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Scientific Citizenship

Microbes Should Be Central to Ecological Education and Outreach

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Our planet is changing rapidly, and responding to the ensuing environmental challenges will require an informed citizenry that can understand the inherent complexity of ecological systems. However, microorganisms are usually neglected in the narratives that we use to understand nature. Here, we advocate for the inclusion of microbial ecology across education levels and delineate the often neglected benefits of incorporating microbes into ecology curricula. We provide examples across education levels, from secondary school (by considering one's self as a microbial ecosystem), to higher education (by incorporating our knowledge of the global ecological role and medical application of microbes), to the general public (by engagement through citizen-science projects). The greater inclusion of microbes in ecological education and outreach will not only help us appreciate the natural world we are part of, but will ultimately aid in building a citizenry better prepared to make informed decisions on health and environmental policies.

INTRODUCTION

Given our dramatic impact on ecosystems (53) and the consequences of such impacts on human welfare, ecology has emerged as a key scientific field for building an informed citizenry (28). However, significant gaps exist in our knowledge about the interrelationships between organisms and the environment. In particular, the lack of awareness of microbial life often represents an important gap in our world view of nature (3, 42). Microbes are, by definition, invisible to the naked eye, and this hampers an appreciation of their enormous diversity and key ecological roles. Along these lines, D'Arcy Thompson, in his classic book *On Growth and Form,* recognized how the microbial world might hide from our regular human intuition:

> Man is ruled by gravitation, and rests on mother earth. […] where the bacillus lives, […] the predominant factors are no longer those of our scale: we have come to the edge of a world of which we have no experience, and where all our preconceptions must be recast. (51)

As a consequence of this microbial ignorance, there are some under-recognized facts about the importance of microbes that are fundamental to understanding the functioning of Earth as an ecological system. These are: i) life on Earth is and has always been predominantly microbial (25); ii) global elemental cycles are fundamentally controlled by the extraordinary metabolic capacities of microorganisms (20); iii) Bacteria and Archaea alone store about 75% of the carbon stored in all plants, and about 10 times more nitrogen and phosphorus than plants (55); iv) every plant or animal harbors microbes, and these microbes are often critical to host health and survival (35). Since the publication of the first microbial ecology textbook (8), scientific interest in microbial ecology, likely triggered by advances in molecular techniques, has been growing steadily (Fig. 1). However, the problem we currently face is one of understanding how we can translate this scholarly enthusiasm to the ecological curriculum and the general public's understanding of environmental issues.

The ubiquity of microorganisms, their relationships with other organisms, and their role in global cycles need to be incorporated in the repertoire of narratives that we use to understand our place in nature and to engage the public understanding of science. This engagement process must begin with early education, but it cannot end there. It should also continue past formal education to reach other members of the public through citizen-science efforts and other outreach activities. Here, we advocate for the broader inclusion of microbes and their relationships with other organisms and the environment across education levels. In particular, we will provide specific strategies for how to incorporate such material by highlighting: i) how the consideration of one's self as a microbial ecosystem encourages an understanding of

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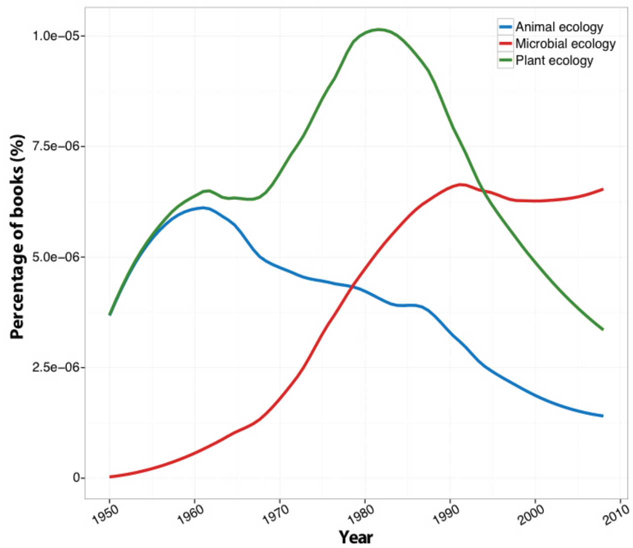

FIGURE 1. Percentage of books published over the past 60 years that mention the terms "animal ecology," "plant ecology," or "microbial ecology" in the text. Data from Google Ngrams (36).

one's place in the broader "macrobial" ecosystem; ii) how to incorporate our knowledge about the roles of microbes into ecological education and environmental policy decisions; iii) how citizen-science efforts can be used to engage the public with the study of microbes in the environment. Broadly, we will explore how microbial ecology education can be fostered across multiple education levels and why the inclusion of microbes in education and public discourse is critical.

PRIMARY AND SECONDARY SCHOOL: EXPLORE YOUR MICROBIOME

Children are unable to draw microorganisms (41), and they usually misrepresent the size and morphological characteristics of microbes (32). For example, children often have the mistaken impression that a virus is larger than a bacterium (27), or that a microbial cell is smaller than a protein (16). These early-childhood misconceptions about microbes are not just restricted to their morphology or size, but also extend to their role in nature. Many studies in classrooms have shown that for children of all ages, microbes are exclusively associated with diseases and deficiencies in hygiene (10, 19, 27). This seems reasonable and reflects the history of microbiology guided by practical problems like health issues and food spoilage. Interestingly, although students acknowledge that germs are everywhere (27), they hold an incomplete picture of the interrelationships between macro- and microorganisms. For example, young students consider microbes as a strictly human problem, rather than seeing microorganisms as one of many organisms in the ecosystem, or as pathogens or symbionts for other organisms (19, 27). In general, students think of humans as the center of the ecosystem rather than one member interdependent with other organisms such as microbes (26, 40).

Recent research in the field of microbial ecology has emphasized just how inescapable and erroneous these misconceptions of microbes are. Studies of the human microbiome (i.e., human-associated microbial communities) have challenged standard conceptions of what the human body is, and have transformed the concept of "germs" from strictly harmful pathogens into the more nuanced idea that most microbes are innocuous or even beneficial to human health. In fact, the human body and its associated microbial communities are now studied using an ecological approach (22). We believe that a valuable, but underutilized, approach to teaching children about the complexity and intricacies of ecosystems is to engage children's interests in microbes by highlighting their relevance and their relationships with other organisms in everyday environments: their own body, pets, parks, and homes. It has been proposed that ecology and environmental education should stress the self to engage students (28). What better way to accomplish this than by demonstrating to children that their bodies represent entire ecosystems? This can be accomplished not just through narrative stories, but also through hands-on activities, including those compiled by the American Society for Microbiology (www.asm.org/index.php/k-12-teachers). For example, by swabbing their mouths and growing bacteria on petri dishes, children can travel back in time and experience the same awe that Antonie van Leeuwenhoek felt when he first observed bacteria from his own teeth under the microscope more than 300 years ago (24). During these classroom activities, teachers should be careful to follow established protocols, e.g., sealing petri dishes or sharing pictures instead of the media plates (9, 18). Such activities not only make the microbial ecosystem personally relevant, but also allow the invisible and abstract to be seen (52) and smelled—resulting in multisensory training, which is more effective in memory formation and recall (48).

Given the aforementioned misunderstandings children often have regarding the biology and the ecological role of microbes, schools should help foster the innate appetite of children to engage with nature (56) by emphasizing that "nature" and the complex communities common in nature can be found on their skin, in their mouths, and in their guts.

COLLEGE: MICROBES RULE THE EARTH

Sergei N. Winogradsky (1856–1953), considered the father of microbial ecology, may have been the first to argue that microbes are fundamental components of ecosystems, often having stressed the intimate connection between microbial and macrobial life forms at the global scale:

> Microbes are the main agents called forth by life and are necessary for the lawful operation of the cycle of life. They are the living bearers of infinitely varied reactives, and one can even say, they are the reactives incarnate, without which many of the necessary processes of that cycle would be inconceivable. (1)

It has been the authors' experience that most biology students at colleges and universities are not aware of the global-scale importance of microbes and their enormous taxonomic and functional diversity. Undergraduates tend to maintain a pre-Winogradsky vision of life's metabolic diversity. At that time only two metabolic mechanisms were known: one triggered by light (photosynthesis), and the other based on the oxidation of organic matter (aerobic respiration). However, during its evolutionary history, microbial life has found diverse ways of obtaining energy and, as a consequence, some species can generate energy by oxidizing inorganic substrates, including sulfur, iron, or ammonia. Another frequent area of ignorance among students is the lack of understanding that microbes dominated Earth for most of its geological history (25). In actuality, the panoply of metabolic processes based on redox reactions evolved exclusively in microbes and has drastically changed (and continues to shape) our environment (20). In all likelihood, the most dramatic biological event on Earth occurred around 2.5 billion years ago when cyanobacteria transformed the Earth to its present oxic status and triggered the evolution of multicellularity (11, 46).

This fundamental information regarding life on Earth could be more effectively incorporated in the contents of introductory ecology courses (34). Mention of microbes in ecology textbooks is generally limited to their unsurpassable role in decomposition and the nitrogen cycle, embellished with a couple of examples about life in extreme conditions and symbiotic lifestyles. This is shocking when we consider that most of the species, biomass, evolutionary history, and sheer abundance of life on Earth is microbial (25, 42, 55).

This macroscopic bias may be in part due to the lack of familiarity that most ecology instructors have with microbial ecology. They are thus more likely to present examples from the animal or plant systems, which are more familiar to them. We call for a broader treatment of microorganisms in general ecology textbooks. While animal and plant models provide an excellent introduction to organismal relationships, as they are visually familiar to students, they should be complemented with microbial examples. More thorough inclusion of microbes would help undergraduate students understand the complexity of metabolisms and the interrelationships among microbial and macrobial life forms on Earth. As an introduction to these relationships, undergraduate students can create a complex microbial ecosystem in a jar known as a Winogradsky column (13, 43). This serves as a convenient, small-scale experiment to study ecological concepts and processes like nutrient cycling, community assembly, organismal interactions, and succession. The metabolic diversity of bacteria along the column can be astonishing: autotrophs (carbon obtained from CO_2), heterotrophs (carbon obtained from organic compounds), phototrophs (energy obtained from light), and chemotrophs (energy obtained from chemical oxidation). Rarely do students get to delve into such a complex ecosystem without undertaking financially burdensome field trips outside the classroom.

In general, more examples and experiments of population and community ecology with microbes, while acknowledging their enormous taxonomic and functional diversity, would help college students increase their understanding of global biogeochemical cycles, community interactions, and the impact of humans on ecosystems.

PUBLIC OPINION: LET'S TALK ABOUT MICROBES

Education does not stop after graduation. In liberal democracies where technological innovation plays a key role, citizens must be able to make informed decisions about scientific issues that are often uncertain, that are subject to interpretation from different perspectives, and that might even clash with public values and worldviews (21, 29). Undeniably, our view of the relationship between humans and nature determines the attitudes we develop and the environmental policies we adopt (15, 54). Currently, microbes are largely missing from our conceptualization of nature, and thus from our view of this relationship.

The best example of environmental policy subject to debate and polarization is the perception of the risks associated with climate change (30). We believe that microbial ecology might help educate the public about the uncertainties inherent in climatic and ecological debates. Due to their "invisible" nature, microbes are abstract entities even though we know that they play a key role in sustaining global-scale ecosystem services such as carbon sequestration, decomposition, nutrient recycling, and water purification (5). Thus, we need to better incorporate microbes in our narrative framing of nature. We already know that microbial infectious diseases have a great economic impact by directly affecting trade and commerce (23), but there are still huge gaps in our understanding of how the modification of global biogeochemical cycles mediated by microbes may impact ecosystems (50). For example, warmer temperatures may accelerate the microbial decomposition of the enormous amounts of organic carbon currently stored in permafrost soils, but the magnitude and direction of this climate feedback from terrestrial ecosystems to the atmosphere remain unresolved (47).

As scientists who are often financially dependent on taxpayers for research support, we need to ensure that the public appreciates the value of their investment in research. Such appreciation can come through public education and outreach. Scientific engagement with adults is just as integral as with younger students, but it presents unique challenges. Unlike secondary school or undergraduate students, the general public is not a captive audience. One way of motivating the general public to learn about science is by providing the public with personal ownership of the research, or by specifically disseminating results directly to them, rather than exclusively through the production of journal articles that typically fail to reach a broad audience of nonscientists. Some funding agencies (such as the National Science Foundation in the USA and the Natural Environment Research Council in the UK) now encourage such public outreach (31, 49).

One increasingly popular way to engage the public with scientific research is through citizen science. Although members of the public have for centuries recorded natural history observations (37), using volunteers in ecological research projects was initiated in 1900 by the National Audubon Society's annual Christmas bird count (www.audubon.org/conservation/science/christmas-bird-count). Approximately 70,000 volunteers now participate in this survey (12). Although ornithology has the largest body of amateur practitioners (6), citizen-science efforts in other fields of ecology have expanded in recent years. One benefit for scientists is that this allows for a greater collection of data across vast geographic and temporal scales than is typically feasible (12, 14). For example, enthusiastic amateur entomologists can now help protect threatened moths (www.mothscount.org), track invasive ladybugs (www.lostladybug.org) and exotic ants (www.schoolofants.org), or study the decline of pollinators (www.greatsunflower.org) by just scouting their backyards. However, the use of citizen scientists in microbial studies has lagged behind (Table 1), and this despite the fact that microbes are everywhere: living inside homes (17), commuting in the subway (45), and residing in the soils of metropolitan parks (44). As recent examples, researchers were able to map the distribution of airborne microbes using the dust collected by citizen scientists from their homes' door trims (4), and also study the presence of different microbes in the metropolitan area of New York City (2). As more and more people move to urban areas, we should learn about the organisms with which we live (33).

Such general public education efforts that we have outlined here will simultaneously provide benefits to the researchers in terms of generating more data and increasing the likelihood of getting funded, while also benefiting the public through the associated outreach materials. As citizens take ownership of the research, they will have a greater investment in a microbial discourse (38). Public outreach efforts such as crowdsourced data mining, citizen-science efforts, and even the "gamification" of analyses to encourage citizen participation are showing promising results across scientific fields in terms of increasing scientific literacy (7). We hope that microbial ecologists will continue to engage with the public in similar veins for the benefit of the field and greater society.

TABLE 1.
Citizen-science projects that involve the study of microorganisms.

Project	Description	Web Site
Wild Life of Our Homes	Bacterial and fungal communities associated with home dust	http://homes.yourwildlife.org
Home Microbiome Study	Bacteria on home surfaces	http://homemicrobiome.com
The Microverse	Microbes on buildings	http://nhm.ac.uk/take-part/citizen-science/microverse.html
MERCCURI	Microorganisms on the International Space Station	http://spacemicrobes.org
Belly Button Biodiversity	Bacteria in navels	http://navels.yourwildlife.org
Autism Microbiome	Gut-associated microbes and autism	https://microbiome.stanford.edu
American Gut	Gut-associated microbial communities in the US population	http://americangut.org
μBiome	Human-associated microbial communities	http://ubiome.com
Kitty Microbiome	Gut-associated microbes in cats	https://catbiome.wordpress.com
Plankton Portal	Identification of marine plankton	www.planktonportal.org
Wolbachia Project	*Wolbachia* symbionts in arthropods	http://discover.mbl.edu
Clumpy	Identification of bacterial infection in plant cells	http://clumpy.ex.ac.uk
GoViral	Flu outbreaks	www.goviralstudy.com
SEA-PHAGES	Bacteriophage genomics	www.hhmi.org/programs/science-education-alliance
Drugs from Dirt	Secondary metabolites from soil	www.drugsfromdirt.org
Citizen Science Soil Collection Program	Fungal natural products from soil	http://npdg.ou.edu/citizenscience
State of the Oyster	Bacterial contamination levels in edible shellfish	http://wsg.washington.edu/mas/ecohealth/state_of_oyster.html
BEACH Program	Monitoring for fecal bacteria in beaches	www.ecy.wa.gov/programs/eap/BEACH/

CONCLUSION

Citizens must be able to make informed decisions regarding scientific issues that affect their personal lives, the prosperity of their communities, and their natural heritage. However, non-scientists can have drastically different ideas about nature from those of the scientific community (21, 29). This decoupling of the public and the scientific community is initiated during childhood. For example, children find certain ideas like ecological concepts involving indirect interactions (26, 40) or conceiving the biological world at microscopic scales (10, 19, 41) particularly difficult to grasp. Moreover, during adulthood, our ideological and political backgrounds will bias our perception and reasoning (29, 30). Education remains our best tool to shape personal judgment, which is particularly important in democracies, where opinions are contested and people make political decisions.

The environmental challenges ahead will require that all citizens have a more complete picture of the natural world, with all of its inescapable complexities, interconnectedness, and uncertainty. Therefore, we cannot neglect the main actors on the Earth's stage, microorganisms, as we should probably be more worried about what we do not know than about what we already know. In this paper we have offered a "call to arms" in bringing microbial ecology into mainstream science education across all levels. We have offered suggestions on how to accommodate such goals, but rather than providing a treatise on such strategies, we hope to stimulate a greater discussion on how to accomplish this in the future.

We argue that the emergent benefits of increasing microbial ecology education far outweigh the costs associated with incorporating a new lesson plan, or the time spent to educate instructors on how to better incorporate microbial examples in classrooms. We encourage the inclusion of microbial ecology in education because microbes help us appreciate the inherent complexity of nature, including our individual microbial ecosystems, and our place in the broader ecosystem. Education is often fueled by imagination, making the microbial world we cannot see a useful focus for teaching basic concepts in ecology and environmental science. The naturalist John Muir endorsed the value of considering our invisible companions to enlarge our perspective of the natural world: "When we think of the small creatures that are visible, we are led to think of many that are smaller still and lead us on and on into infinite mystery." (39)

As we move forward as educators, scientists, and contributors to society, let us not forget to share this microbial world of infinite mystery with our fellow humans.

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