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A model for healthy green infrastructure in cities

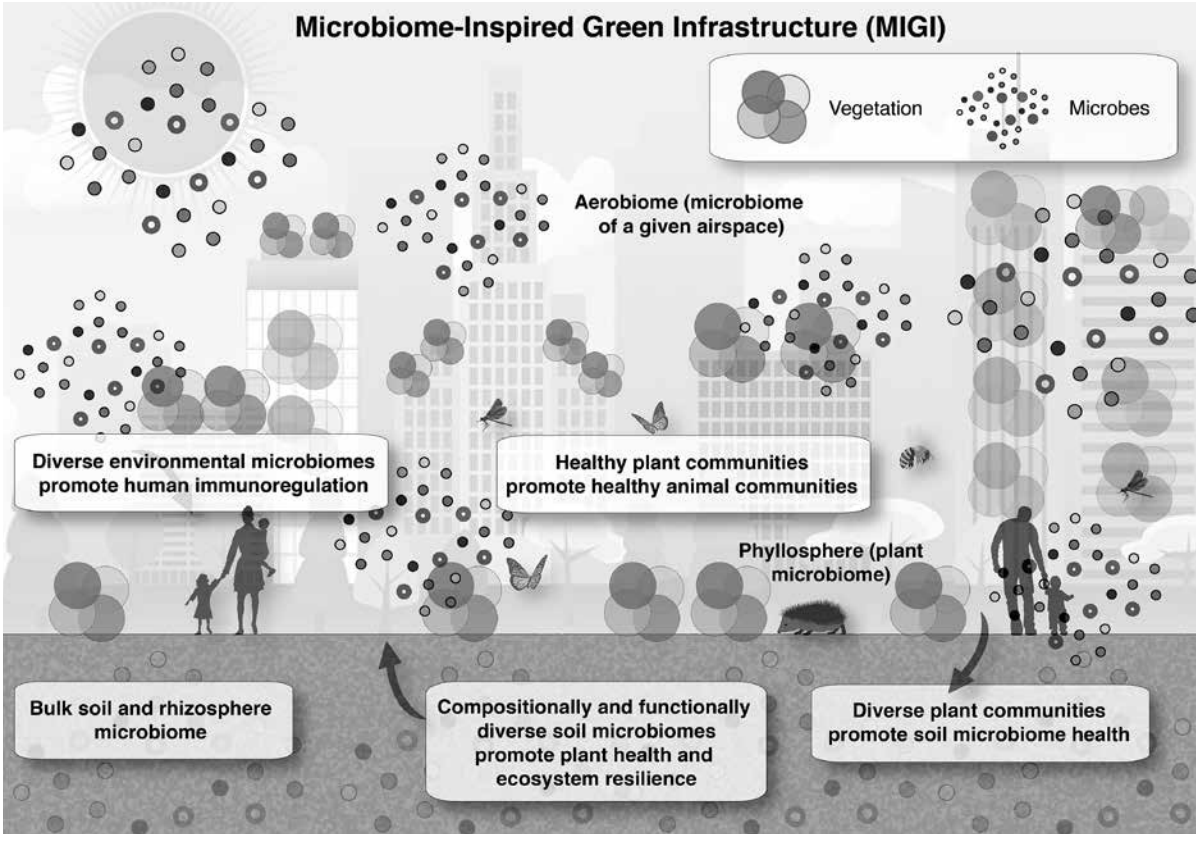
Transactions of personal and environmental microbiomes

Microbiome-Inspired Green Infrastructure: a bioscience roadmap for urban ecosystem health

Jake M. Robinson, Harry Watkins, Ioana Man, Craig Liddicoat, Ross Cameron, Brenda Parker, Marcos Cruz, and Laura Meagher

Microbiome-Inspired Green Infrastructure (MIGI) proposes an integrative system to promote healthy urban ecosystems through multidisciplinary design. Specifically, MIGI is defined as nature-centric infrastructure that is restored, designed, and managed to enhance health-promoting interactions between humans and environmental microbiomes, while sustaining microbially mediated ecosystem functionality and resilience. MIGI also aims to stimulate a research agenda that focuses on the importance of urban environmental microbiomes.

In this 'perspective', we provide details of what MIGI entails from a bioscience and biodesign perspective, highlighting the potential dual benefits for human and ecosystem health. We outline what is known about the relationship between urban microbiomes, green infrastructure, and environmental factors that may affect urban ecosystem health – taken here to mean ecosystem functionality and resilience, as well as human health. We discuss how to start operationalising the MIGI concept based on current knowledge and present an overview of emerging



1 Urban multispecies health. Environmental microbiomes are the foundations of our ecosystems and are essential to plant and animal health (including humans).

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and future considerations in research and practice.

We conclude by highlighting some of the challenges to implementing MIGI and propose a series of workshops to discuss multi-stakeholder needs and opportunities. This research will enable urban landscape managers to incorporate initial considerations for the microbiome in their development projects to promote human and ecosystem health. Although the research is in its infancy, there is considerable potential for MIGI to help deliver sustainable urban development driven by considerations for reciprocal relations between humans and the foundations of our ecosystems – the microorganisms.

Microbiomes and microbial communities

Microbial communities play vital roles in ecosystem processes and provisions, including carbon and nutrient cycling, climate regulation, animal and plant health, and global food security.[1] The ongoing degradation of, and climate-associated changes in, microbial communities – including their structure, complexity, and composition – pose a considerable threat to global macro-level biodiversity across the planet.[2] In parallel with these environmental concerns, non-communicable diseases, specifically chronic non-infectious diseases, are on the rise.[3] For example, the prevalence of asthma,[4] diabetes,[5] allergic rhinoconjunctivitis,[6] and autoimmune disorders[7] has increased worldwide in recent decades. Growing evidence suggests that global trends of ecosystem degradation, urbanisation, and non-communicable diseases are deeply interconnected.[8]

Exposure to diverse environmental microbiomes – the complex network of microorganisms in a given environment – is thought to play an important role in human health.[9] Environmental microorganisms support the development and regulation of the human immune system.[10] Evidence has shown that degraded habitats may harbour a greater relative abundance and diversity of opportunistic human pathogens, and ecological restoration may restore health-regulating assemblages.[11] Moreover, microbial exposure in urban green/blue spaces could improve our health but may depend heavily upon environmental and design factors, including vertical stratification (layering of microbes in the near-surface atmosphere), vegetation presence, complexity and management,[12] airflow, and soil management. However, with appropriate restoration, design, and management strategies, these factors could be optimised to create healthy urban ecosystems, to benefit both human and environmental health.

Ensuring long-term urban ecosystem resilience to environmental challenges will depend on our ability to restore and manage the landscape with considerations for the unseen foundations of our ecosystems – the microorganisms. Complex microbial interactions are involved in maintaining the health of urban plant and animal populations.[13] Considering these microbial interactions as part of any long-term urban development vision will be essential to ensure urban ecosystems can flourish and maintain resilience. However, there are currently few considerations for the role of microbial communities in urban development and landscape design, and multispecies frameworks are rarely used to inform the management of urban ecosystems. Indeed, recognising its importance in sustainability, the recently proposed 'multispecies urbanism' concept puts forward a framework for urban development, driven by considerations for reciprocal relationships between humans and non-humans (including microbes).[14]

Sharing similar principles to multispecies urbanism, Microbiome-Inspired Green Infrastructure was recently proposed as an integrative system to promote healthy urban ecosystems.[15] MIGI can be defined as nature-centric infrastructure that is restored and/or designed and managed to promote interactions between humans and environmental microbiomes, with explicit considerations for sustaining microbially mediated ecosystem functionality and resilience. A considerable challenge to operationalising MIGI is a lack of awareness of the imperative for urban microbiome research and translating existing research into intelligible and practicable outputs. Another challenge is addressing the complex needs and constraints of multiple stakeholders involved in urban landscape management.

Environmental microbiomes, ecosystem functionality, and human health

Ecosystem functionality and resilience context

Microbial communities can be considered the foundations of our ecosystems *[1]*. Soil-microbe-plant interaction studies have demonstrated that plants rely on microbial communities for favourable health.[16] Microbial communities are integral to nutrient and water absorption,[17] and phytohormone production and regulation activities.[18] These microbial communities include arbuscular mycorrhizal fungi and algae, along with symbiotic, associative symbiotic and free-living plant growth-promoting bacteria. Endophytes (microbes living in plant tissues) also benefit plants by enhancing competitive abilities and increasing resistance to pathogens and other abiotic stressors.[19] Soil microbiomes are essential to long-term ecosystem resilience in the face of global challenges such as climate change and degradation.[20] In addition to plant health, microorganisms play roles in carbon sequestration and biogeochemical cycling. It can be further argued that the health of all organisms is interrelated through the cycling of environmental microorganisms from soils to plants and animals and back into the environment.[21]

Microbiome diversity and network complexity have been demonstrated to drive multiple ecosystem functions related to nutrient cycling. For instance, grasslands with poorly developed microbial networks and reduced microbial richness have low multifunctionality due to fewer taxa (or taxonomic groups) that support functional redundancy and uniqueness. With minimal considerations for microbiomes in urban landscape design and management projects, poor ecosystem multifunctionality and stability will likely continue. To promote long-term urban ecosystem health, it is imperative that this trajectory changes. MIGI provides a framework to operationalise this change.

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Human health context

Growing evidence suggests that exposure to naturally diverse environmental microbiomes can improve human health. For example, studies highlight the importance of green space microbiomes to immunoregulation [1 refers]. Jenni Lehtimäki and others have shown that risks of asthma and aeroallergen sensitisation are reduced in rural infants due to exposure to more biodiverse microbiomes (compared to urban),[22] and Matilda Riskumäki and others have identified several environmental taxa that are important in augmenting and/or suppressing systemic inflammatory immune response.[23] A loss of biodiversity in urban areas reduces exposure to diverse environmental microbiomes while increasing exposure to pathogenic microbes.[24] This is corroborated by a review investigating rural vs urban environmental aerobiomes (the microbiome of a given airspace), which showed rural-mediated beneficial immune responses.[25] Recently, a twenty-eight-day biodiversity intervention demonstrated that inoculating a schoolyard environment with biodiverse features (for example, soil and plants from local forest habitats) significantly altered the microbiome of the children and enhanced important immunoregulatory pathways.[9]

Other studies indicate the importance of butyrate-producing bacteria, which may be promoted in biodiverse plant-soil systems,[26] for example, where organic-rich soils experience low redox conditions consistent with the fermentative decomposition of organic matter. Butyrate is a short-chain fatty acid associated with gut health, immunoregulation, and mental health. Exposure to trace level dust containing the putative spore-forming butyrate-producing bacteria *Kineothrix alysoides* has been linked to reduced anxiety-like behaviour.[11] Another recent study showed that spending a short period of time in green spaces can significantly change the human nasal and respiratory microbiome.[27] Indeed, microbiota-mediated environmental health can be thought of as two layers of protective biodiversity.[28] The first layer, our personal microbiome, is key to health. The second layer, the environmental microbiome, represents an important source for replenishing the first; therefore, safeguarding it represents a critical health insurance policy. It is also important to note that many other potential health benefits are associated with engaging with urban nature, including reduced blood pressure, lower levels of stress, anxiety, and increasing positive affect.[29]

Actionable insights for landscape managers

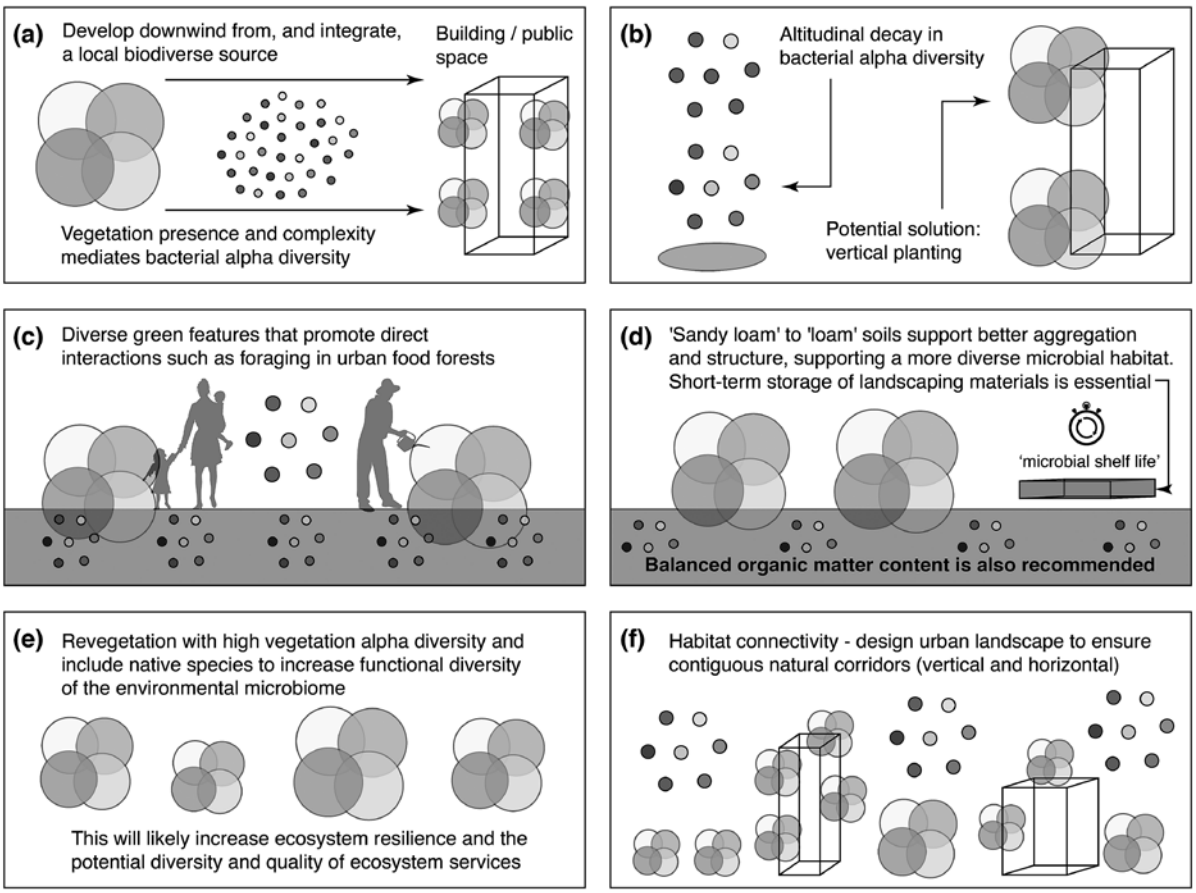
Vegetation, microbiomes, and the built environment

To operationalise the MIGI framework, we can draw upon several relevant studies. For example, one important factor is to ensure humans and other species are exposed to high microbial alpha diversity associated with naturally biodiverse environments from a young age, which is important for immunoregulation.[30] It has been demonstrated that air samples downwind from biodiverse sources (for example, species-rich plant communities) contain more diverse microbial communities than upwind, with ~50% of airborne bacteria in downwind samples deriving from local plant sources.[31] Therefore, a relatively simple intervention for urban designers could be to develop public spaces and buildings downwind from (macro) biodiverse sources and integrate local biodiverse sources within building structures and spaces [2]. Recently, it was shown that urban green space aerobiomes are vertically stratified, with an altitudinal decay in bacterial alpha diversity and possibly a higher relative abundance of pathogenic taxa at higher altitudes.[32] This reflects a transition from local plant and soil-related microbiomes at low heights into a broader urban (typically non-green space) airshed.[33] A potential mitigation measure could be to augment vertical planting in urban areas, allowing exposure to higher natural microbial alpha diversity in the vertical dimension [2 refers, b]. It would also be prudent to design urban areas with greater consideration for inclusive and direct 'hands-on' human engagement with natural features to promote interactions between humans and diverse environmental microbiomes and to foster long-term pro-ecological behaviours [2 refers, c].

Jacob Mills and others provided evidence that revegetation, particularly with native species, can improve urban soil microbiome functional diversity.[34] Other studies show that diverse vegetation communities promote below-ground functional richness, diversity, and resilience.[35] Promoting diversity of local vegetation communities is considered a robust strategy to maintain multifunctional processes under current and future environmental conditions. As such, MIGI strategies could include planting diverse, and where possible, native, vegetation communities to sustain urban ecosystem functionality and resilience [2 refers, e]. However, it is not yet clear to what extent locally native plant populations will tolerate future climate conditions. Studies concerning woody plants offer conflicting views. Some research suggests that intra-population genetic variation may provide sufficient resilience,[36] while others argue that given the range in possible climate futures, including species beyond those that are locally native will be essential in urban environments.[37] As such, further research is required to understand the relationships between locally native microbial populations and non-local/non-native plant species, including outcomes for stress tolerance, nutrient acquisition, and reproduction.

MIGI strategies should also include the promotion of urban-rural habitat connectivity via contiguous vertical and horizontal natural corridors [3, f]. Many urban environments are 'patchy' in quality with connected nature-centric features. To ensure long-term healthy urban ecosystems, we should aim to connect all natural habitats within towns and cities, and provide essential biophysical corridors to the broader landscape. This action has high biodiversity conservation value by providing multispecies resources and improving species interactions and long-term resilience across the landscape, irrespective of species dispersal abilities or population sizes.[38] Enhancing networks of biologically and functionally diverse urban habitats with high

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2 Actionable insights for MIGI, including vegetation complexity, downwind development and local integration of biodiverse source (a); a solution to the concept of vertical stratification (b); hands-on engagement with natural features to promote immunoregulation (c); recommended soil types to promote diverse microbial habitat and short-term storage of landscaping materials (d); revegetation with diverse native plants to promote functional diversity (e); the concept of habitat connectivity via contiguous natural corridors to promote long-term multispecies health (f).

vegetation complexity also has the potential to improve the distribution of quality aerobiomes and augment diverse macroscopic species (animals and plants) that contribute to the collective urban environmental microbiome and broader ecosystem complexity and resilience.

Soil microbiomes

Soil properties will have a key influence on environmental microbiomes associated with MIGI developments. Soil organic matter and clay content (that is, the proportion of clay-sized particles) are associated with structure, aggregation, nutrient and water-holding properties, and therefore the habitat and diversity of microbes.[39] A critical decision during the establishment of MIGI will be whether to use in-situ or imported soils. Where feasible, using soils with a moderate amount of clay content – for example, sandy loams (10–20% clay content) to loams (around 25% clay content) – would be expected to promote microbial diversity. By comparison, sandy soils provide suboptimal microbial habitat, while heavier texture clay soils, often capable of forming suitable aggregation and structure, may be more prone to poorer drainage in wet climates or greater plant stress in dry climates or during dry periods due to higher wilting-point moisture content, where water is unavailable to plants. Whether using existing in-situ soils or importing new bulk soil, it may be necessary to examine constraints to plant growth. Sometimes these constraints will be naturally occurring (for example, shallow depth, impermeable layers, presence of toxic or nutrient-limiting subsoil conditions), while other times, they can result from management history (for example, compaction, acidification).

Where appropriate, addressing soil constraints will help optimise the plant-soil system's biological activity and microbial diversity. If organic matter is being applied, ideally this should be in a nutrient-balanced or pre-composted form so that microbial activity and available nutrients can be harnessed to support the growing vegetation. Ongoing management and human interaction should also be considered. For example, high levels of foot and vehicle traffic can lead to compaction and degradation and may create zones of poor soil microbiome conditions with suboptimal health influence (for example, along paths) within a natural space offering health-promoting microbial exposures. Exposure pathways to permit beneficial human-soil microbiome contact also remains an area for research. Based on available knowledge, low-level exposure to soil (for example, dust) with biodiverse content to help contain potential pathogenic activity would represent a reasonable starting point to supporting immune fitness. It is also expected that soils will gain maximum health-promoting potential by spending the majority of time covered with biodiverse vegetation, which is another consideration for

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designing MIGI exposure pathways.

There is also growing evidence to show that plant communities require complex mycorrhizal networks, acting as conduits of inter-plant communication and facilitating pathogen defence, adaptation, growth, and memory.[40] Indeed, healthy vegetation community phenotypes at higher levels emerge from a multitude of localised and often subterranean entities interacting at lower levels.[41] For example, Jo Birch and others recently demonstrated that plant growth was significantly associated with the number of ectomycorrhizal connections to other plants and the number of genetically distinct fungi that were present.[38] Therefore, we must at least consider the condition and ecology of the substrate and its role in sustaining ecosystem functionality and resilience. This will involve viewing habitat conservation and restoration through the lens of complex systems science. However, many experts in this field could provide appropriate consultation at each stage of a development project.

Interestingly, a recent study showed that landscaping materials like compost and mulch have a 'microbial shelf life', and long-term storage can significantly reduce the availability of bacterial taxa linked to human health and degradation of pollution.[42] This suggests that as part of a holistic MIGI strategy, short-term storage times should be considered when planning the utilisation of landscaping materials *[*2 refers, d*]*

Emerging research and practice

Bioreceptive materials and bio-integrated design

The term bio-integrated design refers to interdisciplinary methodologies that merge together applied biotechnology, architecture, and design to create sustainable built environment systems. It encompasses a range of biologically mediated processes, such as biosilification, biomineralisation, and bioremediation, and the development of material substrates for living systems. Oliviere Guillitte defined the term 'bioreceptivity' to describe the ability of a building material to be colonised by living organisms.[43] In the context of bio-integrated design to enable MIGI, bioreceptivity has been explored through the design of architectural scaffolds to create self-regulating systems which are host to cryptogrammic species as well as microbial biodiversity.[44]

While horizontal surfaces – including roofs, terraces, or pavements – offer scope for plant growth, vertical surfaces – such as building façades and infrastructural walls – offer far harsher environments due to excessive water run-off, strong exposure to winds, and lack of nutrient-rich substrates. But cities have vast xeric, or very dry, surfaces that provide opportunities to be photosynthetically active. Several design steps can accelerate the creation of primary bioreceptivity on vertical surfaces. Porosity and surface roughness are two vital functions: firstly, the calibration of pore size can enable water absorption and retention, reaching colonising organisms through capillary or surface-binding effects; secondly as a means to exploit extrinsic factors for bioreceptivity through the collection of organic material and fixation of cryptogamic surface cover. Different compositions of bioreceptive cementitious materials have been explored based on Magnesium Phosphate Concrete and other Ordinary Portland Concrete (OPC) mixes to create long-term carbon offset.[45] Studies of OPC have shown that apart from altering the physicochemical properties of materials, morphological variations explored via computational design strategies are a powerful means to reduce water run-off and increase moisture retention, extending the residence time to create zones for accelerated growth.[44] In future, quaternary bioreceptive strategies may be used[47] whereby surface additives to a material scaffold such as hydrogels or humic material are applied to enhance colonisation. Further studies are needed to test the role of pH on material substrates in biofilm formation and the establishment of microbial communities, which are vital to establishing cryptogamic growth.

Lichens and, primarily, bryophytes play key roles in designing bioreceptive structures within architecture, provoking a biophilic response[48] through their aesthetic appearance and tactility. However, they are also important components due to their capacity to regulate their photosynthetic activity depending on moisture availability while surviving for long periods without water: poikilohydry. In relation to MIGI, bryophytes harbour ecologies with prokaryotic and eukaryotic algae, bacteria and fungi. Cyanobacteria are keystone species in other nutrient-limited environments such as desert crusts,[49] where their ability to fix nitrogen and carbon enables succession by other organisms through the exchange of metabolites. However, our understanding of the exact ecological roles of microorganisms associated with bryophyte hosts is nascent. For example, while the presence of certain bacteria varies according to the bryophyte species, in one study, *Proteobacteria*, *Actinobacteria*, *Acidobacteria*, *Bacteroidetes*, *Armatimonadetes*, and *Planctomycetes* were detected in all moss microbiomes.[50] Analogous to the urban environment, during the early stages of habitat restoration, it has been shown that bryophyte communities enrich populations of microbial life on calcareous rocks.[51] It may be speculated that colonisation by bryophytes and their associated microbiota could have advantageous effects for growth promotion in other plants due to the presence of bacteria containing genes for the production of indole acetic acid siderophores or solubilisation of phosphate.[52] Through this application of bio-integrated design to produce poikilohydric living walls, it is possible to employ more of the surface area underutilised within our urban environments to deliver MIGI.

Microbial inoculants

Microbial inoculants have recently been used to shift microbiota in landscaping materials towards an immuno-protective assemblage.[53] The authors developed a microbial inoculant from biodiverse sources, for example forest materials, resembling the microbiome of organic soils. After the study subjects contacted these inoculated materials, the relative abundance of opportunist pathogens on the skin significantly decreased. Furthermore, Marja I. Roslund

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and others demonstrated that a biodiversity intervention using microbial inoculants from forest floor materials changed the skin microbiome of children and enhanced immunoregulatory pathways. Several other studies show that microbial inoculants can benefit plant health; for example, via Plant Growth Promoting Rhizobacteria (PGPR).[54] PGPRs have the potential to protect plants from drought and metal stresses and play important roles in plant growth, which itself could minimise the use of harmful synthetically produced chemical fertilisers.[55] Therefore, MIGI strategies could incorporate microbial inoculants to enhance ecosystem health *[*3 refers, b*]*.

Supportive tools

Useful tools are being developed to help with MIGI interventions in the near future. For example, Muhammad Saleem and others have produced a framework to model the environmental microbiome's influence on plant traits and ecosystem functionality, highlighting the possibility of creating an index to monitor and enhance plant growth and soil/ecosystem health.[56] Along similar lines, it could be valuable to develop a form of 'Health Promotion Potential Index' for human health. This could be based on known combinations of environmental microbial factors that promote (or demote) immunoregulation and homeostasis, such as alpha and functional diversity and beneficial taxa that produce health-regulating compounds *[*3 refers, c*]*.

Bioremediation

Emerging bioremediation research could also be considered in MIGI strategies. In-situ bioremediation enables ongoing decontamination or degradation of pollutants without complex excavation or transportation. This could play a role in sequestering metals such as lead and zinc, which are present in many cities as components of urban dusts.[57] Bacteria, fungi, and microalgae have evolved several mechanisms to adsorb or absorb heavy metals. A study investigating river sediments contaminated with cadmium, copper, lead, and zinc hypothesised that species richness might be a function of 'public goods' within the microbial community, such as metallophores, biogenic sulphides, or calcite. Bacteria such as *Pseudomonas* and *Bacillus* may precipitate metal and thus benefit other organisms with spatial proximity by creating detoxified regions.[58]

Chang-Ho Kang and others (2016) showed that the synergistic combination of bacterial strains – including *Viridibacillus arenosi B-21*, *Sporosarcina soli B-22*, *Enterobacter cloacae KJ-46*, and *E. cloacae KJ-47* – was effective at sequestering lead (98.3% effective) and cadmium (85.4%) in soils.[59] Biofilters are being developed that embed bacterial biofilms to absorb heavy metal ions.[60] In terms of MIGI, this kind of strategy could be developed with Sustainable Drainage Systems in mind, for example, a biofilter-embedded rain garden *[*3 refers, d*]*. Numerous organic compounds threaten human health, found in elevated concentrations. Microbial mechanisms that may be employed in MIGI are hydrolysis and oxidation to produce benign compounds through metabolic activity. For instance, endocrine disruptors such as phthalates and alkylphenols are ubiquitous in water systems due to human activity,[61] but there are microbial mechanisms to break these down under certain conditions.[62] Indeed, many bacterial taxa have been identified with significant pollutant degradation properties.[63] As an alternative to contained bioreactor systems, creating stable synthetic ecologies and applying eco-evolutionary principles to enhance bioremediation is compatible with MIGI principles.[64]

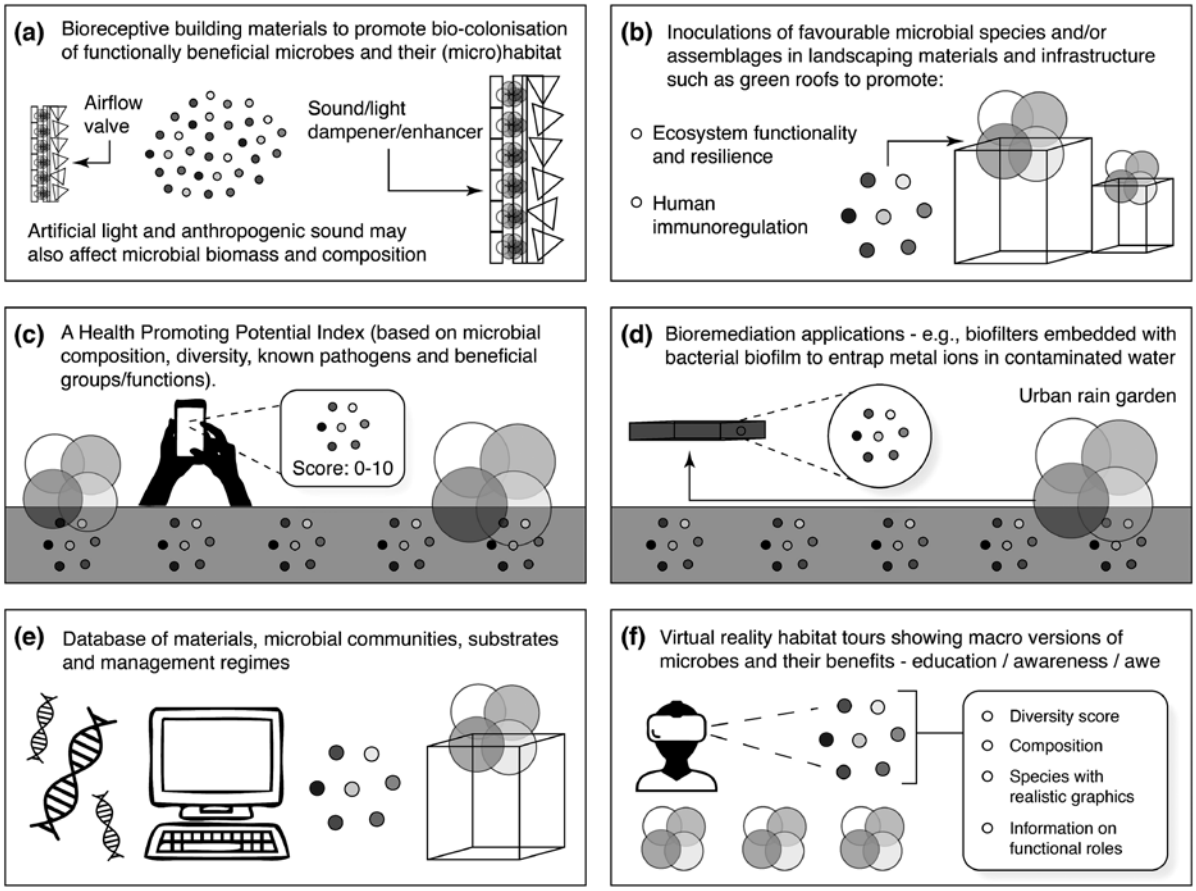
Plant nutrition, soil issues, and anti-microbial resistance

It is suspected that high-dosage artificial agricultural fertilisers are detrimental to mycorrhizal networks, for example, by promoting taxa with pathogenic traits.[65] Studies have suggested that organic or 'natural' fertilisers and plant conditioners outperform chemically synthetic N, P, and K types in promoting plant health/quality.[66] Additional research in this area could bring value to the MIGI concept, particularly research focusing on applying fertilisers sympathetic to soil-plant microbial interactions. There are also physical soil issues to consider in urban landscape management. The loss of organic matter, compaction, and excessive disturbance will likely damage microbial communities.[67] Research to fully understand the implications of these factors could enhance urban ecosystem management. The loss of soil microbial diversity has also been linked to the exacerbation of antimicrobial resistance.[68] Antimicrobial resistance has important implications for human health by making infections harder to treat and increasing risks of disease spread.[69] MIGI researchers aiming to reduce the abundance and diversity of antimicrobial resistance genes in urban environments could explore the strategy of increasing soil microbial diversity.

Emerging biosecurity considerations

Alongside the positive opportunities presented by a multispecies approach to green infrastructure, the threats must be equally researched and mitigated within the MIGI framework. Many of the most pressing biosecurity threats to ecosystems are microbial in nature (for example, in the UK, *Hymenoscyphus fraxineus*, *Phytophthora ramorum*, and *Candidatus liberibacter solanacearum*), threatening urban green infrastructure as well as agricultural crops that urban populations depend upon. However, it is increasingly recognised that most biosecurity research and regulations focus on impacts to agricultural and forestry sectors. Work is urgently required to understand the extent to which urban ecosystems are threatened and what tools are most effective at safeguarding them. Key questions exist at a societal level concerning the mismatch between public perception of biosecurity risk and expert assessment, the capacity for codes of conduct to influence behaviour and the ability to communicate information between policymakers, researchers, and the public. Industry-specific technical questions also exist concerning the risks associated with importing soil for planting, the materials used in packaging for construction projects,[70] or to what extent novel microbial pests and diseases might influence assisted colonisation programmes or

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3 Horizon scan of developmental considerations for MIGI, including interventions (b and d), design and supportive features (a and e), and applications for engagement and to acquire useful urban ecosystem health information (c and f).

substitutions for keystone species die-off.

Regulation and guidance to combat these threats have been developed at international (for example, European and Mediterranean Plant Protection Organisation,[71] Defra Plant Health Risk Register in the UK[72]) and regional levels complemented by industry-specific guidance in many countries.[73] Nevertheless, further work is required to address the open questions and operationalise policy, and MIGI offers an opportunity to address these holistically. One of the core challenges presented by biosecurity threats is that the technical understanding of biosecurity in the construction and development industries is currently at an early stage, with many practitioners confusing biosecurity with concepts such as biodiversity and seeing threats posed by biosecurity risks as someone else's responsibility. Integrating existing schemes within MIGI will be essential to ensure that best practice is developed and so that practitioners can clearly understand how their actions reinforce the biosecurity continuum.[74] Biosecurity is one of many layers that prove challenging to translate between research and practice, and to this end, delivering the plant selection database proposed in the MIGI toolkit will provide not only a common understanding of the tools required to deliver MIGI but also a shared vocabulary for different sectors to draw upon when discussing projects.

Social innovation: promoting stronger human-nature relationships

Other important factors within the MIGI framework include social innovation, education, and stimulating awe for nature, emphasising the foundations of our ecosystems – the diverse microbial communities. Strategies such as 'learning about the land, on the land'[75] could help to inspire pro-ecological behaviours that reinforce a sense of stewardship for our diverse and complex ecosystems. To paraphrase Suzanne W. Simard: 'viewing [ecosystems] through the lens of cognition, microbiome collaborations, and intelligence may contribute to a more holistic approach to studying ecosystems and a greater human empathy and caring for the health of our [landscapes].'[76] Various campaigns also promote the concept of 'nature connectedness': emotional and cognitive connection with the natural world. Studies in this area show increased well-being and pro-ecological behaviour due to enhanced nature connectedness.[77]

Virtual reality systems could be developed to facilitate urban habitat tours for the technologically minded. These could include interactive macroscopic displays of microbial communities while providing information on the composition and functional roles that microbes play in the local ecosystems *[*3 refers, *f]*.

MIGI: challenges to operationalisation

Harry Watkins and others identify barriers to operationalising MIGI, relating to the complexity of urban development projects, and communicating the benefits of MIGI interventions to stakeholders involved in urban planning. To ensure the implementation of green infrastructure strategies, stakeholder buy-in is required throughout green infrastructure planning, design, operation, and

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management.[78] The range of stakeholders includes local authorities, developers and private clients, planning professionals, landowners, landscape specialists, architects, ecologists, statutory agencies, contractors, local businesses, and community groups. There are several government-funded research projects in the UK focusing on green infrastructure, biosecurity, climate change-readiness, and supply chains, such as BRIGIT, Future Oak, and Plant Health Centre. Learning from these projects is prudent. There is already evidence of stakeholder fatigue and pre-existing challenges of engaging with industry sectors that see these aspects as someone else's problem or not aligned with commercial goals. This suggests new approaches are needed and highlights the importance of internationalising research projects to gather robust data from diverse stakeholders.

Although fundamental, adding the lens of microbial ecology to an already expansive multi-stakeholder initiative, MIGI has to reckon with the 'perception that multi-stakeholder initiatives slow down urban planning and policy development processes due to a lack of consensus and different sectoral interests'.[79] Further development should align with the priorities of the stakeholder groups and generate clear, actionable points overlaid onto existing frameworks, rather than increasing complexity. For instance, in the UK, some MIGI considerations overlap with the policies laid out in the London Plan 2021. Its focus on connected landscapes and biodiversity corridors supports the value of connected nature-centric features. Policy G5, Urban Greening, asks that new developments incorporate high-quality landscaping, green roofs, green walls, and nature-based sustainable drainage and introduces an Urban Greening Factor to evaluate the quality and quantity of green space design and delivery.[80] This guidance is currently under consultation and could benefit from MIGI-related input to aid with the ambition of delivering biodiversity net gain. Overlaps could be identified through direct communication with existing built environment biodiversity-centric networks.

MIGI: workshop series proposal

To determine clear action points for future research and address the challenges related to the divergence of interests among stakeholders, it is vital to ascertain diverse priorities and concerns through early consultation.[81] This could also aid the development of a 'common language'[82] that translates researchers' findings into verbal and graphic outputs relevant to non-expert audiences. We are currently developing a series of workshops to discuss what is known about the microbiome in the context of health and ecosystem functionality, and reveal tangible opportunities to include MIGI in urban planning. These workshops provide an opportunity to engage with reflective stakeholders in identifying challenges and specific factors (for example, MIGI toolkits, portfolio of illustrative examples) and alignments between current requirements/protocols and how MIGI could be integrated. During these workshops, we will discuss 'what researchers should be working on', and opportunities and constraints by drawing together the perspectives and needs of different stakeholders. These workshops will form part of a process of long-term engagement and partnership to enhance urban ecosystem health via MIGI strategies.

Developing the MIGI concept has the potential to enhance urban ecosystem functionality and resilience as well as human health.

A greater emphasis on the roles of microbial communities in our urban ecosystems is needed, from below-ground and ground-up. Understanding microbial dynamics will likely have an important role to play in the efficacy of our adaptability and long-term resilience to ongoing global environmental change. MIGI research agendas aim to promote this realm of thinking with considerations for multispecies health.

Jake Robinson is a microbial ecologist. He works at the intersection of ecosystem restoration, urban design, and social research.

Harry Watkins is Director of St Andrews Botanic Garden, Scotland. He researches the interactions between plants and their environments, focusing on climate change resilience and biosecurity risks.

Ioana Man is a Unit Tutor at the Architectural Association School of Architecture, London and Design Lead at Faber Futures.

Craig Liddicoat is a Research Fellow in Restoration Genomics at Flinders University, Adelaide, Australia, where he investigates the role of soil microbes in ecosystem restoration and human health.

Ross Cameron is interested in how plant choice, design and management affects urban ecosystem services.

Brenda Parker is an Associate Professor of Sustainable Bioprocess Design at the Department of Biochemical Engineering, University College London.

Marcos Cruz is an Architect and Professor of Innovative Environments at the Bartlett, University College London.

Laura Meagher is an independent consultant specialising in interdisciplinarity and generation/evaluation of impacts from research.

Notes

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Competing interests
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