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Abstract

Microbiome-Inspired Green Infrastructure (MIGI) was recently proposed as an integrative system to promote healthy urban ecosystems, through multidisciplinary design. Specifically, MIGI is defined as nature-centric infrastructure restored and/or designed and managed to enhance health-promoting interactions between humans and environmental microbiomes, whilst sustaining microbially-mediated ecosystem functionality and resilience. MIGI also aims to stimulate a research agenda that focuses on considerations for the importance of urban environmental microbiomes. In this paper we provide details of what MIGI entails from a bioscience and biodesign perspective, highlighting the potential dual benefits for human and ecosystem health. We present 'what is known' about the relationship between urban microbiomes, green infrastructure and environmental factors that may affect urban ecosystem health (ecosystem functionality and resilience as well as human health). We discuss how to start operationalising the MIGI concept based on current available knowledge, and present a horizon scan of emerging and future considerations in research and practice. We conclude by highlighting challenges to the implementation of MIGI and propose a series of workshops to discuss multi-stakeholder needs and opportunities. This article will enable urban landscape managers to incorporate initial considerations for the microbiome in their development projects to promote human and ecosystem health. However, overcoming the challenges to operationalising MIGI will be essential to furthering its practical development. 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.

1. Introduction

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 [1,2] (Cavicchioli et al. 2019; Guerra et al. 2020). The ongoing degradation of, and climate-associated changes in microbial communities (structure, complexity and composition) pose a considerable threat to global macro-level biodiversity across the planet [3,4,5] (Bach et al. 2020; Greenspan et al. 2020; Tibbett et al. 2020). In parallel with these environmental concerns, noncommunicable diseases (chronic non-infectious diseases) are on the rise [6,7] (Smith et al. 2014; Jairath et al. 2020). For example, in recent decades the prevalence of asthma [8,9] (El-Gamal et al. 2017; Borna et al. 2019), diabetes [10] (Holman et al. 2010), allergic rhinoconjunctivitis [11] (Kainu et al. 2013), and autoimmune disorders [12,13] (Dinse et al. 2020; Paramasivan et al. 2020) has increased worldwide. Growing evidence suggests that the global trends of ecosystem degradation, urbanisation, and noncommunicable diseases are deeply interconnected [14] (Haahtela, 2019).

Exposure to diverse environmental microbiomes—the complex network of microorganisms in a given environment—is thought to play an important role in human health [15,16] (Rook, 2013; Roslund et al. 2020). Environmental microorganisms support the development and regulation of the human immune system [16,17] (Renz and Skevani, 2020; Roslund et al. 2020). 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 [18,19] (Liddicoat et al. 2019; Robinson et al. 2020a). 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

[16,20] (Robinson et al. 2020b; Roslund et al. 2020), 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 [21] (Berg et al. 2017). 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) [22,23] (Rupprecht et al. 2020; Sharma et al. 2021).

Sharing similar principles to multispecies urbanism, Microbiome-Inspired Green Infrastructure, also known as 'MIGI', was recently proposed as an integrative system to promote healthy urban ecosystems [24,25] (Robinson et al. 2018; Watkins et al. 2020). 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 the translation of existing research into intelligible and practicable outputs. Another challenge is addressing the complex needs and constraints of multiple stakeholders involved in urban landscape management [26] (Marzano et al. 2021).

In this paper, our primary objectives are to: **(a)** present what is known about the relationship between urban microbiomes, green infrastructure and environmental processes that affect urban ecosystem health (ecosystem functionality and resilience, and human health); **(b)** discuss how we can operationalise the MIGI concept i.e. actionable insights; **(c)** present a horizon scan of developmental interdisciplinary considerations for MIGI; and, **(d)** highlight challenges to the implementation of MIGI, whilst proposing a series of multi-stakeholder engagement workshops.

This article will help to encourage urban landscape managers to incorporate initial considerations for MIGI in their development projects to promote healthy urban ecosystems for humans and the wider biotic community. Although the research is in its infancy, there is considerable potential for MIGI to help deliver complex ecological and modern urban societal needs.

2. MIGI: the relationship between environmental microbiomes, ecosystem functionality, and human health

2.1. Ecosystem functionality and resilience context

Microbial communities can be considered the foundations of our ecosystems [1] (Cavicchioli et al. 2019) (Fig. 1). Soil-microbe-plant interaction studies have demonstrated that plants rely on microbial communities for favourable health [27] (Nazli et al. 2020). Microbial communities are integral to nutrient and water absorption [28] (Trivedi et al. 2020), and phytohormone production and regulation activities [29] (ur Rehman et al. 2020). These microbial communities include arbuscular mycorrhizal fungi and algae, along with symbiotic, associative symbiotic and free-living plant growth promoting bacteria [27] (Nazli et al. 2020). Endophytes (microbes living in plant tissues) also benefit plants by enhancing competitive abilities and increasing resistance to pathogens and other abiotic stressors [30] (Pavithra et al. 2020). Soil microbiomes are essential to long-term ecosystem resilience in the face of global challenges such as climate change and degradation [31] (Dubey et al. 2019). In addition to plant health, microorganisms play roles in carbon sequestration and biogeochemical cycling [31] (Dubey et al. 2019). It can be further argued that the health of all organisms is interrelated through the cycling of environmental microorganisms from soils, to plants, animals, and back into the environment [32] (van Bruggen et al. 2019) (Fig. 1).

It has been demonstrated that microbiome diversity and network complexity drive multiple ecosystem functions related to nutrient cycling [33] (Wagg et al. 2019). For instance, grasslands with poorly-developed microbial networks and reduced microbial richness have low multifunctionality due to fewer taxa that support functional redundancy and uniqueness [33] (Wagg et al. 2019). With minimal considerations for microbiomes in urban landscape design and management projects, it is likely that poor ecosystem multifunctionality and stability will continue. To promote long-term urban ecosystem health, it is imperative that this trajectory changes. MIGI provides a framework to operationalise this change.

2.2. 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 (Fig. 1). Lehtimäki et al. (2021) showed that risks of asthma and aeroallergen sensitisation are reduced in rural infants due to exposure to more biodiverse microbiomes (compared to urban) [34], and Riskumäki et al. (2021) identified several environmental taxa that are important in augmenting and/or suppressing systemic inflammatory immune responses [35]. A loss of biodiversity in urban areas reduces exposure to diverse environmental microbiomes, whilst increasing exposure to pathogenic microbes [36] (Parajuli et al. 2018). This is corroborated by a review investigating rural vs. urban environmental aerobiomes (microbiome of a given airspace) that showed rural-mediated beneficial immune responses [37] (Flies et al. 2020). Recently, a 28-day biodiversity intervention demonstrated that inoculating a schoolyard environment with biodiverse features (e.g., soil and plants from local forest habitats) significantly altered the microbiome of the children and enhanced important immunoregulatory pathways [16] (Roslund et al. 2020).

Other studies indicate the importance of butyrate-producing bacteria which may be promoted in biodiverse plant-soil systems [18,38] (Liddicoat et al. 2020; Brame et al. 2021), for example where organic-rich soils experience low redox conditions consistent with fermentative decomposition of organic matter. Butyrate is a short chain fatty acid associated with gut health, immunoregulation, and mental health, and exposure to trace level dust containing the putative spore-forming butyrate-producing bacteria *Kineothrix alysoides* is linked to reduced anxiety-like behaviour in mice [18] (Liddicoat et al. 2020). Another recent study showed that spending a short period of time in green spaces can significantly change the human nasal and respiratory microbiome [39] (Selway et al. 2020). Indeed, microbiota-mediated environmental health can be thought of as two layers of protective biodiversity [40] (Ruokolainen et al 2017).

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 a plethora of other potential health benefits are associated with engaging with urban nature, including reduced blood pressure [41] (Ideno et al. 2017), lower levels of stress, anxiety [42,43] (Birch et al. 2020a; Robinson et al. 2021) and increasing positive affect [44] (Cameron et al. 2020).

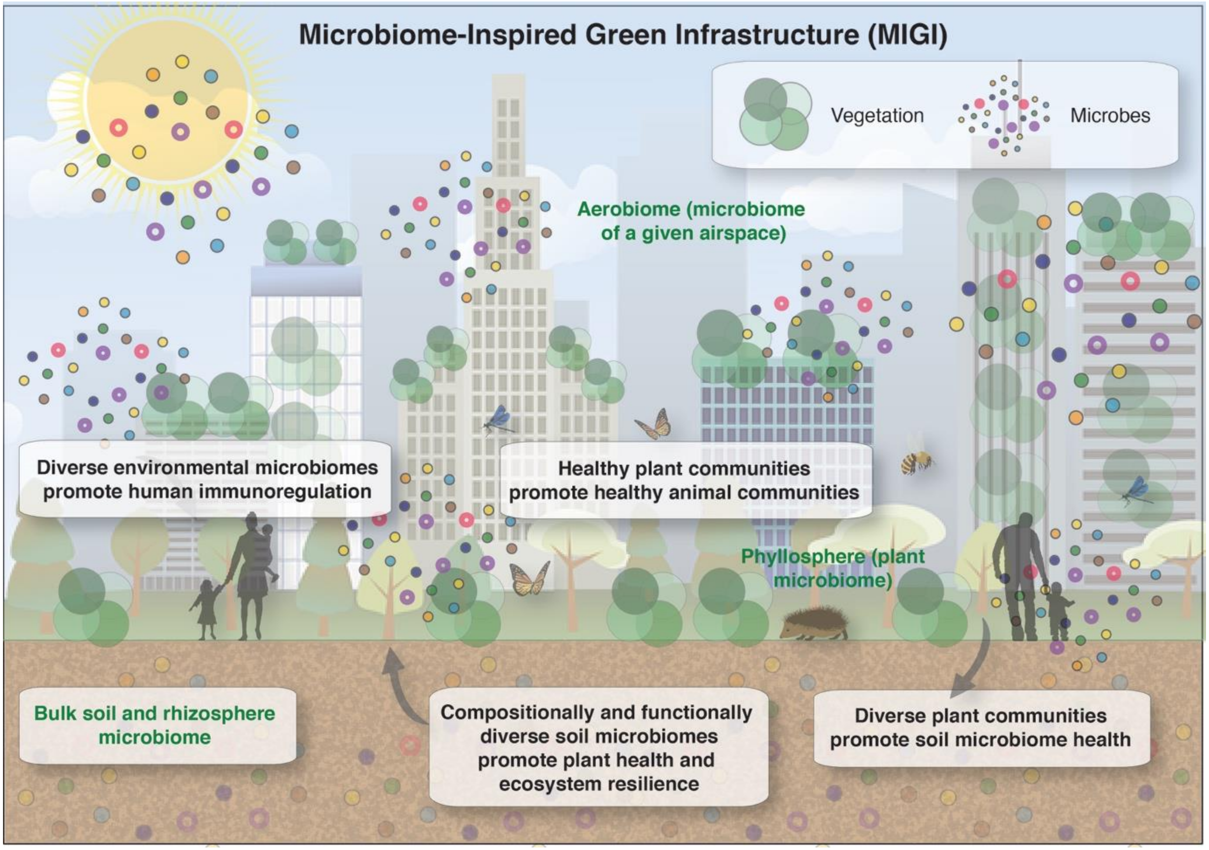

Fig. 1. Urban multispecies health. Environmental microbiomes are the foundations of our ecosystems, and are essential to plant and animal health (including humans).

3. MIGI: actionable insights for landscape managers

3.1. 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 [45,46] (Mulder et al. 2011; Zhang et al. 2020). It has been demonstrated that air samples downwind from biodiverse sources (e.g., species-rich plant communities) contain more diverse microbial communities compared to upwind, with ~50% of airborne bacteria in downwind samples deriving from local plant sources [46] (Lymperopoulou et al. 2016). Therefore, a relatively simple intervention for urban designers could be to develop public spaces and buildings downwind from (macro)biodiverse sources, and to integrate local biodiverse sources within building structures and spaces (Fig. 2, a). 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 [19] (Robinson et al. 2020a). This reflects a transition from local plant and soil-related microbiomes at low heights into a broader urban (typically non-green space) airshed [20] (Robinson et al. 2020b). A potential mitigation measure for this could be to augment vertical planting in urban areas, allowing exposure to higher natural microbial alpha diversity in the vertical dimension (Fig. 2, 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 (Fig 2. c).

Mills et al. (2020) provided evidence that revegetation, particularly with native species, can improve urban soil microbiome functional diversity [47]. Other studies show that diverse vegetation communities promote below-ground functional richness, diversity and resilience [48,49] (Eisenhauer et al. 2018; Canals et al. 2019). Promoting diversity of local vegetation communities is considered a robust strategy to maintain multifunctional processes under current and future environmental conditions [48] (Eisenhauer et al. 2018). As such, MIGI strategies could include the planting of diverse, and where possible, native, vegetation communities to sustain urban ecosystem functionality and resilience (Fig. 2, e). However, it is not yet clear to what extent locally native plant populations will be able to tolerate future climate conditions. Studies on woody plants offer conflicting views, with some research suggesting that intra-population genetic variation may provide sufficient resilience [50] (Borrell et al., 2018), whilst others argue that given the range in possible climate futures, including species beyond those that are locally native will be essential in urban environments [51,52] (Sjöman et al., 2016; Cameron & Blanusa, 2016). 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 (Fig. 3, f). Many urban environments are ‘patchy’ in terms of quality and connected nature-centric features. To ensure long-term healthy urban ecosystems, we should aim to connect all natural habitats within towns/cities and provide essential biophysical corridors to the wider 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 [53] (Christie and Knowles, 2015). Enhancing networks of biologically and functionally diverse urban habitats with high 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.

3.2. Soil microbiomes

Soil properties will have a key influence on environmental microbiomes associated with MIGI developments. Soil organic matter and clay-content (proportion of clay-sized particles) are associated with structure, aggregation, nutrient and water-holding properties, and therefore the habitat and diversity of microbes [54,55,56] (Jastrow and Miller, 1998; Young and Crawford, 2004; Torsvik and Øvreås, 2002). A key decision during the establishment phase of MIGI will be whether to use in-situ or imported soils. Where feasible, using soils with a moderate amount of clay-content, e.g. 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 (e.g. shallow depth, impermeable layers, presence of toxic or nutrient-limiting subsoil conditions), while other times they can result from management history (e.g. compaction, acidification).

Where appropriate, addressing soil constraints will help optimise the biological activity and microbial diversity of the plant-soil system. 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/vehicle traffic can lead to compaction and degradation, and may create zones of poor soil microbiome conditions with sub-optimal health influence (e.g. along paths) within a natural space that is 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 (e.g. 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 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 [57,58] (Filotas et al. 2014; Birch et al. 2020). Indeed, healthy vegetation community phenotypes at higher levels emerge from a multitude of localised and often subterranean entities interacting at lower levels [59] (Ibarra et al. 2020). For example, Birch et al. (2020) 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 [58]. 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 [25] (Watkins et al. 2020).

Interestingly, a recent study showed that landscaping materials (e.g. 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 [60] (Soininen et al. 2021). This suggests that as part of a holistic MIGI strategy, short-term storage times should be considered when planning the utilisation of landscaping materials (Fig. 2, d).

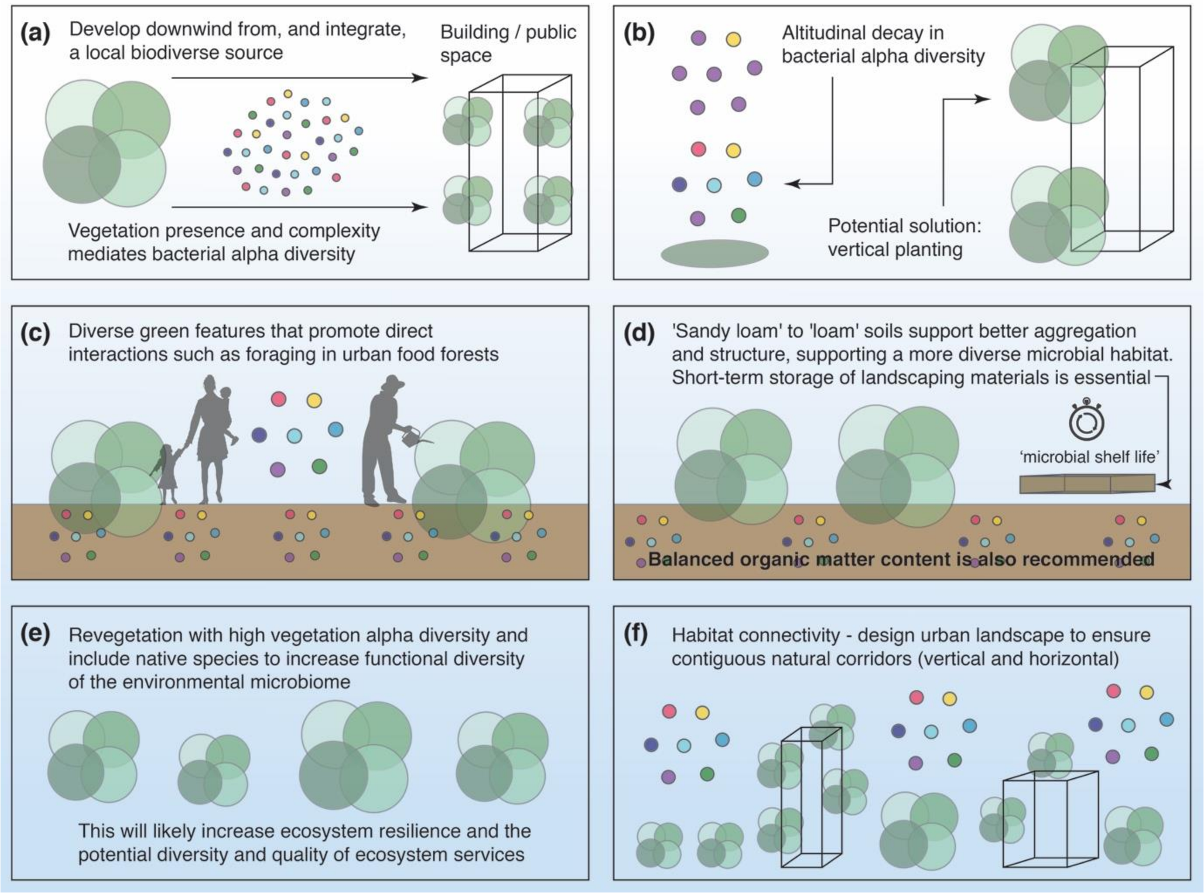

Fig. 2. Actionable insights for MIGI, including vegetation complexity, downwind development and local integration of biodiverse source (a); a solution to the concept of vertical stratification (b); hands-on engagement with natural features to promote immunoregulation (c); recommended soil types to promote 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).

4. MIGI: Horizon scan of emerging research and practice

4.1. *Bioreceptive materials and bio-integrated design*

Bio-Integrated Design refers to interdisciplinary methodologies that merge applied biotechnology, architecture and design, in order to create sustainable systems for the built environment. It encompasses a range of biologically-mediated processes, such as biosilification, biomineralization and bioremediation, as well as the development of material substrates for living systems. Guillitte defined the term ‘bioreceptivity’ to describe the ability of a building material to be colonised by living organisms [61] (Guillitte, 1995). In the context of bio-integrated design to enable MIGI, bioreceptivity has been explored through the design of architectural scaffolds with the goal of creating self-regulating systems which are host to cryptogrammic species as well as microbial biodiversity [62] (Cruz & Beckett, 2016).

Whilst horizontal surfaces including roofs, terraces or pavements offer scope for plant growth, vertical surfaces (e.g. building facades 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 areas of xeric surfaces that offer opportunities to be photosynthetically active. For an accelerated creation of primary bioreceptivity on vertical surfaces, a number of design steps can accelerate this process. 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, and 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 (Manso et al., 2015) and other Ordinary Portland Concrete (OPC) mixes with the aim to create long-term carbon offset [63]. Studies of OPC have shown that apart from altering the physico-chemical 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 [64] (Cruz, 2021). In future, quaternary bioreceptive strategies may be used [65] (Sanmartín et al., 2021) 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 establish cryptogamic growth.

Lichens and, primarily bryophytes play key roles in design of bioreceptive structures within architecture, provoking a biophilic response [66] (Wilson, 1984) 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 [67] (Yeager et al., 2007), where their ability to fix nitrogen and carbon enables succession by other organisms through 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 [68] (Tang et al., 2016). Analogous to the urban environment, during early stages of habitat restoration it has been shown that bryophyte communities enrich populations of microbial life on calcareous rocks [69] (Cao et al., 2020). 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 production of indole acetic acid, siderophores or solubilisation of phosphate [70] (Insuk et al., 2020). Through this application of bio-integrated design to produce poikilohydric living walls, it is possible to employ more of the surface area that is underutilised within our urban environments to deliver MIGI.

4.2. Microbial inoculants

Microbial inoculants have recently been used to shift microbiota in landscaping materials towards an immuno-protective assemblage [71] (Hui et al. 2019). The authors developed a microbial inoculant from biodiverse sources (e.g., forest materials), resembling the microbiome of organic soils. After the study subjects made contact with these inoculated materials, the relative abundance of opportunist pathogens on the skin significantly decreased. Furthermore, Roslund et al. (2020) demonstrated that a biodiversity intervention using microbial inoculants from forest floor materials changed the skin microbiome of children and enhanced immunoregulatory pathways [16]. Several other studies show that microbial inoculants can be beneficial for plant health, for example, via Plant Growth Promoting Rhizobacteria (PGPR) [72] (Sacristán-Pérez-Minayo et al. 2020). 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 [73] (Kumar et al. 2019). Therefore, MIGI strategies could incorporate microbial inoculants to enhance ecosystem health (Fig. 3, b).

4.3. ***Supportive tools***

Useful tools are being developed that could help with MIGI interventions in the near future. For example, Saleem et al. (2019) 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 [74]. 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 (Fig. 3, c).

4.4. 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—present in many cities as components of urban dusts [75] (Alharbi et al., 2019). Bacteria, fungi and microalgae have evolved several mechanisms to adsorb or absorb heavy metals. In a study investigating river sediments contaminated with cadmium, copper, lead and zinc, it was hypothesised that species richness may be a function of "public goods" within the microbial community, such as metallophores, EPC, 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 [76] (Jacquiod et al. 2018).

Kang et al. (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 Pb (98.3% effective) and Cd (85.4%) in soils [77]. Biofilters are being developed that embed bacterial biofilms to absorb heavy metal ions (Priyadarshanee and Das, 2020) [78]. In terms of MIGI, this kind of strategy could be developed with Sustainable Drainage Systems in mind, e.g., a biofilter-embedded rain garden

(Fig. 3, d). There are numerous organic compounds that pose a threat to human health, found in elevated concentrations. Microbial mechanisms that may be employed in MIGI are hydrolysis and oxidation, with the goal of producing benign compounds through metabolic activity. For instance, endocrine disruptors such as phthalates and alkylphenols are ubiquitous in water systems as a result of human activity [79] (Bergé et al., 2014) but there are microbial mechanisms to break these down under certain conditions [80] (Boll et al., 2020). Indeed, many bacterial taxa have been identified that have significant pollutant degradation properties [81] (Ojuederie and Babalola, 2017). As an alternative to contained bioreactor systems, creating stable synthetic ecologies and applying eco-evolutionary principles to enhance bioremediation is compatible with MIGI principles [82] (Borchert et al., 2021).

4.5. 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 [83] (Paungfoo-Lonhienne et al. 2015). Studies have suggested that organic or ‘natural’ fertilisers and plant conditioners outperform chemically synthetic N, P and K types in promoting plant health/quality [84,85] (Hammad at el. 2020; Dahunsi et al. 2021). Additional research in this area could bring value to the MIGI concept, particularly research focusing on the application of 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, excessive disturbance will likely damage microbial communities [86] (Gregory et al. 2015). 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 the spread of antimicrobial resistance [87] (Chen et al. 2019). Antimicrobial resistance has important implications for human health by making infections harder to treat and increasing risks of disease spread [88] (WHO, 2020). MIGI researchers aiming to reduce the abundance and diversity of antimicrobial resistant genes in urban environments could explore the strategy of increasing soil microbial diversity.

4.6. Emerging biosecurity considerations

Alongside the positive opportunities presented by a multispecies approach to green infrastructure, the threats need to be equally researched and mitigated against within the MIGI framework. Many of the most pressing biosecurity threats to ecosystems are microbial in nature (in the UK, for example, *Hymenoscyphus fraxineus, Phytopthora ramorum* and *Candidatus liberibacter solanacearum*), threatening urban green infrastructure as well as agricultural crops that urban populations depend upon. It is increasingly recognised, however, 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 policy makers, 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 [89] (Kemp et al. 2021), or to what extent novel microbial pests and diseases might influence assisted colonisation programmes or substitutions for keystone species die-off.

Regulation and guidance exists to combat and mitigate these threats have been developed at international (e.g. European and Mediterranean Plant Protection Organisation [90] (EPPO, 2020), national (Defra Plant Health Risk Register [91] (Defra, 2014)) and regional levels [92]

(Public Health Agency of Canada, 2018), complemented by industry-specific guidance in many countries [93] (Watkins & Arkell, 2019). Nevertheless, further work is required to address the open questions and operationalise policy, and MIGI offers an opportunity to address these in a holistic manner. 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 such as Plant Healthy (https://planthealthy.org.uk) within MIGI will be essential, not only to ensure that best practice is developed but also so that practitioners can clearly understand how their actions reinforce the biosecurity continuum [94] (Sequeira and Griffin 2014). 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 [19] (Watkins et al., 2020) 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.

4.7. Social innovation: promoting stronger human-nature relationships

Other important factors within the MIGI framework include social innovation, education and stimulating awe for nature, with emphasis on the foundations of our ecosystems—the diverse microbial communities. Strategies such as 'learning about the land, on the land' [95] (Learning the Land, 2021) could help to inspire pro-ecological behaviours that reinforce a sense of stewardship for our diverse and complex ecosystems. To paraphrase Simard (2018) "*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]*" [96]. Various campaigns also promote the concept of ‘nature connectedness’ (emotional and cognitive connection with the natural world). Studies in this area show increases in wellbeing and pro-ecological behaviour as a result of enhanced nature connectedness [97,98] (Capaldi et al. 2014; Capaldi et al. 2015).

For the technologically-minded, virtual reality systems could be developed to facilitate urban habitat tours. These could include interactive macroscopic displays of microbial communities, whilst providing information on the composition and functional roles that microbes play in the local ecosystems (Fig. 3, f).

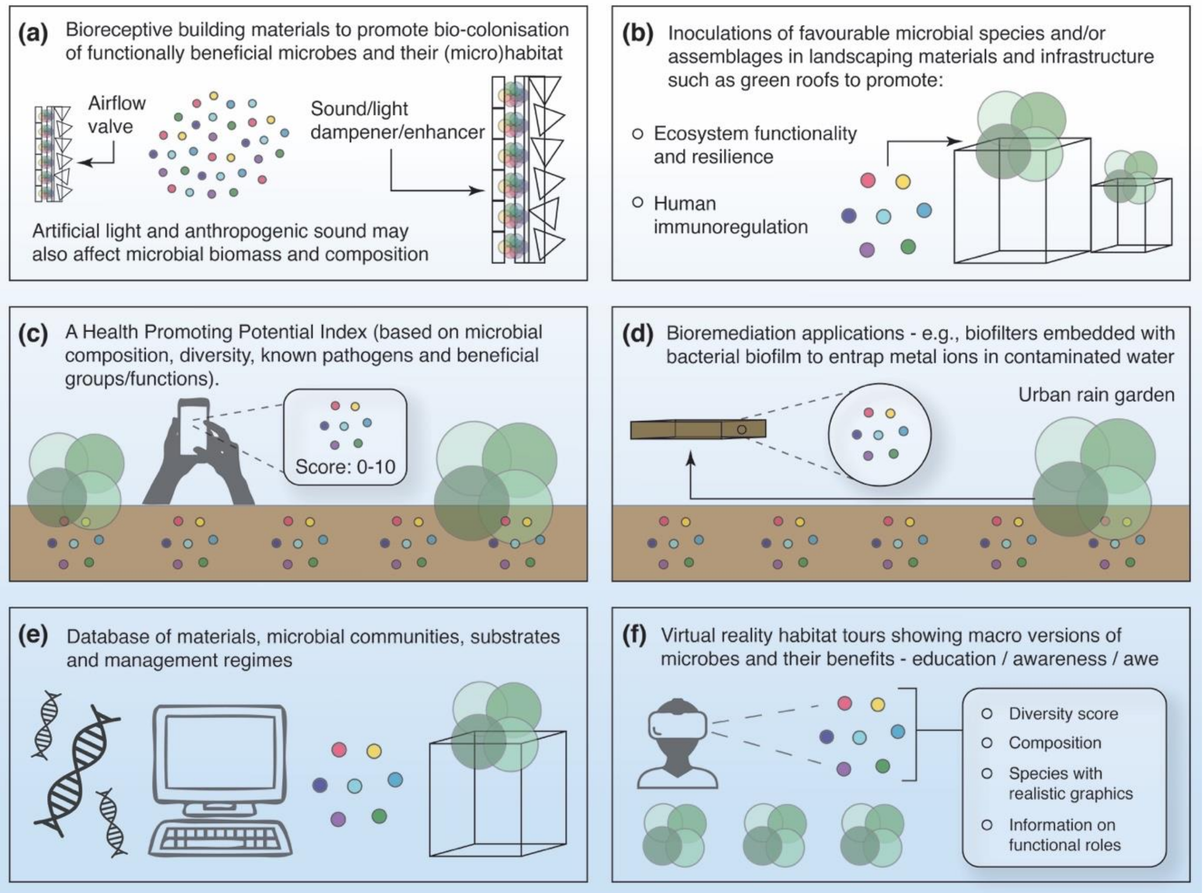

Fig. 3. Horizon scan of developmental considerations for MIGI, including interventions (b and d), design and supportive features (a and e), and applications for engagement and to acquire useful urban ecosystem health information (c and f).

5. MIGI: Challenges to operationalisation

Watkins et al. (2020) 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 [19]. To ensure the implementation of green infrastructure strategies, stakeholder buy-in is required throughout green infrastructure planning, design, operation and management [99] (Smith, 2020). The range of stakeholders include: local authorities, developers and private clients, planning professionals, landowners, landscape specialists, architects, ecologists, statutory agencies, contractors, local businesses and community groups. In the UK, there are a number of government-funded research projects into green infrastructure, biosecurity, climate change-readiness, and supply chains (e.g. BRIGIT, Future Oak, Plant Health Centre). Learning from these projects is prudent as 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 so that robust data can be gathered 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" [100] (Ferreira et al. 2020). Further development should align with the priorities of the stakeholder groups and generate clear, actionable points overlayed 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. The 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 [101] (Greater London Authority, 2021). 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.

6. MIGI: Workshop series proposal

To determine clear action points for future research and address the challenges related to divergence of interests among stakeholders, it is vital to ascertain diverse priorities and concerns through early consultation [102] (Khoshkar et al. 2017). This could also aid the development of a “common language” [103] (Ugolini et al. 2018) 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 a health and ecosystem functionality context, and reveal tangible opportunities to include MIGI in urban planning. These workshops provide an opportunity to engage with reflective stakeholders in identifying not only challenges but also specific factors (e.g. MIGI toolkits, portfolio of illustrative examples) and alignments between current requirements/protocols, and how MIGI could be integrated. During the 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. In this paper, we have provided several examples of MIGI actionable insights in addition to a horizon scan of emerging MIGI-related research and practice. A greater emphasis on the roles of microbial communities (from below-ground and up) in our urban ecosystems is needed. 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. However, overcoming the challenges to operationalising MIGI will be essential to furthering its practical development.

References

1. Cavicchioli, Ricardo, William J. Ripple, Kenneth N. Timmis, Farooq Azam, Lars R. Bakken, and others. 2019. “Scientists’ Warning to Humanity: Microorganisms and Climate Change,” *Nature Reviews. Microbiology*, 17.9: 569–86
2. Guerra, Carlos A., Anna Heintz-Buschart, Johannes Sikorski, Antonis Chatzinotas, Nathaly Guerrero-Ramírez, and others. 2020. “Blind Spots in Global Soil Biodiversity and Ecosystem Function Research,” *Nature Communications*, 11.1: 3870
3. Bach, Elizabeth M., Kelly S. Ramirez, Tandra D. Fraser, and Diana H. Wall. 2020. “Soil Biodiversity Integrates Solutions for a Sustainable Future,” *Sustainability*, 12.7: 2662
4. Greenspan, Sasha E., Gustavo H. Migliorini, Mariana L. Lyra, Mariana R. Pontes, Tamilie Carvalho, and others. 2020. “Warming Drives Ecological Community Changes Linked to Host-Associated Microbiome Dysbiosis,” *Nature Climate Change*, 10.11: 1057–61
5. Tibbett, Mark, Tandra D. Fraser, and Sarah Duddigan. 2020. “Identifying Potential Threats to Soil Biodiversity,” *PeerJ*, 8.e9271: e9271
6. Smith, Katherine F., Michael Goldberg, Samantha Rosenthal, Lynn Carlson, Jane Chen, and others. 2014. “Global Rise in Human Infectious Disease Outbreaks,” *Journal of the Royal Society, Interface*, 11.101: 20140950
7. Jairath, Vipul, and Brian G. Feagan. 2020. “Global Burden of Inflammatory Bowel Disease,” *The Lancet. Gastroenterology & Hepatology*, 5.1: 2–3
8. El-Gamal, Yehia M., Elham M. Hossny, Zeinab A. El-Sayed, and Shereen M. Reda. 2017. “Allergy and Immunology in Africa: Challenges and Unmet Needs,” *The Journal of Allergy and Clinical Immunology*, 140.5: 1240–43

9. Borna, Eivind, Bright I. Nwaru, Anders Bjerg, Roxana Mincheva, Madeleine Rådinger, and others. 2019. “Changes in the Prevalence of Asthma and Respiratory Symptoms in Western Sweden between 2008 and 2016,” *Allergy*, 74.9: 1703–15
10. Holman, N., N. G. Forouhi, E. Goyder, and S. H. Wild. 2011. “The Association of Public Health Observatories (APHO) Diabetes Prevalence Model: Estimates of Total Diabetes Prevalence for England, 2010-2030: Estimates of Total Diabetes Prevalence for England, 2010-2030,” *Diabetic Medicine: A Journal of the British Diabetic Association*, 28.5: 575–82
11. Kainu, Annette, Paula Pallasaho, Päivi Piirilä, Ari Lindqvist, Anssi Sovijärvi, and others. 2013. “Increase in Prevalence of Physician-Diagnosed Asthma in Helsinki during the Finnish Asthma Programme: Improved Recognition of Asthma in Primary Care? A Cross-Sectional Cohort Study,” *Primary Care Respiratory Journal: Journal of the General Practice Airways Group*, 22.1: 64–71
12. Dinse, Gregg E., Christine G. Parks, Clarice R. Weinberg, Caroll A. Co, Jesse Wilkerson, and others. 2020. “Increasing Prevalence of Antinuclear Antibodies in the United States,” *Arthritis & Rheumatology*, 72.6: 1026–35
13. Paramasivam, Arumugam, Jayaseelan Vijayashree Priyadharsini, and Subramanian Raghunandhakumar. 2020. “Implications of M6A Modification in Autoimmune Disorders,” *Cellular & Molecular Immunology*, 17.5: 550–51
14. Haahtela, Tari. 2019. “A Biodiversity Hypothesis,” *Allergy*
15. Rook, Graham A. 2013. “Regulation of the Immune System by Biodiversity from the Natural Environment: An Ecosystem Service Essential to Health,” *Proceedings of the National Academy of Sciences of the United States of America*, 110.46: 18360–67
16. Roslund, Marja I., Riikka Puhakka, Mira Grönroos, Noora Nurminen, Sami Oikarinen, and others. 2020. “Biodiversity Intervention Enhances Immune Regulation

and Health-Associated Commensal Microbiota among Daycare Children," *Science Advances*, 6.42

17. Renz, Harald, and Chrysanthi Skevaki. 2021. "Early Life Microbial Exposures and Allergy Risks: Opportunities for Prevention," *Nature Reviews. Immunology*, 21.3: 177–91
18. Liddicoat, Craig, Philip Weinstein, Andrew Bissett, Nicholas J. C. Gellie, Jacob G. Mills, and others. 2019. "Can Bacterial Indicators of a Grassy Woodland Restoration Inform Ecosystem Assessment and Microbiota-Mediated Human Health?," *Environment International*, 129: 105–17
19. Robinson, Jake M., Christian Cando-Dumancela, Rachael E. Antwis, Ross Cameron, Craig Liddicoat, and others. 2020a. "Exposure to Airborne Bacteria Depends upon Vertical Stratification and Vegetation Complexity," *Scientific Reports.*
20. Berg, Gabriele, Martina Köberl, Daria Rybakova, Henry Müller, Rita Grosch, and others. 2017. "Plant Microbial Diversity Is Suggested as the Key to Future Biocontrol and Health Trends," *FEMS Microbiology Ecology*, 93.5
21. Rupprecht, Christoph D. D., Joost Vervoort, Chris Berthelsen, Astrid Mangnus, Natalie Osborne, and others. 2020. "Multispecies Sustainability," *Global Sustainability*, 3.e34
22. Sharma, A. 2021. The City under Stress: Waking to a Multispecies Urban. *Urban Environments as Spaces of Living in Transformation*, p.7. Online. Available at: https://urbanenv.org/the-city-under-stress/ (Accessed on 8th March 2021).
23. Robinson, Jake, Jacob Mills, and Martin Breed. 2018. "Walking Ecosystems in Microbiome-Inspired Green Infrastructure: An Ecological Perspective on Enhancing Personal and Planetary Health," *Challenges*, 9.2: 40

24. Watkins, Harry, Jake M. Robinson, Martin F. Breed, Brenda Parker, and Philip Weinstein. 2020. “Microbiome-Inspired Green Infrastructure: A Toolkit for Multidisciplinary Landscape Design,” *Trends in Biotechnology*, 38.12: 1305–8
25. Karlsdóttir, B., Pollard, C., Paterson, A., Watkins, H., Marzano, M. 2021. Assessment of large-scale plant biosecurity risks to Scotland from large scale plantings for landscaping and infrastructure projects: Project Final Report. PHC2019/05.
26. Nazli, F., Khan, M.Y., Jamil, M., Nadeem, S.M. and Ahmad, M. 2020. Soil microbes and plant health. In *Plant Disease Management Strategies for Sustainable Agriculture through Traditional and Modern Approaches* (pp. 111-135). Springer, Cham.
27. Trivedi, Pankaj, Jan E. Leach, Susannah G. Tringe, Tongmin Sa, and Brajesh K. Singh. 2020. “Plant-Microbiome Interactions: From Community Assembly to Plant Health,” *Nature Reviews. Microbiology*, 18.11: 607–21
28. ur Rehman, F., Kalsoom, M., Nasir, T.A., Adnan, M., Anwar, S. and Zahra, A. 2020. Chemistry of Plant–Microbe Interactions in Rhizosphere and Rhizoplane. ***Ind J Pure App Biosci,*** 8, pp.11-19. 10.3389/fpls.2018.00112
29. Pavithra, Sumant Bindal, Meenakshi Rana, and Seweta Srivastava. 2019. “Role of Endophytic Microbes against Plant Pathogens: A Review,” *Asian Journal of Plant Sciences*, 19.1: 54–62
30. Dubey, Anamika, Muneer Ahmad Malla, Farhat Khan, Kanika Chowdhary, Shweta Yadav, and others. 2019. “Soil Microbiome: A Key Player for Conservation of Soil Health under Changing Climate,” *Biodiversity and Conservation*, 28.8–9: 2405–29
31. van Bruggen, Ariena H. C., Erica M. Goss, Arie Havelaar, Anne D. van Diepeningen, Maria R. Finckh, and others. 2019. “One Health - Cycling of Diverse Microbial Communities as a Connecting Force for Soil, Plant, Animal, Human and Ecosystem Health,” *The Science of the Total Environment*, 664: 927–37

32. Wagg, Cameron, Klaus Schlaeppi, Samiran Banerjee, Eiko E. Kuramae, and Marcel G. A. van der Heijden. 2019. “Fungal-Bacterial Diversity and Microbiome Complexity Predict Ecosystem Functioning,” *Nature Communications*, 10.1: 4841

33. Lehtimäki, Jenni, Jonathan Thorsen, Morten Arendt Rasmussen, Mathis Hjelmsø, Shiraz Shah, and others. 2020. “Urbanized Microbiota in Infants, Immune Constitution, and Later Risk of Atopic Diseases,” *The Journal of Allergy and Clinical Immunology* <https://doi.org/10.1016/j.jaci.2020.12.621>

34. Riskumäki, Matilda, Ioannis Tessas, Noora Ottman, Alina Suomalainen, Paulina Werner, and others. 2021. “Interplay between Skin Microbiota and Immunity in Atopic Individuals,” *Allergy*, 76.4: 1280–84

35. Parajuli, Anirudra, Mira Grönroos, Nathan Siter, Riikka Puhakka, Heli K. Vari, and others. 2018. “Urbanization Reduces Transfer of Diverse Environmental Microbiota Indoors,” *Frontiers in Microbiology*, 9

36. Flies, Emily J., Laurence J. Clarke, Barry W. Brook, and Penelope Jones. 2020. “Urbanisation Reduces the Abundance and Diversity of Airborne Microbes - but What Does That Mean for Our Health? A Systematic Review,” *The Science of the Total Environment*, 738.140337: 140337

37. Brame, Joel E., Craig Liddicoat, Catherine A. Abbott, and Martin F. Breed. 2021. “The Potential of Outdoor Environments to Supply Beneficial Butyrate-Producing Bacteria to Humans,” *The Science of the Total Environment*, 777.146063: 146063

38. Selway, Caitlin A., Jacob G. Mills, Philip Weinstein, Chris Skelly, Sudesh Yadav, and others. 2020. “Transfer of Environmental Microbes to the Skin and Respiratory Tract of Humans after Urban Green Space Exposure,” *Environment International*, 145.106084: 106084

39. Ruokolainen, Lasse, Jenni Lehtimäki, Antti Karkman, Tari Haahtela, Leena von Hertzen, and others. 2017. “Holistic View on Health: Two Protective Layers of Biodiversity,” *Annales Zoologici Fennici*, 54.1–4: 39–49
40. Birch, Jo, Clare Rishbeth, and Sarah R. Payne. 2020. “Nature Doesn’t Judge You - How Urban Nature Supports Young People’s Mental Health and Wellbeing in a Diverse UK City,” *Health & Place*, 62.102296: 102296
41. Robinson, Jake M., Paul Brindley, Ross Cameron, Danielle MacCarthy, and Anna Jorgensen. 2021. “Nature’s Role in Supporting Health during the COVID-19 Pandemic: A Geospatial and Socioecological Study,” *International Journal of Environmental Research and Public Health*, 18.5: 2227
42. Cameron, Ross W. F., Paul Brindley, Meghann Mears, Kirsten McEwan, Fiona Ferguson, and others. 2020. “Where the Wild Things Are! Do Urban Green Spaces with Greater Avian Biodiversity Promote More Positive Emotions in Humans?,” *Urban Ecosystems*, 23.2: 301–17
43. Mulder, Imke E., Bettina Schmidt, Marie Lewis, Margaret Delday, Christopher R. Stokes, and others. 2011. “Restricting Microbial Exposure in Early Life Negates the Immune Benefits Associated with Gut Colonization in Environments of High Microbial Diversity,” *PloS One*, 6.12: e28279
44. Zhang, Jinya, Fernando Rodríguez, Maria Jesus Navas, Mar Costa-Hurtado, Vanessa Almagro, and others. 2020. “Fecal Microbiota Transplantation from Warthog to Pig Confirms the Influence of the Gut Microbiota on African Swine Fever Susceptibility,” *Scientific Reports*, 10.1: 17605
45. Lymperopoulou, Despoina S., Rachel I. Adams, and Steven E. Lindow. 2016. “Contribution of Vegetation to the Microbial Composition of Nearby Outdoor Air,” *Applied and Environmental Microbiology*, 82.13: 3822–33

46. Mills, Jacob G., Andrew Bissett, Nicholas J. C. Gellie, Andrew J. Lowe, Caitlin A. Selway, and others. 2020. “Revegetation of Urban Green Space Rewilds Soil Microbiotas with Implications for Human Health and Urban Design: Revegetation Rewilds Urban Soil Microbiotas,” *Restoration Ecology*

47. Eisenhauer, N., Hines, J., Isbell, F., van der Plas, F., Hobbie, S.E., Kazanski, C.E., Lehmann, A., Liu, M., Lochner, A., Rillig, M.C. and Vogel, A. 2018. Plant diversity maintains multiple soil functions in future environments. ***Elife***, *7*, p.e41228. 10.7554/eLife.41228.001

48. Canals, R. M., L. Múgica, M. Durán, and L. San Emeterio. 2019. “Soil Bacterial Functional Diversity Mirrors the Loss of Plant Diversity by the Expansion of a Native Tall-Grass in High Mountain Grasslands,” *Plant and Soil*, 445.1–2: 243–57

49. Borrell, James S., Nian Wang, Richard A. Nichols, and Richard J. A. Buggs. 2018. “Genetic Diversity Maintained among Fragmented Populations of a Tree Undergoing Range Contraction,” *Heredity*, 121.4: 304–18

50. Sjöman, Henrik, Justin Morgenroth, Johanna Deak Sjöman, Arne Sæbø, and Ingo Kowarik. 2016. “Diversification of the Urban Forest—Can We Afford to Exclude Exotic Tree Species?,” *Urban Forestry & Urban Greening*, 18: 237–41

51. Cameron, Ross W. F., and Tijana Blanuša. 2016. “Green Infrastructure and Ecosystem Services - Is the Devil in the Detail?,” *Annals of Botany*, 118.3: 377–91

52. Christie, Mark R., and L. Lacey Knowles. 2015. “Habitat Corridors Facilitate Genetic Resilience Irrespective of Species Dispersal Abilities or Population Sizes,” *Evolutionary Applications*, 8.5: 454–63

53. Jastrow, J. D., and R. M. Miller. 2018. “Soil Aggregate Stabilization and Carbon Sequestration: Feedbacks through Organomineral Associations,” in *Soil Processes and the Carbon Cycle* (CRC Press), pp. 207–23

54. Young, I. M., and J. W. Crawford. 2004. “Interactions and Self-Organization in the Soil-Microbe Complex,” *Science (New York, N.Y.)*, 304.5677: 1634–37

55. Torsvik, Vigdis, and Lise Øvreås. 2002. “Microbial Diversity and Function in Soil: From Genes to Ecosystems,” *Current Opinion in Microbiology*, 5.3: 240–45

56. Filotas, Elise, Lael Parrott, Philip J. Burton, Robin L. Chazdon, K. David Coates, and others. 2014. “Viewing Forests through the Lens of Complex Systems Science,” *Ecosphere (Washington, D.C)*, 5.1: art1

57. Birch, Joseph D., Suzanne W. Simard, Kevin J. Beiler, and Justine Karst. 2021. “Beyond Seedlings: Ectomycorrhizal Fungal Networks and Growth of Mature Pseudotsuga Menziesii,” *The Journal of Ecology*, 109.2: 806–18

58. Ibarra, José Tomás, Kristina L. Cockle, Tomás A. Altamirano, Yntze van der Hoek, Suzanne W. Simard, and others. 2020. “Nurturing Resilient Forest Biodiversity: Nest Webs as Complex Adaptive Systems,” *Ecology and Society: A Journal of Integrative Science for Resilience and Sustainability*, 25.2 <https://doi.org/10.5751/es-11590-250227>

59. Soininen, Laura, Mira Grönroos, Marja I. Roslund, and Aki Sinkkonen. 2021. “Long-Term Storage Affects Resource Availability and Occurrence of Bacterial Taxa Linked to Pollutant Degradation and Human Health in Landscaping Materials,” *Urban Forestry & Urban Greening*, 60.127065: 127065

60. Guillitte, O. 1995. “Bioreceptivity: A New Concept for Building Ecology Studies,” *The Science of the Total Environment*, 167.1–3: 215–20

61. Cruz, Marcos, and Richard Beckett. 2016. “Bioreceptive Design: A Novel Approach to Biodigital Materiality,” *Architectural Research Quarterly*, 20.1: 51–64

62. Manso, Sandra, María Ángeles Calvo-Torras, Nele De Belie, Ignacio Segura, and Antonio Aguado. 2015. “Evaluation of Natural Colonisation of Cementitious

Materials: Effect of Bioreceptivity and Environmental Conditions," *The Science of the Total Environment*, 512–513: 444–53

63. Cruz, M. 2021. *Poikilohydric Living Walls - a Bartlett Research Folio*.
64. Sanmartín, P., A. Z. Miller, B. Prieto, and H. A. Viles. 2021. "Revisiting and Reanalysing the Concept of Bioreceptivity 25 Years On," *The Science of the Total Environment*, 770.145314: 145314
65. Wilson, E. O. 1984. *Biophilia / Edward O. Wilson.* [Book]. Harvard University Press.
66. Yeager, Chris M., Jennifer L. Kornosky, Rachael E. Morgan, Elizabeth C. Cain, Ferran Garcia-Pichel, and others. 2007. "Three Distinct Clades of Cultured Heterocystous Cyanobacteria Constitute the Dominant N2-Fixing Members of Biological Soil Crusts of the Colorado Plateau, USA: N2-Fixing Cyanobacteria in Soil Crusts," *FEMS Microbiology Ecology*, 60.1: 85–97
67. Tang, Jing Yan, Jing Ma, Xue Dong Li, and Yan Hong Li. 2016. "Illumina Sequencing-Based Community Analysis of Bacteria Associated with Different Bryophytes Collected from Tibet, China," *BMC Microbiology*, 16.1: 276
68. Cao, Wei, Yuanxin Xiong, Degang Zhao, Hongying Tan, and Jiaojiao Qu. 2020. "Bryophytes and the Symbiotic Microorganisms, the Pioneers of Vegetation Restoration in Karst Rocky Desertification Areas in Southwestern China," *Applied Microbiology and Biotechnology*, 104.2: 873–91
69. Insuk, Chadabhorn, Nattakorn Kuncharoen, Naowarat Cheeptham, Somboon Tanasupawat, and Wasu Pathom-Aree. 2020. "Bryophytes Harbor Cultivable Actinobacteria with Plant Growth Promoting Potential," *Frontiers in Microbiology*, 11: 563047

70. Hui, Nan, Mira Grönroos, Marja I. Roslund, Anirudra Parajuli, Heli K. Vari, and others. 2019. “Diverse Environmental Microbiota as a Tool to Augment Biodiversity in Urban Landscaping Materials,” *Frontiers in Microbiology*, 10: 536

71. Sacristán-Pérez-Minayo, Gonzalo, Domingo Javier López-Robles, Carlos Rad, and Luis Miranda-Barroso. 2020. “Microbial Inoculation for Productivity Improvements and Potential Biological Control in Sugar Beet Crops,” *Frontiers in Plant Science*, 11: 604898

72. Kumar, A., J. S. Patel, V. S. Meena, and P. W. Ramteke. 2019. “Plant Growth-Promoting Rhizobacteria: Strategies to Improve Abiotic Stresses under Sustainable Agriculture,” *Journal of Plant Nutrition*, 42.11–12: 1402–15

73. Saleem, Muhammad, Jie Hu, and Alexandre Jousset. 2019. “More than the Sum of Its Parts: Microbiome Biodiversity as a Driver of Plant Growth and Soil Health,” *Annual Review of Ecology, Evolution, and Systematics*, 50.1: 145–68

74. Alharbi, Badr H., Mohammad J. Pasha, and Mohammed Ahmad S. Al-Shamsi. 2019. “Influence of Different Urban Structures on Metal Contamination in Two Metropolitan Cities,” *Scientific Reports*, 9.1: 4920

75. Jacquiod, Samuel, Valentine Cyriaque, Leise Riber, Waleed Abu Al-soud, David C. Gillan, and others. 2018. “Long-Term Industrial Metal Contamination Unexpectedly Shaped Diversity and Activity Response of Sediment Microbiome,” *Journal of Hazardous Materials*, 344: 299–307

76. Kang, Chang-Ho, Yoon-Jung Kwon, and Jae-Seong So. 2016. “Bioremediation of Heavy Metals by Using Bacterial Mixtures,” *Ecological Engineering*, 89: 64–69

77. Priyadarshanee, Monika, and Surajit Das. 2021. “Biosorption and Removal of Toxic Heavy Metals by Metal Tolerating Bacteria for Bioremediation of Metal

Contamination: A Comprehensive Review," *Journal of Environmental Chemical Engineering*, 9.1: 104686

78. Bergé, A., J. Gasperi, V. Rocher, L. Gras, A. Coursimault, and others. 2014. "Phthalates and Alkylphenols in Industrial and Domestic Effluents: Case of Paris Conurbation (France)," *The Science of the Total Environment*, 488–489: 26–35
79. Boll, Matthias, Robin Geiger, Madan Junghare, and Bernhard Schink. 2020. "Microbial Degradation of Phthalates: Biochemistry and Environmental Implications," *Environmental Microbiology Reports*, 12.1: 3–15
80. Ojuederie, Omena, and Olubukola Babalola. 2017. "Microbial and Plant-Assisted Bioremediation of Heavy Metal Polluted Environments: A Review," *International Journal of Environmental Research and Public Health*, 14.12: 1504
81. Borchert, Erik, Katrin Hammerschmidt, Ute Hentschel, and Peter Deines. 2021. "Enhancing Microbial Pollutant Degradation by Integrating Eco-Evolutionary Principles with Environmental Biotechnology," *Trends in Microbiology*
82. Paungfoo-Lonhienne, Chanyarat, Yun Kit Yeoh, Naga Rup Pinaki Kasinadhuni, Thierry G. A. Lonhienne, Nicole Robinson, and others. 2015. "Nitrogen Fertilizer Dose Alters Fungal Communities in Sugarcane Soil and Rhizosphere," *Scientific Reports*, 5.1: 8678
83. Hammad, Hafiz Mohkum, Abdul Khaliq, Farhat Abbas, Wajid Farhad, Shah Fahad, and others. 2020. "Comparative Effects of Organic and Inorganic Fertilizers on Soil Organic Carbon and Wheat Productivity under Arid Region," *Communications in Soil Science and Plant Analysis*, 51.10: 1406–22
84. Dahunsi, S. O., S. Oranusi, V. E. Efeovbokhan, A. T. Adesulu-Dahunsi, and J. O. Ogunwole. 2021. "Crop Performance and Soil Fertility Improvement Using Organic

Fertilizer Produced from Valorization of Carica Papaya Fruit Peel," *Scientific Reports*, 11.1: 4696

85. Gregory, A. S., K. Ritz, S. P. McGrath, J. N. Quinton, K. W. T. Goulding, and others. 2015. "A Review of the Impacts of Degradation Threats on Soil Properties in the UK," *Soil Use and Management*, 31.Suppl Suppl 1: 1–15
86. Chen, Qing-Lin, Xin-Li An, Bang-Xiao Zheng, Michael Gillings, Josep Peñuelas, and others. 2019. "Loss of Soil Microbial Diversity Exacerbates Spread of Antibiotic Resistance," *Soil Ecology Letters*, 1.1–2: 3–13
87. WHO. 2020. *Anti-microbial resistance*. Online. Available at: https://www.who.int/news-room/fact-sheets/detail/antimicrobial-resistance#:~:text=What%20is%20antimicrobial%20resistance%3F,spread%2C%20severe%20illness%20and%20death.. (Accessed on 20 March 2021).
88. Kemp, Luke, David C. Aldridge, Olaf Booy, Hilary Bower, Des Browne, and others. 2021. "80 Questions for UK Biological Security," *PloS One*, 16.1: e0241190
89. EPPO. 2020. *European and Mediterranean Plant Protection Organisation*. Online. Available at: https://www.eppo.int/index. (Accessed on 28 March 2021).
90. Department for Environment, Food and Rural Affair. 2014. UK Plant Health Risk Register. Online. Available at: https://secure.fera.defra.gov.uk/phiw/riskRegister/downloadEntireRiskRegister.cfm. (Accessed on 28 March 2021).
91. Public Health Agency of Canada 2018. *Biosecurity Program Annual Report 2017-2018.* Online. Available at: https://www.canada.ca/en/public-health/services/publications/health-risks-safety/centre-biosecurity-annual-report-2017-2018.html. (Accessed on 8 March 2021).

92. Watkins, H., and Arkell, T. 2019. *The Landscape Institute (LI) Biosecurity Toolkit for Landscape Consultants*. Online. Available at: https://www.landscapeinstitute.org/technical-resource/biosecurity-toolkit/. (Accessed on 8 March 2021).

93. Sequeira, Ron, and Robert Griffin. 2014. “The Biosecurity Continuum and Trade: Pre-Border Operations,” in *The Handbook of Plant Biosecurity* (Dordrecht: Springer Netherlands), pp. 119–48

94. Learning the Land. 2021. *Learning the Land.* Online. Available at: https://www.learningtheland.ca. (Accessed on 28 March 2021).

95. Simard, Suzanne W. 2018. “Mycorrhizal Networks Facilitate Tree Communication, Learning, and Memory,” in *Memory and Learning in Plants* (Cham: Springer International Publishing), pp. 191–213

96. Capaldi, Colin A., Raelyne L. Dopko, and John M. Zelenski. 2014. “The Relationship between Nature Connectedness and Happiness: A Meta-Analysis,” *Frontiers in Psychology*, 5: 976

97. Capaldi, Colin, Holli-Anne Passmore, Elizabeth Nisbet, John Zelenski, and Raelyne Dopko. 2015. “Flourishing in Nature: A Review of the Benefits of Connecting with Nature and Its Application as a Wellbeing Intervention,” *International Journal of Wellbeing*, 5.4: 1–16

98. Smith, B. 2020. Planning with Nature: *How can Authorities develop and implement a green infrastructure strategy?*. Practice Note. Online. London: Public Practice. Available at: <http://www.publicpractice.org.uk/resources> (Accessed 28 March 2021).

99. Ferreira, Vera, Ana Barreira, Luís Loures, Dulce Antunes, and Thomas Panagopoulos. 2020. “Stakeholders’ Engagement on Nature-Based Solutions: A Systematic Literature Review,” *Sustainability*, 12.2: 640

100. Greater London Authority. 2021. The London Plan: The Spatial Development Strategy For Greater London. Online. London: Greater London Authority, pp.312-333. Available at: <https://www.london.gov.uk/sites/default/files/the_london_plan_2021.pdf> (Accessed 28 March 2021).

101. Khoshkar, Sara, Berit Balfors, and Antoienette Wärnbäck. 2018. “Planning for Green Qualities in the Densification of Suburban Stockholm – Opportunities and Challenges,” *Journal of Environmental Planning and Management*, 61.14: 2613–35

102. Ugolini, Francesca, Giovanni Sanesi, Anna Steidle, and David Pearlmutter. 2018. “Speaking ‘Green’: A Worldwide Survey on Collaboration among Stakeholders in Urban Park Design and Management,” *Forests*, 9.8: 458

Figure captions

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

Fig. 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).

Fig. 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).