environmental microbiology

Environmental Microbiology (2019) 21(5), 1513–1528 doi:10.1111/1462-2920.14611

Editorial

The urgent need for microbiology literacy in society

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Summary

Microbes and their activities have pervasive, remarkably profound and generally positive effects on the functioning, and thus health and well-being, of human beings, the whole of the biological world, and indeed the entire surface of the planet and its atmosphere. Collectively, and to a significant extent in partnership with the sun, microbes are the life support system of the biosphere. This necessitates their due consideration in decisions that are taken by individuals and families in everyday life, as well as by individuals and responsible bodies at all levels and stages of community, national and planetary health assessment, planning, and the formulation of pertinent policies. However, unlike other subjects having a pervasive impact upon humankind, such as financial affairs, health, and transportation, of which there is a widespread understanding, knowledge of relevant microbial activities, how they impact our lives, and how they may be harnessed for the benefit of humankind – *microbiology literacy* – is lacking in the general population, and in the subsets thereof that constitute the decision makers. Choices involving microbial activity implications are often opaque, and the information available is sometimes biased and usually incomplete, and hence creates considerable uncertainty. As a consequence, even evidence-based 'best' decisions, not infrequently lead to unpredicted, unintended, and sometimes undesired outcomes. We therefore contend that *microbiology literacy* in society is indispensable for informed personal decisions, as well as for policy development in government and business, and for knowledgeable input of societal stakeholders in such policymaking. An understanding of key microbial activities is as essential for transitioning from childhood to adulthood as some subjects currently taught at school, and must therefore be acquired during general education. *Microbiology literacy needs to become part of the world citizen job description*. To facilitate the attainment of *microbiology literacy* in society, through its incorporation into education curricula, we propose here a basic teaching concept and format that are adaptable to all ages, from pre-school to high school, and places key microbial activities in the contexts of how they affect our everyday lives, of relevant Grand Challenges facing humanity and planet Earth, and of sustainability and Sustainable Development Goals. We exhort microbiologists, microbiological learned societies and microbiology-literate professionals, to participate in and contribute to this initiative by helping to evolve the basic concept, developing and seeking funding to develop child-friendly, appealing teaching tools and materials, enhancing its impact and, most importantly, convincing educators, policy makers, business leaders and relevant governmental and non-governmental agencies to support and promote this initiative. *Microbiology literacy* in society must become reality.

The context

Microbiomes and biomes

Communities of *micro*organisms create second skins on essentially all body surfaces in contact with the environment of all *macro*organisms of the biosphere—the animals and plants. These microbial skins constitute additional, dynamic, ecophysiological barriers that augment the physical and chemical barrier functions (e.g., to pathogen attack) of epithelial surfaces. But, in addition to their barrier activities, such microbial communities engage in multifaceted interactions with their hosts, provide essential functions and have a pervasive influence on the well-being and biological characteristics of the host partners. For example, plant-associated microbes mediate acquisition of essential minerals including nitrogen for growth (indeed, without microbially mediated nitrogen fixation, there would not have been enough biomass production by plant primary producers for the proliferation and evolution of animal consumers), protect against infections and produce hormone-like compounds that promote plant growth. Some microbes carried by plants are toxic to animals and hence function as a plant defence against predators. Microorganisms protect animals from disease, ferment food inside ruminants such as cows and digest food for insects. Although essentially all *macro*organisms are covered with surface microbial communities, some also contain so-called endosymbiotic *micro*organisms that live *within* host cells. Endosymbionts play important roles in the life cycles of various organisms, like insects (where they may even determine the sex of the host), sponges and plants, and some other *micro*organisms, like protozoa. The intracellular organelles responsible for harvesting solar energy (plastids) in photosynthetic organisms, and for energy generation (mitochondria) in most organisms, evolved from endosymbiotic bacteria. The microbial component of an organism, the so-called *microbiome* [microbiome: 'a characteristic microbial community occupying a reasonably well defined habitat which has distinct physio-chemical properties. The term thus not only refers to the microorganisms involved but also encompasses their theatre of activity' (Whipps *et al.,* 1988)], is an essential feature of an organism's identity and ecophysiology: germ-free animals and plants are laboratory freaks with defective developmental programmes that render them unfit and unable to survive in their natural habitats. The integrated whole, consisting of *microbiome* and host, is termed the *biome.* Perturbation of the microbiome, leading to so-called *dysbiosis*, may disturb its relationship with the host and disrupt functions that contribute to well-being, as evidenced by the herbicide glyphosate-provoked perturbation of the bee gut microbial community, leading to an increase in pathogen susceptibility (Motta *et al.,* 2018).

Humans are 50% microbial

The human *biome* is, in terms of cell numbers, 50% microbial (Sender *et al.,* 2016). Human gut microbes digest much of our food intake and release its nutrients in forms we can assimilate and utilize, provide essential vitamins, amino acids and other micronutrients that we cannot make ourselves, produce hormone-like compounds and thereby act as a second endocrine system (Brown and Hazen, 2015) and play currently unfolding roles in a range of physical and mental diseases (Wang *et al.,* 2017; Du Toit, 2019). A classic example of human microbiome *dysbiosis* is antibiotic-induced perturbation of the gut microbial community, leading to *Clostridium difficile* gaining the upper hand and causing pseudomembranous colitis (Bartlett, 1979). It is crucial we recognize that from birth to death we live in an intimate, dynamic and mutually beneficial relationship with our microbial partners, an integrated, reciprocal relationship that to a significant extent specifies what and how—and hence who—we are (and, of course, who they are). To update Descartes: *I think, therefore we are.*

> *We may fret about how little we know and can trust our human acquaintances, while knowing essentially nothing about our most intimate and influential friends. Attainment of an ability to maximize our personal well-being will require that we comprehend*
>
> - *what our microbial partners are doing,*
> - *what impact their activities have on us,*
> - *how our microbial partners and their activities are affected by what we do, and*
> - *how we can improve our partnerships for mutual benefit*

Microbes in the service of humanity

Microbes not only affect us personally as individuals, they have been exploited in the service of humankind since time immemorial, initially in the production of fermented food and drinks (beer, wine, fermented milk products), leavened bread, binding materials (retting of flax), the maintenance of soil fertility (the use of legumes containing nitrogen-fixing bacteria, fertilization with microbial biomass) and, subsequently, reduction of pollution through degradation of household and industrial wastes and provision of clean drinking water. In particular, the fermentation of food to conserve it and improve its nutritional quality and, later, improvements in hygiene, through the microbial treatment of human wastes and concomitant reduction of their pathogen load, contributed significantly to the rise of civilization and the quality and longevity of human life.

In more recent times, microbes have taken centre stage of the burgeoning bioeconomy (e.g., see Timmis *et al.,* 2017a). Coincidentally, there has been a major shift in the global economic framework, designated the 4th Industrial Revolution (4IR). Along with unlimited connectivity, artificial intelligence, massive sensing, big data processing, robotics and many other features, the 4IR also envisions the sustainable production of goods in the context of a circular economy with zero waste, no harmful emissions, and in which everything is recycled (e.g., see Nielsen, 2017). Microbially mediated processes are ideally suited to the 4IR, because they do not require extreme conditions, high energy inputs and toxic reagents. New materials and wastes created, and reactants involved, are generally readily recycled. As a consequence, microbial biocatalysis-mediated chemical transformations, which were previously a somewhat marginal complement to chemical processes, and focused on the production of a small number of high/added value bioactive molecules, have emerged as a veritable and environmentally sustainable alternative to large scale chemical conversion of renewable feedstocks into products. At the core of these developments are cell factories (mostly microbial) and enzymes obtained from them, either natural or reprogrammed.

An indicative selection of the vast range of current microbial processes, in addition to biocatalysis, includes

- the manufacture of diverse foods (yoghurt, cheese, natto, single cell protein, chocolate, ripened sausage, pickles, probiotics), food flavourings (vanilla, soy sauce, kimchi, paa deak, soumbala) and food supplements (vitamins, amino acids, folate, probiotics),
- the production of pharmaceuticals (antibiotics, hormones, biologics), vaccines, diagnostics and biosensor monitoring systems and personal care products,
- protecting and promoting growth of crop plants,
- fermentations for the production of diverse chemicals and biomaterials (bioplastics, microbial cellulose),
- green chemical engineering, like electrosynthesis, and use of the greenhouse gas carbon dioxide as a material for chemical synthesis,
- energy production (biogas, microbial fuel cells),
- recovery of natural resources (e.g., metals, by industrial bioleaching, which is replacing highly polluting thermal processes),
- treatment of waste streams and bioremediation of polluted sites,
- biocleaning–biorestoration and biopreservation of historical cultural heritage objects (monuments, statues, frescos, paintings, documents).

In addition, there is a vast array of new applications under development, including microbial therapies for diseases caused by microbiota *dysbiosis* (pseudomembranous colitis, inflammatory bowel disease, obesity, diabetes, and various psychological conditions; e.g., Rossen *et al.,* 2015), synthetic biology reprogramming of biotechnologically relevant cells and organisms to achieve high level production/activity, ecosystem-level bioengineering and so on. The amazing metabolic versatility of microbes continuously yields new opportunities for the sustainable production of bulk and speciality chemicals and materials (Lee *et al.,* 2019).

The ability to recognize new opportunities of microbial activities in a timely manner, to accurately assess benefits and possible risks, and to take evidence-based decisions on actions needed to facilitate their exploitation, is essential for knowledge-based, biocentric economies to be competitive and to progress significantly towards sustainable practices. It absolutely necessitates adequate knowledge of the underlying microbiology at all levels in the decision chain, including the general public as key stakeholders.

Policy decisions based on knowledge of underlying microbiological processes will be the basis of future progress, well-being, achievement of sustainability and the advancement of civilisation. The rapidity and direction of our future progress depends heavily on the degree of our commitment to

- *agnostically explore microbiological processes and thereby continuously evolve our capacity to predict and identify potential novel microbially based commercial applications*[1]
- *adequately harness new applications for improvement of human and planetary health,*
- *expand on, and improve, contemporary applications, and*
- *design appropriate evidence-based decision and resource allocation systems that incentivize and facilitate pertinent research, development and commercialisation activities, and adequately incorporate relevant stakeholder preferences.*

[1] New discoveries are the output of research. Research is, however, organized in disciplines and groups of related disciplines, which to some extent act as impediments to discoveries of a transdisciplinary nature. Importantly, many of the changes needed for environmental protection, human health and food security require transdisciplinary research planning and implementation. Because microbiology is so broad in its nature and applications, and so pervasive in its impacts on life and the planet, *microbiology literacy* would make researchers inherently more interdisciplinary. This would undoubtedly accelerate the development of innovative solutions and management options for many of the critical environmental/health problems we currently face.

Microbes pervasively and profoundly affect us personally and collectively

Microbes can impact on our lives in so many ways and are thus relevant to many personal decisions we take, such as whether to give birth by caesarean (aseptic) or natural delivery (colonization of the newborn by maternal microbes; Wampach *et al.,* 2018), breast-feed [delivery to the baby of protective antibodies against pathogens, human milk oligosaccharides favouring bifidobacteria thought to orchestrate healthy development of immune systems (Gomez de Agüero *et al.,* 2016; Moossavi *et al.,* 2018), maternal microbes present in breast milk, etc. (Milani *et al.,* 2017)], frequently use powerful disinfectants to clean the home (reduce exposure of infants to microbiome diversification and its health benefits: Finlay and Arrieta, 2016; Gilbert and Yee, 2016; Bach, 2018; Sharma and Gilbert, 2018; or indeed hospitals: see Caselli, 2017), be vaccinated or treated for an infection (Lane *et al.,* 2018), use phosphorus-containing household cleaning products (Richards *et al.,* 2015; can contribute to eutrophication and harmful algal blooms in local waters), use germicidal soaps (can cause dysbiosis of skin microbiota; Gilbert and Yee, 2016), acquire a companion dog (facilitates microbiota exchanges, Trinh *et al.,* 2018; increases phosphorus inputs into the watershed, Hobbie *et al.,* 2017) or what food to eat (e.g., beef, which has a substantial methane footprint; beef and dairy products whose consumption is correlated with cancers, zur Hausen *et al.,* 2017; other meats and vegetables: provenance, shelf-life, associations with known risk factors, etc.) and how to store and prepare it, how much to ventilate/humidify/dehumidify our homes, and so forth.

This may be exemplified by consideration of just one activity we engage in with some considerable pleasure—holiday and leisure—which can expose us to diverse infections and microbially caused diseases, some life-threatening, that are absent from or less prevalent in our home environments, through

- *bathing*, in fresh and seawater (e.g., *Cryptosporidium*, *Vibrio vulnificus*, *Leptospira*, etc.) and in non-adequately chlorinated pools and especially hot tubs (*Mycobacterium, Pseudomonas, Legionella, Candida*, *Trichophyton, Giardia*, etc.),
- *eating,* uncooked or contaminated food, especially seafood (e.g., *Salmonella*, *Vibrio*, EHEC, *Campylobacter*, *Listeria*, *Norovirus*, hepatitis viruses and diverse parasites), and even adequately cooked food containing heat stable toxins (including the lethal red tide neurotoxin and several mycotoxins),
- *drinking,* contaminated fluids (e.g., water, fruit juices, etc.),

- *sexual activity,* with new partners (classical STIs, but also HIV, etc.),
- *selection of holiday destination*, where infectious agents like yellow fever, malaria, Zika virus, hepatitis virus, dengue virus, Lyme disease and tuberculosis, may be endemic and
- *selection of accommodation and wellness facilities*, including cruise ships (e.g., *Cyclospora, Norovirus, Legionella* and mycobacteria).

Of course, business travel can expose us to similar hazards, and medical tourism can carry additional, surgery- and hospital-associated risks.

Microbial activities equally influence collective undertakings, and their consideration is essential for many strategic/policy decisions, such as the introduction of a new feedstock/creation of a new waste in an industrial production facility, introduction of a new ingredient in a food product, establishment of a new food supply chain, introduction of a new public health measure, implementation of new agricultural practices or introduction of new measures to protect our marine systems from degradation.

If we are to make – whether at the personal or policy level – effective decisions that have a high probability of resulting in predictable and intended outcomes, we must know which microbial activities are relevant and how these activities might impact on, and be affected by, the implementation. Routine decisions in our lives need to be informed by a basic understanding of

- *which adverse consequences can result from our actions, and*
- *how we can modify our behaviour to avoid or mitigate such consequences for us and others.*

Microbes pervasively and profoundly affect the entire biosphere

Microbes were the first forms of life, originating almost four billion years ago, and are its future: they will continue to inhabit planet Earth long after humans and other life forms have disappeared. The invisible world of the microbes represents far greater evolutionary and metabolic diversity than the visible organisms familiar to us. In terms of biomass, 90% of life in the oceans is microbial. Photosynthetic algae and cyanobacteria form a major component of marine plankton and are the basis of oceanic food webs. *Prochlorococcus* and *Synechococcus* remove about 10 billion tons of carbon per year from the air, corresponding to about two-thirds of the total carbon fixation in the oceans. Microbes regulate global and local biogeochemical processes that fundamentally influence greenhouse gas emissions to the atmosphere, affect climate change, as well as regulating the health of humans, animals, plants, soil and the water supply. They generate 50% of the oxygen we breathe. Early microbes produced the oxygen that enabled all oxygen-using organisms to evolve, as well as the ozone layer that enabled life to move from the deep oceans to land. They are the supreme waste recyclers and regenerators of the planet. Microbes are ubiquitous, and their activities sustain and influence the quality of all life on the planet. *They are the life support system of the biosphere.* Although we humans consider ourselves to be the stewards of planetary health, microbes are much more powerful agents of influence, regulation and change of planetary activities. *In extremis*: if a cohort of microbes performing a critical process in nutrient cycling were to be lost from the biosphere, and could not be replaced by another functionally equivalent cohort, life on Earth as we know it would cease to exist.[2] The global environmental microbiome is, in terms of activities and dimension, the only ally that we may count on for reverting the impact of polluting emissions resulting from industrial activities, intensive agriculture and human overpopulation (de Lorenzo *et al.,* 2016)

[2] Although at first sight, this notion (especially in combination with the other statement below *all microbes are everywhere*) might seem rather far-fetched, it is worth pondering the following: changes in environmental-habitat conditions, for example, through global warming, can make them unfavourable for their inhabitants. The consequences are that the inhabitants must (1) migrate to more favourable habitats, (2) adapt-evolve new properties that are better aligned with the new conditions or (3) die, and if geographically restricted, perhaps go extinct. Evolution is affected most easily by rapidly reproducing organisms. But microbes in a number of habitats of the biosphere reproduce extremely slowly. If changes occur rapidly, it is conceivable that they can die out. If any belong to a cohort mediating a critical biosphere function, there could well be serious consequences. Curtis (2006) has expressed this rather pointedly: *'... if the last blue whale choked to death on the last panda, it would be disastrous but not the end of the world. But if we accidentally poisoned the last two species of ammonia-oxidizers, that would be another matter. It could be happening now and we would not even know...'*.

It is essential that we collectively recognize the pivotal role microbes play in planetary processes and health, and acquire knowledge of what microbes do and can do, so that we may develop effective partnerships and strategies for co-stewardship of the health of our planet. It is imperative that we

- *understand and appreciate the delicate balance between microbiologically mediated nutrient cycles, planetary function and the health of the biosphere, and*
- *ensure we do not (even unintentionally) adversely impact microbial cohorts/communities that play a crucial role in biosphere functioning.*

Harnessing microbial activities is crucial to solving some grand challenges and attaining sustainable development goals

Humanity is currently facing major challenges that include an imbalance in access to food, clean water, healthcare, education, energy and raw materials, persisting poverty, loss of populated land due to global warming-caused rising sea levels, desertification; these are some of the *Grand Challenges.* The needs of humanity and of planet Earth, and an action plan to satisfy these needs in a sustainable manner, are detailed in the UN Sustainable Development Goals (SDGs; United Nations (2015) Transforming ourWorld: The 2030 Agenda for Sustainable Development. https://sustainabledevelopment.un.org/post2015/transformingourworld). A recent issue of Microbial Biotechnology (2017) explored the range of microbial technologies that are contributing/show potential to contribute to attainment of SDGs, including those that can ameliorate problems of food supply for a continuously growing world population (Garcia *et al.,* 2017; Trivedi *et al.,* 2017), of greenhouse gas production, global warming and some of its negative consequences, of global pollution, and to maximize exploitation of renewables and sustainability of world consumption of natural resources, and so forth (e.g., de Lorenzo, 2017; Verstraete and de Vrieze, 2017). This issue also addressed the exceptional potential of microbial biotechnology for another SDG, namely *sustainable economic growth and employment creation*, relating to new enterprises, employment and wealth, in part in the context of the Bioeconomy (Timmis *et al.,* 2017b), but also in other contexts. A series of Editorials in the same journal under the overarching title of *The microbiome as a source of new enterprises and job creation,* in 2017 and 2018, explored the capacity of microbiome technology to generate new enterprises and employment opportunities.

Many of the actions that must be implemented on the long road towards addressing Grand Challenges and achieving the SDGs will involve microbial processes. The major policy decisions needed to set these actions in motion/maintain them/increase their contributions require knowledge of relevant microbial activities and how these can be channelled for maximal beneficial effect.

Decisions based on knowledge of underlying microbiological processes could prevent major, in some cases, global disasters

Microbes are central actors and key stakeholders in planetary and biological evolution. An absence of due recognition, knowledge and consideration of microbial contributions to relevant processes, and a planning that fails to take into account the roles microbes may play in any intended change, renders policy development and implementation at all levels (international, national, regional and individual) risk-laden, sub-optimal or ineffective and, in worst cases, counter-productive. Some examples of potentially preventable disasters negatively impacted/caused by decisions-policies/lack of decisions-policies include:

The antibiotic resistance crisis. Already in the 1960s/early 1970s, leading microbiologists like Falkow (Falkow *et al.,* 1961; Falkow, 1970, 1975), Watanabe (Watanabe, 1963; Watanabe, 1966) and Levy (Levy *et al.,* 1976; Levy, 1982) warned about the growing emergence and spread of antibiotic resistance due to over-prescription and non-clinical use of antibiotics (indeed, Alexander Fleming, the discoverer of penicillin, already warned of the danger in his Nobel Lecture in 1945: https://www.nobelprize.org/uploads/2018/06/fleming-lecture.pdf). Similar warnings have been repeatedly issued since then, some related to the use of antibiotics in aquaculture (e.g., Cabello, 2006), but to little avail. Today, we consider antibiotic resistance to be one of the most important challenges in medicine because it renders an increasing number of previously treatable life-threatening infections no longer treatable. (http://www.wpro.who.int/entity/drug_resistance/resources/global_action_plan_eng.pdf). The risk posed by antibiotic resistance in 2050 is projected in the international report *Tackling drug-resistant infections globally: final report and recommendations* (https://amr-review.org/sites/default/files/160518_Final%20paper_with%20cover.pdf) to cost a cumulative $ 100 trillion and cause 10 million otherwise preventable deaths per year (interestingly, its first of four recommendations is the need for a *Global public awareness campaign* targeting in particular children and teenagers. Curiously, although the campaign was costed at $ 40–100m per year, the recommended campaign did not include basic education). Despite this, nonclinical use of antibiotics in animal husbandry and aquaculture is predicted to increase by 67% during the period 2010–2030 (https://amr-review.org/sites/default/files/160518_Final%20paper_with%20cover.pdf). If health authorities, politicians and business leaders (and, crucially, the general public) had been aware of the ability of microbes to rapidly evolve and disseminate new functions in response to changes in their environment—in this case, the massive, environmental introduction of powerful antimicrobial compounds—and thus able to appreciate the warnings of Falkow et al., we might be in a very different situation today.

The return of virtually eradicated childhood diseases. Entirely avoidable was the re-emergence of measles, whooping cough and diphtheria, due to a reduction in vaccination acceptance and coverage, reflecting a fundamental lack of understanding of vaccine-associated risk, the underlying microbiology and nonevidence-based personal choices—vaccine hesitancy—in countries which had virtually eradicated these diseases (Lane *et al.,* 2018).

The rise in allergies. Although serious childhood infections need to be seriously combatted, milder infections and reasonable exposure to environmental microbes is thought to facilitate development of a healthy immune system in infants (Bach, 2018). The rise of *microbiophobia* (germaphobia), and advertising campaigns which create perceptions that all microbes are bad and must be eliminated to achieve a safe domestic environment, may have significantly contributed to the current explosion in immune dysfunction in our society (e.g., allergies, asthma, eczema and even neurological disorders). Indeed, it was recently shown that a protective effect against skin cancer provided by skin microbes is reduced through use of aggressive germicidal soaps (Nakatsuji *et al.,* 2018). Such consequences could have been ameliorated if appropriate measures had been taken to provide education on the need to balance hygienic practices to reduce pathogen burden with strategies to maintain a healthy microbiota that provides us with key ecophysiological services, including effective immune system education, through microbial exposure from soils, animals and plants (Finlay and Arrieta, 2016; Gilbert *et al.,* 2017).

The greenhouse gas crisis. Microbes both produce and consume greenhouse gases (Cavicchioli *et al.,* submitted); therefore, efforts to reduce microbial emissions, on one hand, and to increase consumption, on the other hand, are crucial. When microbial participation in issues is considered, it is pivotal to understand quantitative aspects and the fact that processes may not be linear. Fixation of the greenhouse gas CO_2 by microbes and plants is slow in comparison to its release from burning fossil fuels by humans—the normal cycle of things is out of balance—which is why CO_2 levels are rapidly rising: our plant and microbial friends cannot keep up with human activities. Greenhouse gas emissions result in global warming, which in turn causes thawing of permafrost soils, which then allows new microbial production of methane and CO_2, thereby amplifying and exacerbating the consequences of fossil fuel consumption.

The production of animal meat, especially from ruminants, is accompanied by substantial emissions of the greenhouse gas methane, a fact that has been known for a long time. Meat production is itself based on forage-fodder production, which in turn is linked to nitrogenous fertilizer use. Urea, which is broken down by soil microbes into ammonia and the greenhouse gas CO_2, has a long history of widespread use as a nitrogenous fertilizer in agriculture (although is currently being phased out). Other nitrogenous fertilizers lead to microbial production of the extremely potent greenhouse gas N_2O (and, of course, eutrophication: run-off nutrient-induced harmful algal blooms in adjoining waterways/-bodies that can cause fish die-off, hypoxia and imposition of restrictions on use of affected water bodies). Clearly, important personal and policy decisions need to have been/are still to be made concerning the amounts of meat production and consumption in excess of essential dietary needs.

Nutrient run-off into coastal waterways results in rapid consumption of oxygen by resident microbiota, which in turn contributes to the rapid expansion of oxygen minimum zones. In identifying nine planetary boundaries for a sustainable future, including climate change, biodiversity loss and ozone depletion, the nitrogen cycle was identified as the most seriously compromised boundary due to the fact that application of human-made fertilizers now exceeds all natural processes in providing this vital nutrient to the biosphere (Rockström *et al.,* 2009). There is currently a debate in many countries about restricting the use of these fertilizers, but the need to feed the growing world population and produce food at a price affordable for the poorer members of society, quite apart from the business of agriculture and its supply chains, are confounding factors. It seems logical that farmers should be encouraged to lead on decision-making and formulating sound policies as they, more than anyone else, understand the relationship between soil nitrogen amendments and crop productivity. Nevertheless, microbial involvement in the issue of greenhouse gas emissions relating to nitrogenous fertilizers is rarely a major element of the personal and policy debate/decision process, which is where it needs to be to make such discussions meaningful and effective. More generally, recent policy decisions limiting greenhouse gas emissions deal primarily with anthropogenic emissions and essentially ignore that fact that microbes are pivotally involved in both the production and consumption of significant amounts of greenhouse gases, including N_2O and CH_4, in addition to CO_2. In any case, we are all affected in diverse ways by global warming and hence are key stakeholders. For example, it changes the global distribution of pathogens and their vectors, and thereby results in the emergence of diseases among new, immunologically naïve populations of humans and animals, and defence-naïve plants, with the possibility of epidemic spread.

The soil crisis. Soil is the essential skin of the Earth. It supports plant growth and is home to an incredible diversity of animals and microbes which mediate an amazing range of biogeochemical processes that characterize soil functions and determine its health. Soil filters surface waters that percolate into aquifers that provide potable water to billions of people. Soil contains precious nutrients, and three times as much carbon as is contained in the Earth's atmosphere. But the Earth's soil is rapidly eroding, often ending up in streams, rivers and oceans, releasing its nutrients along the way. Most countries are losing their topsoil many times faster than it is produced by soil-generating processes (rock weathering). Increasingly extreme weather events are elevating the rate of erosion. Soil microorganisms produce polysaccharides that act as glue to give soil structure and stability and thereby augment its resistance to erosion. The disastrous soil loss from much of the Earth's agricultural land that is predicted to occur before the end of the 21st century will result in the inability to produce food needed to feed the world's population, release of vast amounts of nutrients that will pollute our waterways, and release carbon that will increase global warming. If this crisis is to be averted, it is absolutely imperative that policy-makers institute knowledge-based strategies to better harness microbial activities which improve soil stability. To ensure that this happens, it is equally imperative that world citizens, as central stakeholders, appreciate the seriousness of the problem and the microbial options available. But, for this, acquisition of *microbiology literacy* is essential.

Pollutant accumulation in the environment and food webs. It is not sufficient to know that microbes participate in an environmental process, it is essential to know what they do well and what they do less well. Historically, it has been convenient to assume that the well-known metabolic versatility of microbes will take care of all polluting materials released from industry, households, hospitals and so forth, without considering the possibility that there will be limitations. But, although microbes can degrade an amazing range of organic materials, the metabolism of some is slow, sometimes very slow. Therefore, if their production and release into the environment is faster than the ability of microbes to degrade them, such materials accumulate and pollute, as evidenced by the finding of long-lived toxic chemicals, like PCBs and dioxins in the current food web, decades after the prohibition of their manufacture and the currently unfolding disaster of petrochemical-derived plastic pollution.

A range of serious issues currently facing us, including the insidious spread among pathogens of resistance to last resort drugs, soil erosion, the problem of plastic oceans and its impact on wildlife health, and microplastics formation and accumulation in the food web, was predictable and to a significant extent avoidable if

- *policy makers had been able to understand the likely outcomes of their decisions on microbiological processes and the long-term implications, and*
- *a greater spectrum of societal stakeholders had been empowered much earlier to appreciate the risks of contemporary policies and behaviours*

The exposome and the particular problem of chronic long-term exposure to low levels of biologically active substances

One of the *Grand Challenges* that is particularly relevant to the issue of *microbiology literacy* is biological and chemical pollution of the biosphere, because human decisions are both the problem—they can lead to policies that result in pollution—and the key to its solution—they can produce policies that mitigate pollution (*reduce, remediate, recycle*). Biological pollution, especially faecal pollution associated with major conurbations, although largely controlled in high income countries, occasionally presents problems due to technical failures or extreme weather events, and can still be problematic in lower income countries. However, industrialized animal husbandry for meat production is adding a further dimension through the large-scale generation of animal wastes that include enormous volumes of faecal matter containing antibiotic-enriched and -resistant microbes, including pathogens. Although some of this waste is rendered harmless in anaerobic digesters, some remains in the environment where it may constitute a hazard.

Although the toxicity and life cycles of new chemicals and pharmaceuticals are generally assessed before introduction into circulation, such assessments mostly provide information about acute toxicity detectable over short periods of time, mostly in standard models that bear little relationship to the particular inherent hazards the chemicals may possess. Assessment of acute toxicity for those organisms most directly affected, and low-level chronic toxicity that manifests itself over the long term, is extremely challenging. Many biologically active chemicals, particularly pharmaceuticals in manufacturing waste streams and hospital and household wastewaters, are active at very low concentrations, and some of them pass unchanged through waste treatment facilities into the environment. Added to this is the fact that some chemicals may be partially degraded by environmental microbes to new metabolites that are not captured in environmental impact assessments, that can be toxic in different ways to those of the original chemicals and that may be even more toxic than the chemicals initially entering the environment. Chronic low-level exposure to such chemicals and metabolites may have insidious population-level consequences. Compounds widely distributed in the environment include xenoestrogens—endocrine disruptors (Monneret, 2017)—which are considered to be responsible at least in part for falling levels of fertility in humans and other animals, and insecticides responsible for declining numbers of pollinators, like bees (Godfray *et al.,* 2015; Christen *et al.,* 2018).

Another, even more challenging, issue is that diverse polluting chemicals become mixed together in the environment and the impact of mixtures of chemicals, especially chronic exposure at low concentrations, on the health of humans and the environment is essentially unknown, but undoubtedly significant. Microbes have, or can evolve, the capacity to degrade many such compounds and will often be the primary agents of removal from the environment. However, they may not be able to degrade others, at least at meaningful rates, especially where they are present at very low concentrations and even more so when they are present in complex mixtures.

In summary, despite the complexity of biological and chemical pollution, and the equally complex microbial capacity to render pollutants harmless, the only way forward to reduce existing pollution will be to improve our understanding of relevant microbial processes and exploit them. For new chemicals, including those produced using synthetic microbiology, responsible design must include defined end-points for their life cycles. But, to repeat: whatever the limitations the microbial world may have, it remains the only agent we can count on for counteracting the exceptional pollution burden weighing on the planet (de Lorenzo *et al.,* 2016).

It is essential that microbial degradative abilities and limitations be appreciated, understood and become central to development of control and mitigation policies which, ultimately, will govern our level of exposure to environmental pollutants. Concerted, coherent and sustainable (global) policies are needed to

- *streamline identification, evaluation and monitoring of the types and levels of bioactive substances, and mixtures thereof, in our environment, at local, regional, and global levels,*
- *improve our understanding of how these substances impact on planetary, community and individual health,*
- *coordinate efforts to remove them from the environment, mitigate their toxic effects, and reduce their entry into and migration though the food web, and*
- *develop measures to reduce our level of exposure to such pollutants.*

Global connectivity and microbial reactions to change

Last, but not least, two key characteristics of our planet need to be emphasized. The first is connectivity: all of the planetary surface and atmosphere are connected by water, wind and mechanical supply chains of human products, which move much of what is on the surface and in the atmosphere around via land, sea and air transportation vehicles, sometimes for thousands of kilometres. A widely appreciated consequence of this *physical connectivity* is the transport of plastic waste to all parts of the oceans, far from the sites where they are discarded, and the finding of toxic polychlorinated biphenyls—PCBs—in polar animals, extremely remote from their sites of production and use. Thus, although we may believe the potential hazards of a chemical at its production facility to be safely managed, connectivity and distribution mechanisms may lead to distant problems. But also biological agents contribute to connectivity and movement in the biosphere, by active and passive movement, be it by flight, in the case of flying insects, birds and air-travelling humans, swimming and floating in the case of aquatic organisms, and so forth, and air- and water-suspended seeds, pollen and plankton. The explosive global spread of severe acute respiratory syndrome (SARS) in 2003, the annual influenza epidemic originating in Asia, an outbreak of enterohaemorrhagic *E. coli* in Germany transmitted by organic fenugreek seed sprouts imported from Egypt, expansion of diseases due to increased immigration, such as increasing tuberculosis in African countries like Morocco and tick-transmitted African viruses in Spain, are examples of the consequences of *biological connectivity.* International trade also plays a significant role in the spread of pathogens and may be responsible for current geographic spread of diverse plant diseases caused by *Xylella fastidiosa,* one of the most serious plant pathogens worldwide, having a huge economic impact for agriculture, public gardens and the environment. Unlike many vector-transmitted pathogens, which have host-specific vectors and thus a restricted host range, *X. fastidiosa* is transmitted by a range of sap-feeding vectors, and thereby infects a wide range of plant hosts. Ballast waters in ships that are picked up and discharged at diverse points of the globe may create new populations of non-indigenous, sometimes dangerous organisms, such as toxic algal species, that represent biosecurity problems. And desert dusts, rich in phosphorous, iron and microbes, are transported by air currents to distant places: dust from the Sahara regularly falls in Europe and fertilizes the waters of the Gulf of Mexico and the Sargasso Sea, allowing blooms of algae to develop.

Just as water and air connectivity mediates distribution of long-lived chemicals, including radioactive materials, throughout the biosphere and atmosphere, so they ensure distribution of tiny, almost weightless microbes. But: unlike chemicals, microbes can reproduce, opportunistically colonize and impact any site that they find favourable. The global distribution of microbes is encapsulated in the mantra: *all microbes are everywhere.* A corollary, perhaps more meaningful, mantra might be: *if microbes are able to profit by influencing a process somewhere, they will be there and exert this ability.*

A second important characteristic of the planet is the fact that changes, caused by natural events or accidental or deliberate actions of humans, often provoke a response, sometimes an unexpected response, which results in a consequence that may be different from that anticipated. It may be due to physico-chemical or, frequently, biological, especially microbiological, responses. Therefore, when we decide that we must undertake an action of some sort, in addition to the usual considerations of feasibility, cost, logistics and so forth, we need to take into account that microbes are not passive to significant anthropogenic changes—intentional and unintentional—to the environment: they actively respond to, and thereby modify, the consequences of our actions, positively and negatively. We always need to pose the question: are microbial activities directly or indirectly involved in or affected by the process under discussion and, if so, what are their possible/likely responses to the proposed action? Unfortunately, we have not yet learned how to discuss with microbes, so cannot ask them what they will do when we make changes. Therefore, evidence-based predictions from monitoring and modelling how microbes respond to environmental change, and caution, are essential. To vandalize the well-worn motto—*think globally, act locally*—we may exhort people to *act locally, but only after due consideration of the potential for local, regional and global reactions that may lead to collateral consequences (including non-intuitive consequences that may be entirely different from the topic under consideration).*

The interconnected nature of our planet necessitates that, before we act, we must be able to

- *judiciously assess potential spill-over effects, the degree of impact and pertinent pathways, of local action on microbiological activities in regions of varying proximity, and at the global level,*
- *properly map and model impact scenarios, including effect longevity and countermeasures, using adequate methods,*
- *carefully consider alternative courses of action when we, based on conservative assumptions, lack confidence in our predictions, and*
- *monitor, review and improve policies, and empower local entities to prevent uncoordinated or rogue actions, that unintentionally or otherwise might cause adverse effects.*

The problem

The problem is that knowledge of microbes and their activities is presently concentrated in a small group of specialists, the microbiologists. Of course, society has always made use of specialists to advise decision makers, for example economists to advise governments about the cost of implementation of new policies. The issue here is that microbial activities are so pervasive and directly and intimately affect the everyday decisions of everyone in society, that the option for timely consultation of microbiologists or interrogation of microbiology knowledge is, despite internet access to relevant information, in most situations impractical or impossible. Thus, we have on one hand microbiologists, who have little influence on policy decisions at any level, and on the other policy makers and decision takers who lack key knowledge essential for informed decisions. *How will we effectively address crises facing us, if neither the underlying causes of the crises nor potential solutions* (e.g., Brüssow, 2017) *can be understood and assessed by policy makers and stakeholders?*

If we are to avoid repeating mistake patterns of the past that have led to catastrophic outcomes of the type described above, the essential information underpinning correct perception of issues, appropriate choices, and optimal, evidence-based policy decisions, must be an integral component of our individual and collective knowledge base. In order to avoid triggering preventable disastrous events in the future,

- *basic knowledge of microbiological processes and activities, and of their multidirectional interactions and interdependencies, must not only become part of public awareness, but*
- *intermediate knowledge of these processes must be part of pertinent policy makers' skill-sets, and*
- *decision systems must more adequately require evidence-based criteria and expert review.*

A path towards a solution: attainment of microbiology literacy in society

Key elements of microbiology must become part of basic education

Some members of society, such as educators, politicians, captains of industry, heads of national and international agencies and so forth, have the greatest need of microbiology knowledge because their decisions have greater societal impacts than those of others. Nevertheless, all individuals make microbially relevant decisions and develop microbially relevant practices every day. Moreover, we are all stakeholders in major policy decisions affecting our health and well-being and those of our planet. To be able to exercise our citizens' rights and fulfil our responsibilities to competently inform decision makers, whether as voters or members of interest groups, we must be microbiology literate. There is thus a crucial need for *microbiology literacy* at all levels of society: *microbiology literacy must become part of the job description of adults.*

A common knowledge repository and critical assessment ability acquired during childhood education are generally considered to be essential for passage into adulthood. Until now, knowledge of the native language, a foreign language, history, geography, current affairs, mathematics, physics, chemistry and biology and so forth, have been considered to constitute essential subjects of a balanced education, That is: knowledge of these subjects is considered to be an essential attribute of maturation, necessary for the associated responsibilities of family and employment, of the obligation to process newly arriving information for personal and professional lives, and of the need to make productive daily decisions that navigate us through life's twists and turns. We, as did Bergey in 1916, contend that knowledge and understanding of microbes and their activities is as essential to general education as these subjects.

Microbiology must become a core element of the school curriculum in order that decision makers are adequately informed, and that all other stakeholders possess a basic understanding of how society and its actions are intimately interconnected and -related with our microbial world. As a consequence, societal stakeholders will become empowered to

- *take informed decisions for themselves (and others, e.g., offspring),*
- *critically assess the arguments for and against decision alternatives and thereby deliver informed preferences to those taking decisions on their behalf, and*
- *be able to hold to account those who do not take decisions based on scientific evidence.*

A personal experience-centric teaching concept and format for all age groups, with emphasis on the grand challenges and sustainable development goals

Because microbes affect our lives from day 1 (indeed, they affect us much earlier), teaching should start at the beginning of primary education and be a common thread throughout all education levels, to empower decision makers at all levels to take informed decisions on best practice and to provide young and old with the knowledge to understand the basis of such decisions. People must comprehend the difference between what is rather certain, what is probable and what is unknown. Individuals must be able to make evidence-based risk: benefit assessments that enable them to make decisions about fundamentally beneficial actions that carry some degree of risk or to constructively interact with agencies that take such decisions on their behalf. And, they must know what new knowledge needs to be obtained to make best, evidence-based policies in the future.

We envision microbiology curricula developing for kindergarten, primary school, secondary school and high school, in addition to microbiology teaching curricula for teacher training in tertiary education (see also e.g. Bergey, 1916; Savage and Bude, 2014; Scalas et al, 2017;

https://enviroliteracy.org/environment-society/environmental-health/microorganisms/; http://www.actionbioscience.org/biodiversity/wassenaar.html, https://schaechter.asmblog.org/schaechter/2013/04/whose-planet-is-it-anyway-1.html). They should also be available as a public education service, updating microbiology literate individuals and enabling those who did not receive instruction at school to learn the basics and catch up on new progress. Although the development of these curricula will be the remit of the teaching bodies concerned, to facilitate their implementation we propose a series of topics—a *microbiology literacy* framework (*Microbiology education in school and pre-school: a child experience-centric framework*, Timmis, K. N. et al, in preparation)—and a teaching format involving a simple initial question relating to everyday experience, followed by exposure of the underlying microbiology in simple language, its relevance to *Grand Challenges* and SDGs, its relationship to biogeosphere processes and planetary health and, importantly, its consequence for decision-making e.g.

- Daddy: I really would like a hamburger at the bowling alley this afternoon, but Jenny told me yesterday that cows contribute to global warming: is this true? *(Greenhouse gases, sources and sinks, rumen digestion, methane emissions, global warming, rising sea levels and weather extremes, how do they affect us, SDG-13: Combat climate change);*
- Mummy: we were told in class that Joanne has measles: why was she not immunised like me? *(Vaccine efficacy, risks, correlations and causalities, risk:benefit considerations, herd immunity, collateral benefits of immunisation, SDG-3: Ensure healthy lives);*
- Mummy: you always tell me to wash my hands after going to the toilet, because poo is nasty. But what happens to it after it is flushed away? *(Sewage treatment, faecal pathogens, faecal indicators as proxies of faecal pathogen load and water quality, SDG-6: Sanitation for all);*
- Miss: why don't plants grow in the dark? *(Plants and photosynthetic microbes capture solar energy and make biomass: the base of the food web; photosynthesis, chloroplasts, mitochondria originated from early microbes; plants and photosynthetic microbes provide food for the world, energy, renewable chemical feedstocks, non-polluting, sustainable development, SDGs 2: End hunger, 7: Ensure access to sustainable energy, 12: ensure sustainable production patterns)*

This approach has the merit that the relevance/importance of the underlying microbiology to society becomes apparent to students at the onset of the lesson.

The goals of the collection of selected topics are to

- *aid in the development of appropriate curricula for different age levels in diverse societal and cultural settings,*
- *reveal the major planetary-biosphere-human processes and problems impacted or underpinned by microbial ecophysiological activities*
- *inform how these activities affect our well-being and that of other members of the biosphere,*
- *reveal how microbial activities are influenced by our actions and the ensuing consequences,*
- *indicate how we may steer or exploit microbial activities for personal, human, planetary benefit, and to contribute towards attainment of the SDGs.*
- *provide a perspective of our place in the wider world, and how we are microbially connected in the global village and with the rest of the biosphere.*

The *microbiology literacy* knowledge framework will initially consist of a 100 or so experience-centric topics, grouped under the categories of Human Well-being, Planet Earth, Water, Plants, Animals, Nutrition-Food-Beverages, and Biotechnology, which will soon become available, *gratis*, online. These topics will certainly be improved and refined over time.

It must be emphasized that, in spite of the lack of visibility of the subjects under discussion—the microbes—the teaching of microbiological topics can be particularly fascinating for children, because microbiology is a hands-on experimental subject and students can carry out amazing experiments at various school levels. Suggestions for simple experiments relevant to each topic category will also be made available online. Moreover, there are many interesting microbial processes carried out by commercial enterprises (brewing, cheese making, bread production, fermentations and so forth) and public agencies (waste treatment plants, diagnostic laboratories and so forth) that can, depending on what is locally available, be experienced at first hand by means of school excursions. Again, an illustrative list of potential excursions, with organizational suggestions for teachers of how to orchestrate the experience for maximum knowledge gain, interest and enjoyment for students, will be made available online.

The topics provided in the knowledge framework are neither exhaustive in range nor structured in a manner requiring them to be treated in their entirety for any particular age group audience. Except for some introductory topics, most will be understandable as stand-alones and hence constitute a modular system of options for selection and matching, according to teacher preferences and student learning styles and objectives. Nevertheless, the overarching goal is for children to become familiar with all topics over the course of their school careers.

It must be emphasized that it is not intended to create *microbiology literacy* by teaching the discipline of microbiology and creating microbiology professionals. Rather, the intention is to deliver an adequate knowledge base of precisely those microbial activities central to empowerment of society to achieve improvements in everyday life, evidence-based policy development and planetary stewardship.

And, it is essential that society rapidly comes to appreciate that the widespread prejudice that microbes are our enemies is not only incorrect but engendering dangerous behavioural practices. Microbes are just like humans: most have little or no direct influence on our lives, many are highly beneficial and only a few are dangerous to us. And like humans, it is the bad guys—those that cause disease or material deterioration—that get most press and about which we know the most. Nevertheless, it is crucial that microbes as a whole are depicted as our friends, as they not only quietly aid us in our lives but can be called upon to solve major problems, such as increasing food yields, and that especially the essential microbial 50% of our own body cells are represented as closest family.

It is essential that knowledge of microbes in society is raised to dispel the harmful belief and practice of microbiophobia. This is one central message of the microbiology literacy aid and will be at the forefront of its use in school curricula.

Let's do it!

*Macro*organisms—animals and plants—are not only major members of the biosphere but are also integral

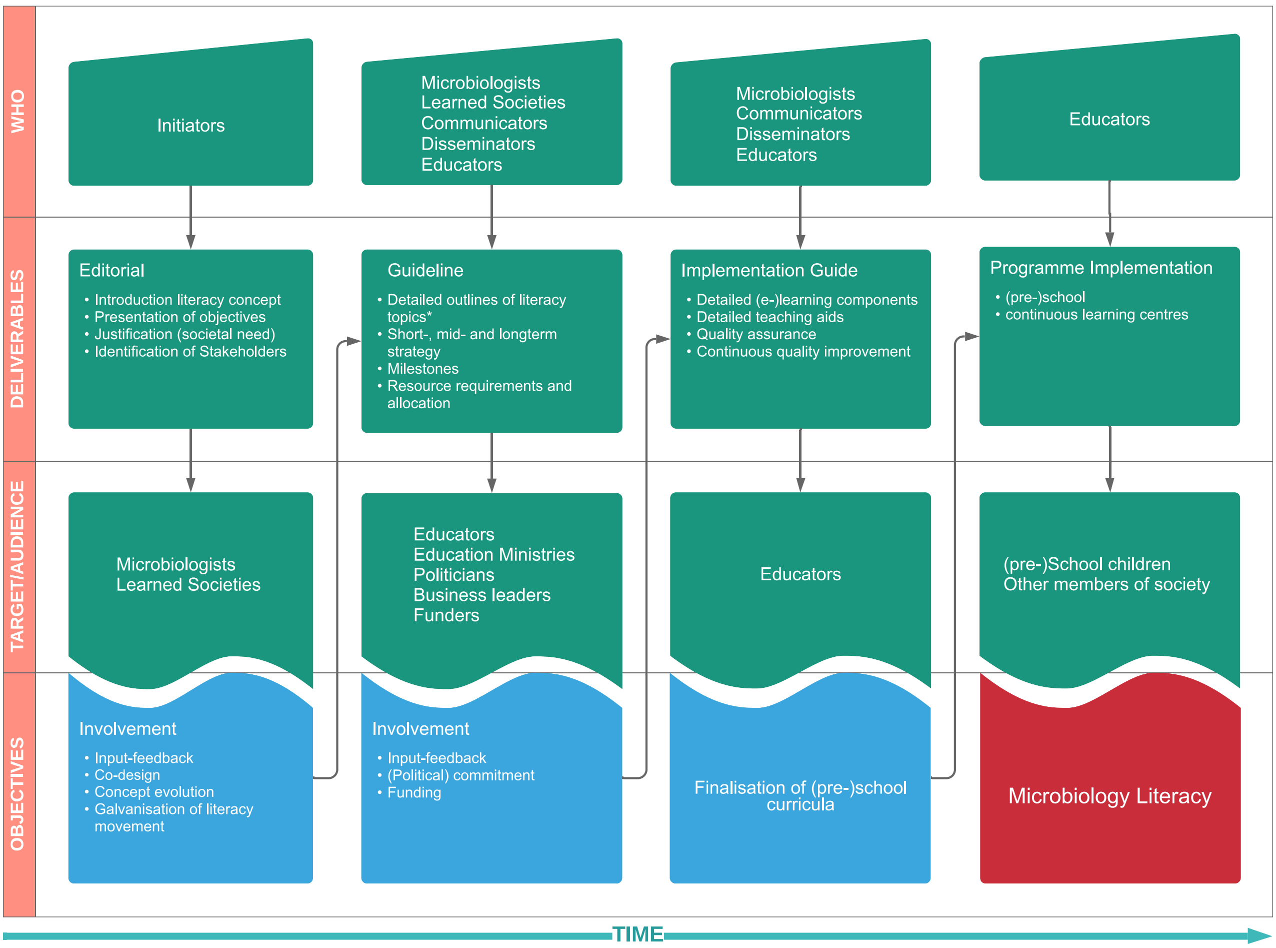

Fig. 1. Microbiology literacy initiative.
* Microbiology education in school and pre-school: a child experience-centric framework, Timmis, K. N. *et al.*, in preparation.

components of human society, evolution, civilization and the human psyche itself. As domesticated species, they provide food, fibre, comfort, pleasure and well-being and, as wild species, sources of wonder, hobbies and diversity. Conservation of *macro*organisms is our primordial responsibility. As a result, biology—essentially animal and plant biology—has historically been a core subject of education, both in its own right and as a foundation for the teaching of human biology and for reproduction education. Popular interest in, and appreciation of, *macro*organisms increased enormously in recent years as a result of blockbuster television documentaries presented by David Attenborough (https://www.theatlantic.com/science/archive/2016/05/every-episode-of-david-attenboroughs-life-series-ranked/480678/). In contrast, because of their size, microbes are mostly invisible to the general public—*out of sight, out of mind*—so not generally on radar screens, except when they create newsworthy mayhem, like AIDS, Ebola and red tides. This invisible component of the biosphere is largely neglected in general education. Nevertheless, in recent times, astounding discoveries about microbiomes and their varied influences on human biology and behaviour have significantly raised awareness of microbes in the general population. Despite this, microbes remain essentially abstract entities, less comprehensible than the internet, and on a par with how memory works. But their significance is immeasurably greater than the internet—we survived without internet until it arrived, but we could not survive, nor could ever have survived, without our microbial life support systems. It is therefore essential that the microbial world, in all its amazing, inherent, but microscopic beauty, transits from abstraction to pictorial perception and substance and takes up its rightful position in the human psyche. Visual aids will thus take centre stage in literacy classes and the exploding arena of microbial art (e.g., https://www.bbc.com/news/uk-england-oxfordshire-45099420) will stimulate the imagination. It must become routine that, when microbes are discussed, our children can immediately visualize them in their mind's eyes and imagine what they are doing. As microbes transit from the abstract and take form, they will become real; children will have their favourites! Cuddly teddy bears and woolly sheep will be joined by steamy Methano, wily Wolbo and prickly Diatoma, who all have their individual (anthropocentric) characters assigned by agile toy manufacturers. They may even become TV cartoon favourites in the not-too-distant future.

This Editorial has three fundamental aims, placed in context in Fig. 1 which is a roadmap to the introduction of *microbiology literacy* topics into school curricula.

The first is to expose the crucial knowledge and competence deficits in society needed to reach adequate evidence-based decisions on a variety of personal and societal issues and to present the case for a *microbiology literate* society, to be achieved through incorporation of a framework of key microbiology themes in basic education.

The second is to encourage microbiologists, microbiological learned societies and microbially literate professionals, to participate in and contribute to this initiative, by further evolving the basic framework, contributing ideas and materials for topics, videos and class experiments, and developing and seeking funding for creation of the necessary teaching tools and materials.

And the third, most important, aim of this Editorial is to urge microbiologists, microbiological learned societies and microbially-literate professionals with contact to and influence with educators, politicians, business leaders, relevant governmental and non-governmental agencies, and others, to join forces in an international effort to convince these facilitators of the crucial need to achieve microbiology literacy in society (*we are all stakeholders in planetary and human health: can we really afford to ignore a fundamental basis of our ability to solve current crises?*), and to persuade them to champion its progression to the next stage, implementation. To facilitate this, we have, where possible, avoided specialist terms in this Editorial, so that it can be used for multiple audiences.

Acknowledgements

This initiative builds on earlier efforts of inspiring microbiologists who recognized the fundamental need to improve microbiology literacy in our societies. By raising awareness of the issue, and creating excellent, child-centric texts and diverse teaching materials that can be integrated into, and facilitate the evolution of, *microbiology literacy* teaching curricula, they laid a superb foundation.

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