmental health, One Health promotes a more holistic and integrated approach to policy and decision-making. The global action plan on antimicrobial resistance (GAP-AMR), developed by the World Health Organization (WHO), the Food and Agriculture Organization of the United Nations (FAO), and the World Organisation for Animal Health (WOAH), is a concrete example of the One Health framework in action. This plan outlines a comprehensive strategy for addressing the growing threat of antimicrobial resistance that spans human and animal health, as well as the environment [11]. These examples, while diverse in their origins and applications, share a common thread: they move beyond a purely anthropocentric worldview to recognize the intrinsic value and interconnectedness of all life. They provide valuable precedents for developing more inclusive and effective legal, regulatory, and ethical frameworks that can better protect the interests of non-human species, including the vast and vital world of microorganisms.

5. Weighing Different Values in Policy and Decision-Making

Weighing the different values that arise in the consideration of current human generations, non-human species, the environment, and future generations is one of the most challenging aspects of bioethical decision-making. A key principle is the adoption of a long-term, intergenerational perspective. This requires moving beyond short-term political and economic cycles to consider the potential impacts of our actions on future generations and the planet as a whole. The concept of sustainable development, as defined by the Brundtland Commission, provides a useful starting point: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [12].

In the context of emerging technologies, this means that the pursuit of innovation must be balanced with a commitment to responsible stewardship. The ethical framework for emerging technologies proposed by the Presidential Commission for the Study of Bioethical Issues offers a useful model. This framework emphasizes the importance of public beneficence, which requires that the development and deployment of new technologies should be aimed at promoting the public good, while also minimizing risks [8]. It also highlights the principle of justice and fairness, which requires that the benefits and burdens of new technologies should be distributed equitably. When it comes to weighing the interests of non-human species, we must move beyond a purely instrumental view of nature and recognize the intrinsic value of all life. The Rights of Nature movement provides a powerful legal and ethical framework for doing so [9]. By granting legal personhood to ecosystems, this framework gives them a voice in the decision-making process and ensures that their interests are considered alongside those of humans. Bioethics mediation can also play a crucial role in this process [7]. By providing a structured and inclusive forum for dialogue, mediation can help to identify and reconcile the competing values and interests of different stakeholders. This can lead to more robust and ethically sound decisions that are more likely to be accepted and implemented by all parties. Ultimately, the process of weighing these different values must be a democratic one, involving broad public engagement and deliberation. It requires a commitment to transparency, accountability, and inclusivity, and a willingness to grapple with complex ethical questions in an open and honest way.

6. How Existing Frameworks Could Be More Inclusive

Many existing legal, regulatory, and ethical frameworks could be made more inclusive of non-human species, particularly microbes, through targeted reforms and a shift in perspective. The One Health framework, while already a significant step forward, could be further enhanced by formally expanding its scope to encompass the full spectrum of microbial life and its role in ecosystem health [2]. This would involve moving beyond a focus on pathogens and antimicrobial resistance to include the study of beneficial microbes and the promotion of microbial biodiversity. This could be achieved by integrating microbiome research into all aspects of One Health, from surveillance and risk assessment to policy development and implementation. Environmental protection laws, such as the Endangered Species Act (ESA) in the United States, could also be adapted to be more inclusive of microbial life. Currently, the ESA and similar laws in other countries are primarily focused on the conservation of macroscopic plants and animals. To make these laws more inclusive of microbes, we would need to develop new criteria for identifying and protecting endangered microbial species and communities. This would require significant investment in microbial ecology research, as well as the development of new legal and regulatory tools for microbial conservation. The principles of the Rights of Nature movement could also be integrated into existing legal and regulatory systems [9]. This would not necessarily require a complete overhaul of our legal system, but could be achieved through a more gradual process of legal reform. For example, courts could begin to interpret existing environmental laws in a way that recognizes the intrinsic value of ecosystems and their right to exist and flourish. Legislatures could also pass laws that grant legal personhood to specific ecosystems, following the model of the Te Urewera Act in New

Zealand [10]. Finally, ethical review processes for research and technology development could be made more inclusive of non-human species. This would involve ensuring that ethical review boards have the expertise to assess the potential impacts of new research and technologies on microbial ecosystems. It would also require the development of new ethical guidelines for research involving microbes, particularly in the context of emerging technologies like synthetic biology.

7. Ensuring Adequate Accommodation of Ethical Considerations

Ensuring that ethical considerations regarding non-human species, particularly microbes, are adequately accommodated in policy and decision-making requires a multi-pronged approach that combines education, public engagement, institutional reform, and the development of new ethical frameworks.

A critical first step is to improve public and policymaker understanding of the vital roles that microbes play in our world. This can be achieved through targeted education and outreach initiatives that communicate the science of microbiology in an accessible and engaging way. By fostering a greater appreciation for the microbial world, we can create a more receptive environment for policies that take the interests of microbes into account. Public engagement and democratic deliberation are also essential. Decisions about how to weigh the interests of non-human species should not be made by experts alone but should involve a broad and inclusive public dialogue. This can be facilitated through a variety of mechanisms, such as citizens' assemblies, consensus conferences, and participatory workshops. These processes can help to ensure that a wide range of values and perspectives are considered and can lead to more robust and ethically sound decisions. Institutional reform is also needed to ensure that ethical considerations are embedded in the decision-making process. This includes strengthening the role of ethical review boards and ensuring that they have the expertise to assess the potential impacts of new research and technologies on microbial ecosystems. It also involves creating new institutional structures, such as a permanent Presidential Commission for the Study of Bioethical Issues in the US, that can provide ongoing guidance on emerging ethical issues [8]. Finally, we need to continue to develop and refine our ethical frameworks to better accommodate the interests of non-human species. This includes further developing the concepts of microbial stewardship and the Rights of Nature and exploring how they can be integrated into existing legal and regulatory systems. It also involves drawing on a wider range of ethical traditions, including Indigenous knowledge systems, which often have a more holistic and relational understanding of the natural world. By taking these steps, we can move towards a more inclusive and ethically responsible approach to policy and decision-making that recognizes the profound interconnectedness of all life on Earth.

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Adeniyi Olarewaju Adeleye (BSc, MPH, MSc, PhD)
Department of Environmental Sciences, Faculty of Physical Sciences, Federal University Dutse, Dutse, Jigawa State, Nigeria.

Advantages and Prospective Problems of Non-Human-Species in Policy and Decision-Making

Benefits

The inclusion of the non-human species in policy and decision-making processes, especially microorganisms, enhances environmental stewardship and long-term sustainability. Microbes are the foundation of ecosystem services like biogeochemical cycling, climate regulation, soil fertility, and human health. The consideration of microbial communities in policies can decrease unintentional ecological disturbance, create a more resilient Earth system, and better predict the risk of emerging technologies (Falkowski et al., 2008; Cavicchioli et al., 2019). In addition, the idea that microbes are stakeholders is consistent with precautionary and intergenerational justice, considering that they are the core agents in maintaining biospheric functions that will be relied upon by future generations (Rockstrom et al., 2009).

Potential Complications

The main issues are microbial invisibility, taxonomic ambiguity, and functional redundancy, which make it difficult to represent them in the policy. A great number of microbial species have not been cultured yet, and their ecological functions are indirectly determined, resulting in epistemic uncertainty in the decisions of governance (Solden et al., 2016). Also, microbial ecosystems might be inconsistent with policies targeting the protection of organisms, in which disruption can occasionally increase activity (Prosser et al., 2007). The translation of complex microbial data into a form of policy measurement is thus a big challenge.

Current Procedures to Integrate Non-Human Species in the Policy and Decision-making Process

The existing methods of inclusion of non-human species in policy are as follows:

1. Environmental Impact Assessments (EIAs) and Strategic Environmental Assessments (SEAs) use microbial indicators for the health of the environment (European Commission, 2017).
2. The ecological monitoring model (long-term ecological monitoring) that monitors microbial responses to environmental change and technological intervention through long-term ecological monitoring (such as metagenomics and environmental DNA (eDNA)).
3. Planetary boundary systems that implicitly incorporate a microbial process in the definitions of safe operating spaces related to humanity (Steffen et al., 2015).

Although they are effective, these methodologies tend to treat microorganisms as instruments instead of focusing on them as having an ecological value of their own.

Suggested Methodologies and Frames of Improved Inclusion of Non-Human Species

To enhance inclusion of non-human species, especially microbes, the following structures are suggested:

1. Microbial-Inclusive Technology Assessment (MITA): an upgrading of technology assessment which assesses effects on microbial diversity, functionality, and evolution specifics.
2. One Health and Planetary Health models, with microbial communities in their explicit roles as key players and not as ancillary factors (Horton et al., 2014).
3. Ethical impact assessments and EIAs, which include ecological ethics and intergenerational justice to evaluate long-term microbial ecosystem impacts of novel technologies, including geoengineering or synthetic biology (Jasanoff and Hurlbut, 2018).
4. Adaptive Governance models, which enable the policies to change as the knowledge of the microbial system advances based on real-time monitoring.

Current Legal, Regulatory, or Ethical Frameworks Extensive of Non-Human Species

Several frameworks that show good practice are highlighted below:

1. CBD is inclusive and precautionary since it specifically acknowledges a microorganism as a constituent of biodiversity and extends protection to biodiversity at the ecosystem level (CBD, 1992).
2. Integration: The EU Water Framework Directive, which incorporates the aspects of biological quality and microbial pointers of water management, gives a binding ecological protection (European Union, 2000).
3. Legislation of Rights of Nature (for instance in Ecuador, constitutional), establishing ecosystems with legal status and including microbial life as part and parcel of ecosystems (Kauffman and Martin, 2017).

These frameworks can work well since they do not only focus on species conservation but rather on systems-based governance.

Balancing Values Between the Humans, the Non-Human species, the Environment and the Future generations

Pluralistic ethical reasoning is necessary in balancing these values. Intergenerational justice requires that the existing advantage of new technologies not affect the microbial functioning needed by future ecosystem stability. Ecological ethics is in favor of giving the non-human species intrinsic value whereas the utilitarian views focus on the microbes that are important to humanity in terms of their ecosystem services. Multi-criteria decision analysis should be implemented in policymaking, which will incorporate ecological thresholds, social benefits, and long-term uncertainty (Raworth, 2017).

Agreements that would be more inclusive of non-human species should be pursued religiously. Some of the regulatory systems might be enhanced through:
1. Making microbial diversity and microbial functions explicitly considered in biosafety and biosecurity policies, synthetic biology and geoengineering in particular.
2. Increasing climate governance systems to recognize microbial feedback in both the carbon and the nitrogen processes.
3. Remodeling IP regimes to incorporate more ethical issues of bioprospecting and exploitation of microbial resources (Oldham et al., 2014).

Securing the Ethical Implications of Non-Human Species which can be sufficiently accommodated

A number of ways that ethical inclusion can be attained are highlighted below:

1. Incorporating ecological ethics expertise in consultations.
2. Demanding open participatory deliberation, even scientific representation of non-human interests.
3. It should be required to monitor the post implementation effects of microbes and ecosystems and where the regulation triggers intervention in case of exceeding the set thresholds.

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Emmanuel Okyere Sakyi
National Public Health and Reference Laboratory, Ghana

1. Why Microbial Systems Must Be Considered in Emerging Technology Governance

Microorganisms underpin planetary health. They regulate carbon sequestration, nitrogen cycling, methane production, soil fertility, oceanic primary productivity, and antimicrobial effectiveness. Despite this foundational role, microbes are rarely explicitly incorporated into ethical or regulatory analyses of emerging technologies.

Failure to consider microbial systems risks overlooking long-term ecological feedback and intergenerational consequences. Antimicrobial resistance (AMR), for example, demonstrates how anthropogenic pressures can reshape microbial evolution in ways that undermine human health globally (WHO, 2015) [1]. Environmental reservoirs of resistance genes highlight that microbial systems are not passive background conditions but dynamic actors within Earth systems.

Incorporating microbial interests into policy offers several benefits such as:

- Strengthened ecosystem resilience
- More robust One Health governance
- Improved anticipation of long-term environmental impacts
- Better alignment with intergenerational justice principles
- However, complications arise due to microbial invisibility, rapid evolutionary dynamics, and limited regulatory metrics for microbial biodiversity. These challenges should prompt methodological innovation rather than exclusion.

2. Benefits and Complications of Including Microbial Systems in Policy

Benefits

Explicitly incorporating microbial systems into policy enhances:

- Ecosystem resilience – Microbes drive biogeochemical cycles (carbon, nitrogen, phosphorus) essential for planetary stability.
- Public health protection – Environmental reservoirs of AMR directly influence clinical treatment outcomes (WHO, 2015) [1].
- Sustainable technology development – Synthetic biology, geoengineering, and biotechnology interventions may alter microbial community dynamics.
- One Health implementation – Recognition of interconnected human–animal–environment systems (Quadripartite Joint Plan of Action, 2022) [2].

The 2016 O'Neill Review on AMR emphasized that resistance is a global ecological problem, not solely a clinical issue [3]. Environmental reservoirs of resistance genes amplify selective pressures across sectors.

Complications

Challenges in incorporating microbial systems include:

- Microbial invisibility and complexity.

- Rapid evolutionary adaptation.
- Difficulty assigning intrinsic value to microorganisms outside instrumental human benefit.
- Limited regulatory metrics for microbial biodiversity compared to macro-species conservation.

Despite these challenges, failure to integrate microbial systems risks long-term systemic harm to both current and future generations.

3. Existing Methodologies That Incorporate Microbial or Environmental Interests

Several frameworks partially incorporate microbial considerations:

One Health Governance

The FAO–UNEP–WHO–WOAH One Health Joint Plan of Action (2022–2026) recognises the interconnectedness of human, animal, and environmental health [2]. While microbes are central to disease ecology and AMR, environmental microbial surveillance remains unevenly implemented.

Environmental Impact Assessment (EIA)

EIAs assess biodiversity impacts but rarely include microbial diversity or resistome profiling. Advances in metagenomics now allow microbial baseline assessment and environmental AMR monitoring, yet these tools are not routinely embedded in regulatory processes.

Wastewater-Based Surveillance (WBS)

WBS has emerged as a governance-relevant tool for monitoring pathogens and resistance genes at population scale. UNEP (2023) identifies environmental AMR surveillance as critical to global mitigation efforts [3]. This approach demonstrates how microbial indicators can inform policy decisions in real time.

Precautionary and Intergenerational Frameworks

The Rio Declaration (1992) embeds the precautionary principle in environmental governance [4], while the Brundtland Commission (1987) emphasises obligations to future generations [5]. These principles provide ethical foundations for including microbial systems in emerging technology oversight.

4. Implications for Solar Radiation Modification (SRM)

Solar Radiation Modification aims to reduce global temperatures by reflecting incoming sunlight. While ethical debates often centre on immediate human outcomes, SRM would inevitably alter climatic and ecological conditions that structure microbial life.

Soil Microbial Systems and Carbon Cycling

Soil microbes regulate carbon storage and greenhouse gas fluxes. Temperature and moisture shifts influence microbial respiration and decomposition dynamics (Crowther et al., 2016) [6]. If SRM alters regional climate patterns unevenly, it may disrupt soil–carbon–microbe feedback loops, potentially affecting long-term climate stability.

Marine Microbial Ecosystems

Marine phytoplankton, largely microbial, contribute approximately half of global primary productivity and are central to carbon cycling (Falkowski et al., 2008) [7]. Changes in solar radiation intensity and ocean stratification could influence microbial photosynthesis, nutrient cycling, and marine food webs.

Pathogen Ecology and Antimicrobial Resistance

Climate variability influences pathogen distribution and horizontal gene transfer dynamics in environmental systems (Singer et al., 2016) [8]. Altered hydrological or temperature patterns associated with SRM may shift environmental resistome profiles, with indirect consequences for future public health.

These potential effects illustrate that SRM governance must extend beyond human temperature outcomes to include microbial ecological feedbacks and evolutionary consequences.

6. Proposed Frameworks for Inclusion

To better integrate microbial systems into emerging technology governance, including SRM, the following measures are recommended:

Microbial-Ecology Impact Assessment (MEIA)

Regulatory review of emerging technologies should require assessment of impacts on:

- Microbial diversity and ecosystem function
- Biogeochemical cycling processes
- Environmental resistome amplification

This would complement existing environmental impact assessments.

Integration of Microbial Indicators into Climate Modelling

Earth-system models used in SRM evaluation should incorporate microbial feedback mechanisms affecting carbon, nitrogen, and methane cycles.

Environmental AMR Surveillance as a Governance Tool

AMR genes can serve as measurable indicators of ecological stress and anthropogenic pressure. Integrating resistome monitoring into environmental policy would operationalise microbial inclusion.

Precautionary Oversight of Earth-System Interventions

Given microbial evolutionary dynamics operate across generations, SRM governance should explicitly apply precautionary and intergenerational ethics frameworks when scientific uncertainty exists.

Weighing Human, Environmental, and Intergenerational Interests

Ethical analysis of SRM and other emerging technologies must balance:

- Immediate human climate risk mitigation
- Protection of non-human species and ecosystems
- Long-term evolutionary and ecological consequences
- Justice for future generations

Short-term human benefit should not override potential systemic ecological disruption. Microbial evolution, once altered, cannot easily be reversed; resistance genes and ecological shifts persist beyond policy cycles.

An intergenerational lens; consistent with sustainable development principles (Brundtland, 1987) [5] which supports the integration of microbial stewardship into governance. Protecting microbial ecosystem stability is aligned with safeguarding future human wellbeing.

7. Strengthening Existing Frameworks

Existing governance mechanisms could be made more inclusive by:

- Mandating environmental microbial monitoring alongside climate intervention research
- Embedding microbial ecosystem indicators into biodiversity strategies
- Requiring baseline microbial data prior to large-scale environmental manipulation
- Including environmental microbiologists in SRM advisory bodies

Frameworks such as the Convention on Biological Diversity (1992) [9] and the WHO Global Action Plan on AMR (2015) [1] provide foundations but require stronger operationalisation of microbial metrics.

8. Ensuring Ethical Consideration of Microbial Systems

To ensure adequate accommodation of microbial considerations:

- Include environmental microbiologists in regulatory advisory panels.
- Integrate metagenomic surveillance into environmental governance.
- Establish enforceable discharge standards targeting antimicrobial residues.
- Embed microbial stewardship within national and international AMR strategies.
- Promote interdisciplinary ethics frameworks incorporating ecological microbiology.

9. Conclusion

Microorganisms are foundational components of Earth systems. Emerging technologies such as Solar Radiation Modification have the potential to reshape climatic conditions that structure microbial life, with cascading effects on ecosystem stability, carbon cycling, pathogen ecology, and antimicrobial resistance.

Ethical and regulatory analysis of SRM should therefore:

- Explicitly incorporate microbial ecological impact
- Apply precautionary and intergenerational principles
- Integrate microbial indicators into environmental monitoring
- Recognise microbial systems as central to planetary health

Incorporating microbial perspectives strengthens both ethical robustness and long-term policy resilience.

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Muhammed Duman
Bursa Uludag University, Faculty of Veterinary Medicine, Department of Aquatic Animal Diseases, Turkey

From an aquatic microbiology perspective, non-human species in this debate are, to a very large extent, microorganisms: animal pathogens, zoonotic pathogens and environmental microorganisms that mediate ecosystem processes. If we want to meaningfully include these non-human species in policy and decision-making on emerging technologies and interventions, the first requirement is a robust methodological framework for detecting and characterizing them. Without reliable identification, any attempt to "account for" microbes in regulation or governance risks being symbolic rather than effective.

Microorganisms are not only agents of disease; they are also sensitive and early indicators of the relationship between living organisms and their environment. In aquatic systems, microbial communities respond quickly to changes in nutrient loading, temperature, contaminants and host density, and microbial bioindicators have long been used to detect ecosystem change and stress (Paerl et al., 2003). In this sense, microbial communities are among the most informative non-human species for signaling when systems are in a non-pathological, balanced state and when that balance is being disrupted. For policy purposes, this suggests a framework in which long-term microbial monitoring is used to define baselines and acceptable ranges of variation for key taxa or functional groups, and deviations from these baselines trigger investigation or intervention. In other words, non-human microbial species can be treated as quantitative indicators that feed directly into decision thresholds in environmental and public health policy.

To make such a framework operational, standardization of sampling is crucial. Microbial communities in water, sediments, biofilms, fish or shellfish tissues and aquatic plants can differ markedly, and each matrix requires clear guidance on where, when and how samples should be collected. For water, this may mean specifying depth, distance from shore or cages, volume, and pre-filtration steps; for sediments, the depth interval and coring method; for diseased animals or humans, the precise tissue or organ, lesion margins and aseptic handling; for plants, the rhizosphere, phyllosphere or endophytic compartments. Instead of prescribing a single universal protocol, I would advocate framework-type guidance that links sampling design to the specific questions being asked: for example, whether the aim is to detect a specific pathogen, to characterize a whole community, or to follow an indicator group over time. What matters for inclusion in policy is that sampling approaches are explicitly defined, reproducible and appropriate to the decision they will inform.

Once appropriate samples are in hand, the next critical step is identification. Here, it is useful to distinguish between three main categories of questions, each requiring a different methodological approach. If the policy or management question focuses on a single microbial agent or strain, for example, an aquatic pathogen of fish or a zoonotic agent with known or suspected risk, whole-genome sequencing and comparative genomic analysis should be considered the standard. Genome-resolved approaches support accurate species and strain identification, detection of virulence and antimicrobial resistance determinants, and robust phylogenetic placement, which are essential for risk assessment and for tracking the spread of problem strains across time and space.

If the question concerns the composition of a microbial community and we need relatively high taxonomic resolution and functional insight, shotgun metagenomic sequencing is the most appropriate method. Shotgun metagenomics analyses all DNA in a sample and can identify bacteria, archaea, viruses and eukaryotes to finer taxonomic levels than marker-gene approaches, while also providing information on genes and pathways relevant to ecosystem function or pathogenicity. Multiple comparative studies have shown that whole-genome shotgun metagenomics recovers greater taxonomic diversity and provides finer resolution of community dynamics than 16S rRNA gene amplicon sequencing, particularly for less abundant taxa and viruses. For environmental governance, this level of detail is important when we want to understand how emerging technologies or interventions alter community structure and function, or to monitor potential increases in ecologically or clinically relevant genes, such as toxins or antibiotic resistance determinants.

If the objective is instead to obtain a general picture of relative community composition, for instance, to track broad shifts in major bacterial groups over time or between sites, then 16S rRNA (or other marker gene) amplicon sequencing remains a useful and cost-effective tool. Such approaches are well established for describing proportional changes in microbial communities and can be integrated into routine monitoring programmes as indicators of ecosystem status or emerging imbalance. However, they should be used with a clear understanding of their limitations in taxonomic resolution and in detecting minority taxa, and they should not be over-interpreted as providing precise species-level identifications (Durazzi et al., 2021; Dadlani, 2023).

Within this framework, traditional culture-based microbiology still has a role, but it should not be the primary or sole basis for including microbial non-human species in policy. It is well known that only a fraction of environmental microorganisms are readily culturable under standard laboratory conditions, historically estimated to be a very small percentage of the total community, leading to the "great plate count anomaly" (Lagkouvardos et al., 2017; Epstein, 2013). Although newer culturomics methods have increased the proportion of taxa that can be isolated in some systems, culture-based approaches remain biased towards fast-growing, opportunistic organisms and cannot, on their own, represent the full diversity or functional capacity of microbial communities. In an evidence framework, culture can therefore be seen as complementary: essential for phenotypic testing such as antimicrobial susceptibility, virulence assays and experimental work, but always interpreted alongside culture-independent genomic and metagenomic data.

Taken together, these elements point towards a tiered methodological framework for incorporating microbial non-human species into decision-making. At the base of the framework, long-term, standardized 16S-based surveillance can provide cost-effective indicators of community balance and early warning of major shifts. At an intermediate level, targeted shotgun metagenomic surveys can be deployed to characterize community-level responses to specific interventions or technologies, and to track genes of concern across time, sites and hosts. At the highest level of resolution, whole-genome sequencing of key pathogens and indicator strains can underpin detailed risk assessments and regulatory actions. Crucially, this framework should be embedded in policy instruments that explicitly recognize microbial indicators as part of environmental and health assessment, for instance, in aquatic ecosystem indices, discharge standards for aquaculture or wastewater, and guidelines on antimicrobial use (Verhille, 2013; National Research Council, 2004; Carvalho et al., 2025).

In summary, including microbial non-human species in policy and decision-making is not only desirable but also practically achievable with existing methods, provided that we invest in standardized sampling, genome-resolved identification, and multi-level monitoring. In aquatic systems, where microbes mediate the link between environmental change, animal health and human exposure, such a framework would allow decision makers to use microbial data as a structured, quantitative basis for anticipating risk, evaluating the impacts of emerging technologies and guiding interventions that respect both ecosystem integrity and the interests of future generations.

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