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1 **Abstract**

2 Microbiome-Inspired Green Infrastructure (MIGI) was recently proposed as an integrative
3 system to promote healthy urban ecosystems, through multidisciplinary design. Specifically,
4 MIGI is defined as nature-centric infrastructure restored and/or designed and managed to
5 enhance health-promoting interactions between humans and environmental microbiomes,
6 whilst sustaining microbially-mediated ecosystem functionality and resilience. MIGI also
7 aims to stimulate a research agenda that focuses on considerations for the importance of
8 urban environmental microbiomes. In this paper we provide details of what MIGI entails
9 from a bioscience and biodesign perspective, highlighting the potential dual benefits for
10 human and ecosystem health. We present ‘what is known’ about the relationship between
11 urban microbiomes, green infrastructure and environmental factors that may affect urban
12 ecosystem health (ecosystem functionality and resilience as well as human health). We
13 discuss how to start operationalising the MIGI concept based on current available knowledge,
14 and present a horizon scan of emerging and future considerations in research and practice.
15 We conclude by highlighting challenges to the implementation of MIGI and propose a series
16 of workshops to discuss multi-stakeholder needs and opportunities. This article will enable
17 urban landscape managers to incorporate initial considerations for the microbiome in their
18 development projects to promote human and ecosystem health. However, overcoming the
19 challenges to operationalising MIGI will be essential to furthering its practical development.
20 Although the research is in its infancy, there is considerable potential for MIGI to help
21 deliver sustainable urban development driven by considerations for reciprocal relations
22 between humans and the foundations of our ecosystems — the microorganisms.

23

24

25 **1. Introduction**

26 Microbial communities play vital roles in ecosystem processes and provisions including
27 carbon and nutrient cycling, climate regulation, animal and plant health, and global food
28 security ^{1,2} (Cavicchioli et al. 2019; Guerra et al. 2020). The ongoing degradation of, and
29 climate-associated changes in microbial communities (structure, complexity and
30 composition) pose a considerable threat to global macro-level biodiversity across the planet
31 ^{3,4,5} (Bach et al. 2020; Greenspan et al. 2020; Tibbett et al. 2020). In parallel with these
32 environmental concerns, noncommunicable diseases (chronic non-infectious diseases) are on
33 the rise ^{6,7} (Smith et al. 2014; Jairath et al. 2020). For example, in recent decades the
34 prevalence of asthma ^{8,9} (El-Gamal et al. 2017; Borna et al. 2019), diabetes ¹⁰ (Holman et al.
35 2010), allergic rhinoconjunctivitis ¹¹ (Kainu et al. 2013), and autoimmune disorders ^{12,13}
36 (Dinse et al. 2020; Paramasivan et al. 2020) has increased worldwide. Growing evidence
37 suggests that the global trends of ecosystem degradation, urbanisation, and noncommunicable
38 diseases are deeply interconnected ¹⁴ (Haahtela, 2019).

39

40 Exposure to diverse environmental microbiomes—the complex network of microorganisms
41 in a given environment—is thought to play an important role in human health ^{15,16} (Rook,
42 2013; Roslund et al. 2020). Environmental microorganisms support the development and
43 regulation of the human immune system ^{16,17} (Renz and Skevani, 2020; Roslund et al. 2020).
44 Evidence has shown that degraded habitats may harbour a greater relative abundance and
45 diversity of opportunistic human pathogens, and ecological restoration may restore health-
46 regulating assemblages ^{18,19} (Liddicoat et al. 2019; Robinson et al. 2020a). Moreover,
47 microbial exposure in urban green/blue spaces could improve our health but may depend
48 heavily upon environmental and design factors including vertical stratification (layering of
49 microbes in the near-surface atmosphere), vegetation presence, complexity and management

50 ^{16,20} (Robinson et al. 2020b; Roslund et al. 2020), airflow, and soil management. However,
51 with appropriate restoration, design and management strategies, these factors could be
52 optimised to create healthy urban ecosystems, to benefit both human and environmental
53 health.

54

55 Ensuring long-term urban ecosystem resilience to environmental challenges will depend on
56 our ability to restore and manage the landscape with considerations for the unseen
57 foundations of our ecosystems — the microorganisms. Complex microbial interactions are
58 involved in maintaining the health of urban plant and animal populations ²¹ (Berg et al.
59 2017). Considering these microbial interactions as part of any long-term urban development
60 vision will be essential to ensure urban ecosystems can flourish and maintain resilience.

61 However, there are currently few considerations for the role of microbial communities in
62 urban development and landscape design, and multispecies frameworks are rarely used to
63 inform the management of urban ecosystems. Indeed, recognising its importance in
64 sustainability, the recently proposed ‘multispecies urbanism’ concept puts forward a
65 framework for urban development, driven by considerations for reciprocal relationships
66 between humans and non-humans (including microbes) ^{22,23} (Rupprecht et al. 2020; Sharma
67 et al. 2021).

68

69 Sharing similar principles to multispecies urbanism, Microbiome-Inspired Green
70 Infrastructure, also known as ‘MIGI’, was recently proposed as an integrative system to
71 promote healthy urban ecosystems ^{24,25} (Robinson et al. 2018; Watkins et al. 2020). MIGI can
72 be defined as nature-centric infrastructure that is restored and/or designed and managed to
73 promote interactions between humans and environmental microbiomes, with explicit
74 considerations for sustaining microbially-mediated ecosystem functionality and resilience. A

75 considerable challenge to operationalising MIGI is a lack of awareness of the imperative for
76 urban microbiome research, and the translation of existing research into intelligible and
77 practicable outputs. Another challenge is addressing the complex needs and constraints of
78 multiple stakeholders involved in urban landscape management ²⁶ (Marzano et al. 2021).

79

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

87

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

93

94 **2. MIGI: the relationship between environmental microbiomes,** 95 **ecosystem functionality, and human health**

96

97 *2.1. Ecosystem functionality and resilience context*

98 Microbial communities can be considered the foundations of our ecosystems ¹ (Cavicchioli et
99 al. 2019) (Fig. 1). Soil-microbe-plant interaction studies have demonstrated that plants rely

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

113

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

122

123 ***2.2. Human health context***

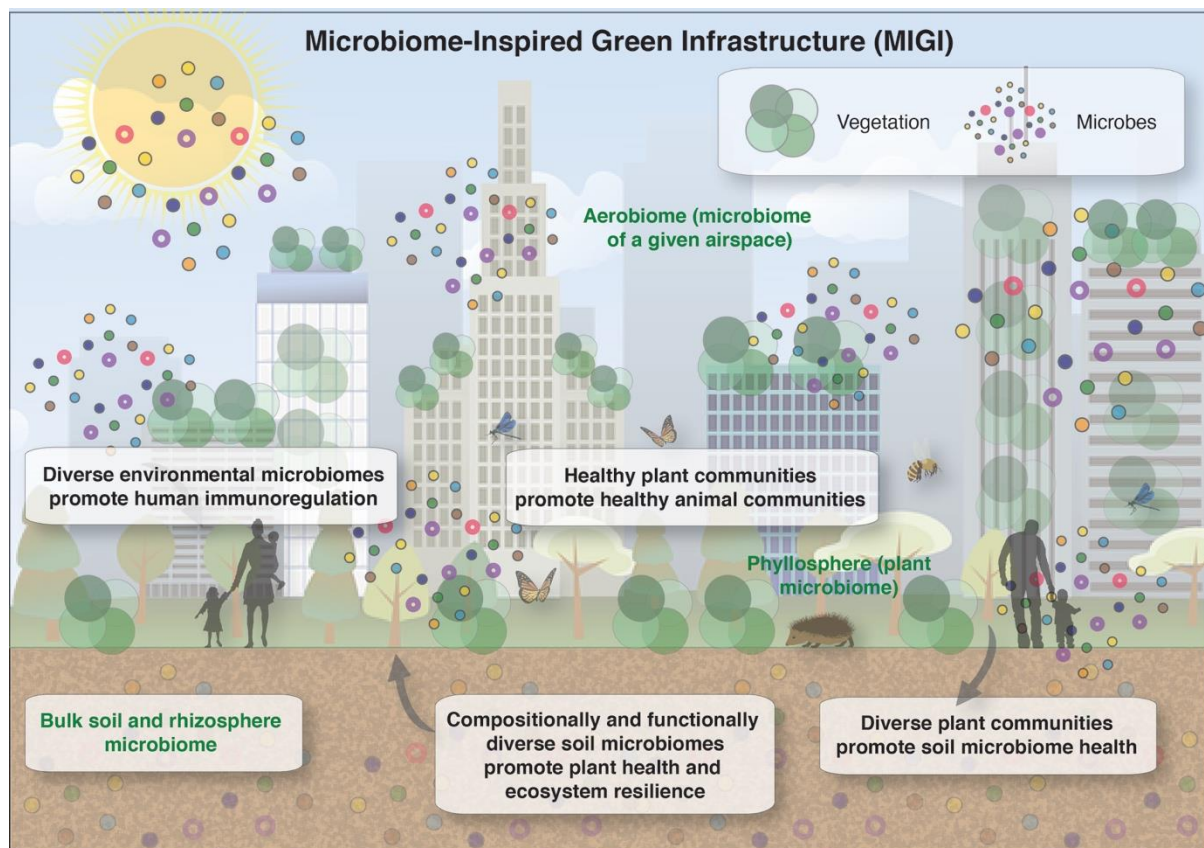
124 Growing evidence suggests that exposure to naturally-diverse environmental microbiomes
125 can improve human health. For example, studies highlight the importance of green space
126 microbiomes to immunoregulation (Fig. 1). Lehtimäki et al. (2021) showed that risks of
127 asthma and aeroallergen sensitisation are reduced in rural infants due to exposure to more
128 biodiverse microbiomes (compared to urban)³⁴, and Riskumäki et al. (2021) identified
129 several environmental taxa that are important in augmenting and/or suppressing systemic
130 inflammatory immune responses³⁵. A loss of biodiversity in urban areas reduces exposure to
131 diverse environmental microbiomes, whilst increasing exposure to pathogenic microbes³⁶
132 (Parajuli et al. 2018). This is corroborated by a review investigating rural vs. urban
133 environmental aerobiomes (microbiome of a given airspace) that showed rural-mediated
134 beneficial immune responses³⁷ (Flies et al. 2020). Recently, a 28-day biodiversity
135 intervention demonstrated that inoculating a schoolyard environment with biodiverse features
136 (e.g., soil and plants from local forest habitats) significantly altered the microbiome of the
137 children and enhanced important immunoregulatory pathways¹⁶ (Roslund et al. 2020).

138

139 Other studies indicate the importance of butyrate-producing bacteria which may be promoted
140 in biodiverse plant-soil systems^{18,38} (Liddicoat et al. 2020; Brame et al. 2021), for example
141 where organic-rich soils experience low redox conditions consistent with fermentative
142 decomposition of organic matter. Butyrate is a short chain fatty acid associated with gut
143 health, immunoregulation, and mental health, and exposure to trace level dust containing the
144 putative spore-forming butyrate-producing bacteria *Kineothrix alysoides* is linked to reduced
145 anxiety-like behaviour in mice¹⁸ (Liddicoat et al. 2020). Another recent study showed that
146 spending a short period of time in green spaces can significantly change the human nasal and
147 respiratory microbiome³⁹ (Selway et al. 2020). Indeed, microbiota-mediated environmental
148 health can be thought of as two layers of protective biodiversity⁴⁰ (Ruokolainen et al 2017).

149 The first layer, our personal microbiome, is key to health. The second layer, the
 150 environmental microbiome, represents an important source for replenishing the first;
 151 therefore safeguarding it represents a critical health insurance policy. It is also important to
 152 note that a plethora of other potential health benefits are associated with engaging with urban
 153 nature, including reduced blood pressure ⁴¹ (Ideno et al. 2017), lower levels of stress, anxiety
 154 ^{42,43} (Birch et al. 2020a; Robinson et al. 2021) and increasing positive affect ⁴⁴ (Cameron et
 155 al. 2020).

156



158 **Fig. 1.** Urban multispecies health. Environmental microbiomes are the foundations of our
 159 ecosystems, and are essential to plant and animal health (including humans).
 160

161 3. MIGI: actionable insights for landscape managers

162 3.1. Vegetation, microbiomes, and the built environment

163 To operationalise the MIGI framework, we can draw upon several relevant studies. For
164 example, one important factor is to ensure humans (and other species) are exposed to high
165 microbial alpha diversity associated with naturally-biodiverse environments from a young
166 age, which is important for immunoregulation ^{45,46} (Mulder et al. 2011; Zhang et al. 2020). It
167 has been demonstrated that air samples downwind from biodiverse sources (e.g., species-rich
168 plant communities) contain more diverse microbial communities compared to upwind, with
169 ~50% of airborne bacteria in downwind samples deriving from local plant sources ⁴⁶
170 (Lymperopoulou et al. 2016). Therefore, a relatively simple intervention for urban designers
171 could be to develop public spaces and buildings downwind from (macro)biodiverse sources,
172 and to integrate local biodiverse sources within building structures and spaces (Fig. 2, a).
173 Recently, it was shown that urban green space aerobiomes are vertically stratified, with an
174 altitudinal decay in bacterial alpha diversity, and possibly a higher relative abundance of
175 pathogenic taxa at higher altitudes ¹⁹ (Robinson et al. 2020a). This reflects a transition from
176 local plant and soil-related microbiomes at low heights into a broader urban (typically non-
177 green space) airshed ²⁰ (Robinson et al. 2020b). A potential mitigation measure for this could
178 be to augment vertical planting in urban areas, allowing exposure to higher natural microbial
179 alpha diversity in the vertical dimension (Fig. 2, b). It would also be prudent to design urban
180 areas with greater consideration for inclusive and direct ‘hands-on’ human engagement with
181 natural features to promote interactions between humans and diverse environmental
182 microbiomes, and to foster long-term pro-ecological behaviours (Fig 2. c).
183
184 Mills et al. (2020) provided evidence that revegetation, particularly with native species, can
185 improve urban soil microbiome functional diversity ⁴⁷. Other studies show that diverse
186 vegetation communities promote below-ground functional richness, diversity and resilience
187 ^{48,49} (Eisenhauer et al. 2018; Canals et al. 2019). Promoting diversity of local vegetation

188 communities is considered a robust strategy to maintain multifunctional processes under
189 current and future environmental conditions⁴⁸ (Eisenhauer et al. 2018). As such, MIGI
190 strategies could include the planting of diverse, and where possible, native, vegetation
191 communities to sustain urban ecosystem functionality and resilience (Fig. 2, e). However, it
192 is not yet clear to what extent locally native plant populations will be able to tolerate future
193 climate conditions. Studies on woody plants offer conflicting views, with some research
194 suggesting that intra-population genetic variation may provide sufficient resilience⁵⁰ (Borrell
195 et al., 2018), whilst others argue that given the range in possible climate futures, including
196 species beyond those that are locally native will be essential in urban environments^{51,52}
197 (Sjöman et al., 2016; Cameron & Blanusa, 2016). As such, further research is required to
198 understand the relationships between locally-native microbial populations and non-local/non-
199 native plant species, including outcomes for stress tolerance, nutrient acquisition, and
200 reproduction.

201

202 MIGI strategies should also include the promotion of urban-rural habitat connectivity via
203 contiguous vertical and horizontal natural corridors (Fig. 3, f). Many urban environments are
204 ‘patchy’ in terms of quality and connected nature-centric features. To ensure long-term
205 healthy urban ecosystems, we should aim to connect all natural habitats within towns/cities
206 and provide essential biophysical corridors to the wider landscape. This action has high
207 biodiversity conservation value by providing multispecies resources and improving species
208 interactions and long-term resilience across the landscape, irrespective of species dispersal
209 abilities or population sizes⁵³ (Christie and Knowles, 2015). Enhancing networks of
210 biologically and functionally diverse urban habitats with high vegetation complexity, also has
211 the potential to improve the distribution of quality aerobiomes, and augment diverse

212 macroscopic species (animals and plants) that contribute to the collective urban
213 environmental microbiome, and broader ecosystem complexity and resilience.

214

215 ***3.2. Soil microbiomes***

216 Soil properties will have a key influence on environmental microbiomes associated with
217 MIGI developments. Soil organic matter and clay-content (proportion of clay-sized particles)
218 are associated with structure, aggregation, nutrient and water-holding properties, and
219 therefore the habitat and diversity of microbes^{54,55,56} (Jastrow and Miller, 1998; Young and
220 Crawford, 2004; Torsvik and Øvreås, 2002). A key decision during the establishment phase
221 of MIGI will be whether to use in-situ or imported soils. Where feasible, using soils with a
222 moderate amount of clay-content, e.g. sandy loams (10-20% clay content) to loams (around
223 25% clay content) would be expected to promote microbial diversity. By comparison, sandy
224 soils provide suboptimal microbial habitat, while heavier texture clay soils (often capable of
225 forming suitable aggregation and structure) may be more prone to poorer drainage in wet
226 climates, or greater plant stress in dry climates or during dry periods due to higher wilting-
227 point moisture content (where water is unavailable to plants). Whether using existing in-situ
228 soils, or importing new bulk soil, it may be necessary to examine constraints to plant growth.
229 Sometimes these constraints will be naturally occurring (e.g. shallow depth, impermeable
230 layers, presence of toxic or nutrient-limiting subsoil conditions), while other times they can
231 result from management history (e.g. compaction, acidification).

232

233 Where appropriate, addressing soil constraints will help optimise the biological activity and
234 microbial diversity of the plant-soil system. If organic matter is being applied, ideally this
235 should be in a nutrient-balanced, or pre-composted form, so that microbial activity and
236 available nutrients can be harnessed to support the growing vegetation. Ongoing management

237 and human interaction should also be considered. For example, high levels of foot/vehicle
238 traffic can lead to compaction and degradation, and may create zones of poor soil
239 microbiome conditions with sub-optimal health influence (e.g. along paths) within a natural
240 space that is offering health-promoting microbial exposures. Exposure pathways to permit
241 beneficial human-soil microbiome contact also remains an area for research. Based on
242 available knowledge, low-level exposure to soil (e.g. dust) with biodiverse content to help
243 contain potential pathogenic activity, would represent a reasonable starting point to
244 supporting immune fitness. It is also expected that soils will gain maximum health-promoting
245 potential by spending the majority of time covered with biodiverse vegetation, which is
246 another consideration for designing MIGI exposure pathways.

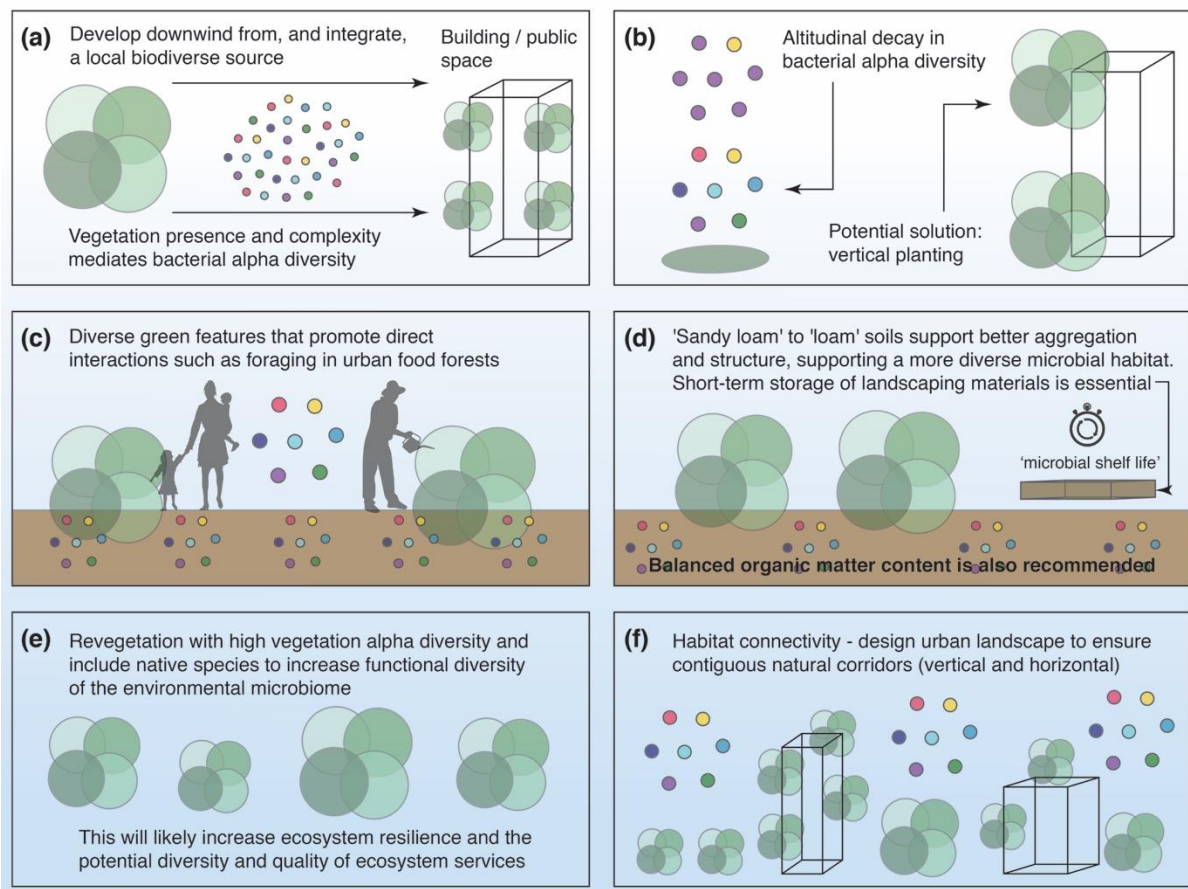
247

248 There is also growing evidence to show that plant communities require complex mycorrhizal
249 networks, acting as conduits of inter-plant communication, and facilitating pathogen defence,
250 adaptation, growth, and memory^{57,58} (Filotas et al. 2014; Birch et al. 2020). Indeed, healthy
251 vegetation community phenotypes at higher levels emerge from a multitude of localised and
252 often subterranean entities interacting at lower levels⁵⁹ (Ibarra et al. 2020). For example,
253 Birch et al. (2020) recently demonstrated that plant growth was significantly associated with
254 the number of ectomycorrhizal connections to other plants, and the number of genetically
255 distinct fungi that were present⁵⁸. Therefore, we must at least consider the condition and
256 ecology of the substrate and its role in sustaining ecosystem functionality and resilience. This
257 will involve viewing habitat conservation and restoration through the lens of complex
258 systems science. However, many experts in this field could provide appropriate consultation
259 at each stage of a development project²⁵ (Watkins et al. 2020).

260

261 Interestingly, a recent study showed that landscaping materials (e.g. compost and mulch)
 262 have a ‘microbial shelf life’, and long-term storage can significantly reduce the availability of
 263 bacterial taxa linked to human health and degradation of pollution⁶⁰ (Soininen et al. 2021).
 264 This suggests that as part of a holistic MIGI strategy, short-term storage times should be
 265 considered when planning the utilisation of landscaping materials (Fig. 2, d).

266



267

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

275

276

277 4. MIGI: Horizon scan of emerging research and practice

278 **4.1. Bioreceptive materials and bio-integrated design**

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

288

289 Whilst horizontal surfaces including roofs, terraces or pavements offer scope for plant
290 growth, vertical surfaces (e.g. building facades and infrastructural walls) offer far harsher
291 environments due to excessive water run-off, strong exposure to winds and lack of nutrient
292 rich substrates. But cities have vast areas of xeric surfaces that offer opportunities to be
293 photosynthetically active. For an accelerated creation of primary bioreceptivity on vertical
294 surfaces, a number of design steps can accelerate this process. Porosity and surface roughness
295 are two vital functions. Firstly, the calibration of pore size can enable water absorption and
296 retention, reaching colonising organisms through capillary or surface-binding effects, and
297 secondly as a means to exploit extrinsic factors for bioreceptivity through the collection of
298 organic material and fixation of cryptogamic surface cover. Different compositions of
299 bioreceptive cementitious materials have been explored based on Magnesium Phosphate
300 Concrete (Manso et al., 2015) and other Ordinary Portland Concrete (OPC) mixes with the
301 aim to create long-term carbon offset ⁶³. Studies of OPC have shown that apart from altering
302 the physico-chemical properties of materials, morphological variations explored via

303 computational design strategies are a powerful means to reduce water run-off and increase
304 moisture retention, extending the residence time to create zones for accelerated growth ⁶⁴
305 (Cruz, 2021). In future, quaternary bioreceptive strategies may be used ⁶⁵ (Sanmartín et al.,
306 2021) whereby surface additives to a material scaffold such as hydrogels or humic material
307 are applied to enhance colonisation. Further studies are needed to test the role of pH on
308 material substrates in biofilm formation and the establishment of microbial communities
309 which are vital to establish cryptogamic growth.

310

311 Lichens and, primarily bryophytes play key roles in design of bioreceptive structures within
312 architecture, provoking a biophilic response ⁶⁶ (Wilson, 1984) through their aesthetic
313 appearance and tactility. However, they are also important components due to their capacity
314 to regulate their photosynthetic activity depending on moisture availability while surviving
315 for long periods without water - *poikilohydry*. In relation to MIGI, bryophytes harbour
316 ecologies with prokaryotic and eukaryotic algae, bacteria and fungi. Cyanobacteria are
317 keystone species in other nutrient limited environments such as desert crusts ⁶⁷ (Yeager et al.,
318 2007), where their ability to fix nitrogen and carbon enables succession by other organisms
319 through exchange of metabolites. However, our understanding of the exact ecological roles of
320 microorganisms associated with bryophyte hosts is nascent. For example, while the presence
321 of certain bacteria varies according to the bryophyte species, in one study *Proteobacteria*,
322 *Actinobacteria*, *Acidobacteria*, *Bacteroidetes*, *Armatimonadetes* and *Planctomycetes* were
323 detected in all moss microbiomes ⁶⁸ (Tang et al., 2016). Analogous to the urban environment,
324 during early stages of habitat restoration it has been shown that bryophyte communities
325 enrich populations of microbial life on calcareous rocks ⁶⁹ (Cao et al., 2020). It may be
326 speculated that colonisation by bryophytes and their associated microbiota could have
327 advantageous effects for growth promotion in other plants due to the presence of bacteria

328 containing genes for production of indole acetic acid, siderophores or solubilisation of
329 phosphate ⁷⁰ (Insuk et al., 2020). Through this application of bio-integrated design to produce
330 poikilohydric living walls, it is possible to employ more of the surface area that is
331 underutilised within our urban environments to deliver MIGI.

332

333 **4.2. Microbial inoculants**

334 Microbial inoculants have recently been used to shift microbiota in landscaping materials
335 towards an immuno-protective assemblage ⁷¹ (Hui et al. 2019). The authors developed a
336 microbial inoculant from biodiverse sources (e.g., forest materials), resembling the
337 microbiome of organic soils. After the study subjects made contact with these inoculated
338 materials, the relative abundance of opportunist pathogens on the skin significantly
339 decreased. Furthermore, Roslund et al. (2020) demonstrated that a biodiversity intervention
340 using microbial inoculants from forest floor materials changed the skin microbiome of
341 children and enhanced immunoregulatory pathways ¹⁶. Several other studies show that
342 microbial inoculants can be beneficial for plant health, for example, via Plant Growth
343 Promoting Rhizobacteria (PGPR) ⁷² (Sacristán-Pérez-Minayo et al. 2020). PGPRs have the
344 potential to protect plants from drought and metal stresses and play important roles in plant
345 growth, which itself could minimise the use of harmful synthetically produced chemical
346 fertilisers ⁷³ (Kumar et al. 2019). Therefore, MIGI strategies could incorporate microbial
347 inoculants to enhance ecosystem health (Fig. 3, b).

348

349 **4.3. Supportive tools**

350 Useful tools are being developed that could help with MIGI interventions in the near future.
351 For example, Saleem et al. (2019) produced a framework to model the environmental
352 microbiome's influence on plant traits and ecosystem functionality, highlighting the

353 possibility of creating an index to monitor and enhance plant growth and soil/ecosystem
354 health⁷⁴. Along similar lines, it could be valuable to develop a form of 'Health Promotion
355 Potential Index' for human health. This could be based on known combinations of
356 environmental microbial factors that promote (or demote) immunoregulation and
357 homeostasis, such as alpha and functional diversity and beneficial taxa that produce health-
358 regulating compounds (Fig. 3, c).

359

360 **4.4. Bioremediation**

361 Emerging bioremediation research could also be considered in MIGI strategies. In-situ
362 bioremediation enables ongoing decontamination or degradation of pollutants without
363 complex excavation or transportation. This could play a role in sequestering metals such as
364 lead and zinc—present in many cities as components of urban dusts⁷⁵ (Alharbi et al., 2019).
365 Bacteria, fungi and microalgae have evolved several mechanisms to adsorb or absorb heavy
366 metals. In a study investigating river sediments contaminated with cadmium, copper, lead and
367 zinc, it was hypothesised that species richness may be a function of “public goods” within the
368 microbial community, such as metallophores, EPC, biogenic sulphides or calcite. Bacteria
369 such as *Pseudomonas* and *Bacillus* may precipitate metal and thus benefit other organisms
370 with spatial proximity by creating detoxified regions⁷⁶ (Jacquiod et al. 2018).

371

372 Kang et al. (2016) showed that the synergistic combination of bacterial strains including
373 *Viridibacillus arenosi* B-21, *Sporosarcina soli* B-22, *Enterobacter cloacae* KJ-46 and *E.*
374 *cloacae* KJ-47 was effective at sequestering Pb (98.3% effective) and Cd (85.4%) in soils⁷⁷.
375 Biofilters are being developed that embed bacterial biofilms to absorb heavy metal ions
376 (Priyadarshane and Das, 2020)⁷⁸. In terms of MIGI, this kind of strategy could be
377 developed with Sustainable Drainage Systems in mind, e.g., a biofilter-embedded rain garden

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

388

389 ***4.5. Plant nutrition, soil issues, and anti-microbial resistance***

390 It is suspected that high-dosage artificial agricultural fertilisers are detrimental to mycorrhizal
391 networks, for example, by promoting taxa with pathogenic traits ⁸³ (Paungfoo-Lonhienne et
392 al. 2015). Studies have suggested that organic or ‘natural’ fertilisers and plant conditioners
393 outperform chemically synthetic N, P and K types in promoting plant health/quality ^{84,85}
394 (Hammad et al. 2020; Dahunsi et al. 2021). Additional research in this area could bring value
395 to the MIGI concept, particularly research focusing on the application of fertilisers
396 sympathetic to soil-plant microbial interactions. There are also physical soil issues to
397 consider in urban landscape management. The loss of organic matter, compaction, excessive
398 disturbance will likely damage microbial communities ⁸⁶ (Gregory et al. 2015). Research to
399 fully understand the implications of these factors could enhance urban ecosystem
400 management. The loss of soil microbial diversity has also been linked to the exacerbation of
401 the spread of antimicrobial resistance ⁸⁷ (Chen et al. 2019). Antimicrobial resistance has
402 important implications for human health by making infections harder to treat and increasing

403 risks of disease spread ⁸⁸ (WHO, 2020). MIGI researchers aiming to reduce the abundance
404 and diversity of antimicrobial resistant genes in urban environments could explore the
405 strategy of increasing soil microbial diversity.

406

407 ***4.6. Emerging biosecurity considerations***

408 Alongside the positive opportunities presented by a multispecies approach to green
409 infrastructure, the threats need to be equally researched and mitigated against within the
410 MIGI framework. Many of the most pressing biosecurity threats to ecosystems are microbial
411 in nature (in the UK, for example, *Hymenoscyphus fraxineus*, *Phytophthora ramorum* and
412 *Candidatus liberibacter solanacearum*), threatening urban green infrastructure as well as
413 agricultural crops that urban populations depend upon. It is increasingly recognised, however,
414 that most biosecurity research and regulations focus on impacts to agricultural and forestry
415 sectors. Work is urgently required to understand the extent to which urban ecosystems are
416 threatened and what tools are most effective at safeguarding them. Key questions exist at a
417 societal level, concerning the mismatch between public perception of biosecurity risk and
418 expert assessment, the capacity for codes of conduct to influence behaviour and the ability to
419 communicate information between policy makers, researchers and the public. Industry-
420 specific technical questions also exist concerning the risks associated with importing soil for
421 planting, the materials used in packaging for construction projects ⁸⁹ (Kemp et al. 2021), or to
422 what extent novel microbial pests and diseases might influence assisted colonisation
423 programmes or substitutions for keystone species die-off.

424

425 Regulation and guidance exists to combat and mitigate these threats have been developed at
426 international (e.g. European and Mediterranean Plant Protection Organisation ⁹⁰ (EPPO,
427 2020), national (Defra Plant Health Risk Register ⁹¹ (Defra, 2014)) and regional levels ⁹²

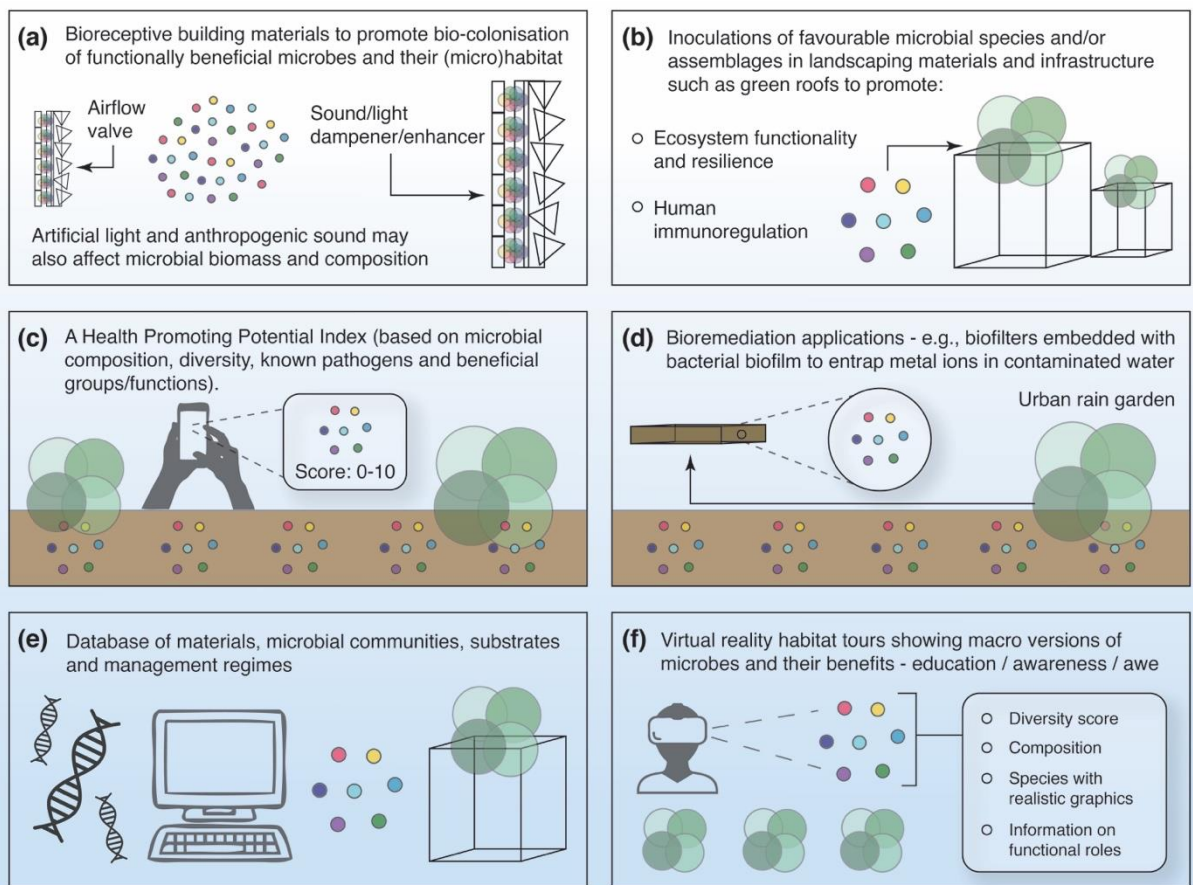
428 (Public Health Agency of Canada, 2018), complemented by industry-specific guidance in
429 many countries⁹³ (Watkins & Arkell, 2019). Nevertheless, further work is required to
430 address the open questions and operationalise policy, and MIGI offers an opportunity to
431 address these in a holistic manner. One of the core challenges presented by biosecurity threats
432 is that the technical understanding of biosecurity in the construction and development
433 industries is currently at an early stage, with many practitioners confusing biosecurity with
434 concepts such as biodiversity, and seeing threats posed by biosecurity risks as someone else's
435 responsibility. Integrating existing schemes such as Plant Healthy
436 (<https://planthealthy.org.uk>) within MIGI will be essential, not only to ensure that best
437 practice is developed but also so that practitioners can clearly understand how their actions
438 reinforce the biosecurity continuum⁹⁴ (Sequeira and Griffin 2014). Biosecurity is one of
439 many layers that prove challenging to translate between research and practice, and to this
440 end, delivering the plant selection database proposed in the MIGI toolkit¹⁹ (Watkins et al.,
441 2020) will provide not only a common understanding of the tools required to deliver MIGI
442 but also a shared vocabulary for different sectors to draw upon when discussing projects.

443

444 ***4.7. Social innovation: promoting stronger human-nature relationships***

445 Other important factors within the MIGI framework include social innovation, education and
446 stimulating awe for nature, with emphasis on the foundations of our ecosystems—the diverse
447 microbial communities. Strategies such as ‘learning about the land, on the land’⁹⁵ (Learning
448 the Land, 2021) could help to inspire pro-ecological behaviours that reinforce a sense of
449 stewardship for our diverse and complex ecosystems. To paraphrase Simard (2018) “*viewing*
450 *[ecosystems] through the lens of cognition, microbiome collaborations, and intelligence may*
451 *contribute to a more holistic approach to studying ecosystems and a greater human empathy*
452 *and caring for the health of our [landscapes]”⁹⁶. Various campaigns also promote the*

453 concept of ‘nature connectedness’ (emotional and cognitive connection with the natural
 454 world). Studies in this area show increases in wellbeing and pro-ecological behaviour as a
 455 result of enhanced nature connectedness^{97,98} (Capaldi et al. 2014; Capaldi et al. 2015).
 456
 457 For the technologically-minded, virtual reality systems could be developed to facilitate urban
 458 habitat tours. These could include interactive macroscopic displays of microbial
 459 communities, whilst providing information on the composition and functional roles that
 460 microbes play in the local ecosystems (Fig. 3, f).
 461



462
 463 **Fig. 3.** Horizon scan of developmental considerations for MIGI, including interventions (b
 464 and d), design and supportive features (a and e), and applications for engagement and to
 465 acquire useful urban ecosystem health information (c and f).
 466

467

468 5. MIGI: Challenges to operationalisation

469 Watkins et al. (2020) identify barriers to operationalising MIGI, relating to the complexity of
470 urban development projects, and communicating the benefits of MIGI interventions to
471 stakeholders involved in urban planning ¹⁹. To ensure the implementation of green
472 infrastructure strategies, stakeholder buy-in is required throughout green infrastructure
473 planning, design, operation and management ⁹⁹ (Smith, 2020). The range of stakeholders
474 include: local authorities, developers and private clients, planning professionals, landowners,
475 landscape specialists, architects, ecologists, statutory agencies, contractors, local businesses
476 and community groups. In the UK, there are a number of government-funded research
477 projects into green infrastructure, biosecurity, climate change-readiness, and supply chains
478 (e.g. BRIGIT, Future Oak, Plant Health Centre). Learning from these projects is prudent as
479 there is already evidence of stakeholder fatigue and pre-existing challenges of engaging with
480 industry sectors that see these aspects as someone else's problem or not aligned with
481 commercial goals. This suggests new approaches are needed and highlights the importance of
482 internationalising research projects so that robust data can be gathered from diverse
483 stakeholders.

484

485 Although fundamental, adding the lens of microbial ecology to an already expansive multi-
486 stakeholder initiative, MIGI has to reckon with the “perception that multi-stakeholder
487 initiatives slow down urban planning and policy development processes due to a lack of
488 consensus and different sectoral interests” ¹⁰⁰ (Ferreira et al. 2020). Further development
489 should align with the priorities of the stakeholder groups and generate clear, actionable points
490 overlaid onto existing frameworks, rather than increasing complexity. For instance, in the
491 UK, some MIGI considerations overlap with the policies laid out in the London Plan 2021.
492 The focus on connected landscapes and biodiversity corridors supports the value of
493 connected nature-centric features. Policy G5 Urban Greening asks that new developments

494 incorporate high quality landscaping, green roofs, green walls and nature-based sustainable
495 drainage and introduces an Urban Greening Factor to evaluate the quality and quantity of
496 green space design and delivery ¹⁰¹ (Greater London Authority, 2021). This guidance is
497 currently under consultation and could benefit from MIGI-related input to aid with the
498 ambition of delivering biodiversity net gain. Overlaps could be identified through direct
499 communication with existing built environment biodiversity-centric networks.

500

501 **6. MIGI: Workshop series proposal**

502 To determine clear action points for future research and address the challenges related to
503 divergence of interests among stakeholders, it is vital to ascertain diverse priorities and
504 concerns through early consultation ¹⁰² (Khoshkar et al. 2017). This could also aid the
505 development of a “common language” ¹⁰³ (Ugolini et al. 2018) that translates researchers’
506 findings into verbal and graphic outputs relevant to non-expert audiences. We are currently
507 developing a series of workshops to discuss what is known about the microbiome in a health
508 and ecosystem functionality context, and reveal tangible opportunities to include MIGI in
509 urban planning. These workshops provide an opportunity to engage with reflective
510 stakeholders in identifying not only challenges but also specific factors (e.g. MIGI toolkits,
511 portfolio of illustrative examples) and alignments between current requirements/protocols,
512 and how MIGI could be integrated. During the workshops we will discuss ‘what researchers
513 should be working on’, and opportunities and constraints by drawing together the
514 perspectives and needs of different stakeholders. These workshops will form part of a process
515 of long-term engagement and partnership to enhance urban ecosystem health via MIGI
516 strategies.

517

518 Developing the MIGI concept has the potential to enhance urban ecosystem functionality and
519 resilience as well as human health. In this paper, we have provided several examples of MIGI
520 actionable insights in addition to a horizon scan of emerging MIGI-related research and
521 practice. A greater emphasis on the roles of microbial communities (from below-ground and
522 up) in our urban ecosystems is needed. Understanding microbial dynamics will likely have an
523 important role to play in the efficacy of our adaptability and long-term resilience to ongoing
524 global environmental change. MIGI research agendas aim to promote this realm of thinking
525 with considerations for multispecies health. However, overcoming the challenges to
526 operationalising MIGI will be essential to furthering its practical development.

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870

871 **Figure captions**

872

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

875

876 **Fig. 2.** Actionable insights for MIGI, including vegetation complexity, downwind
877 development and local integration of biodiverse source (a); a solution to the concept of
878 vertical stratification (b); hands-on engagement with natural features to promote
879 immunoregulation (c); recommended soil types to promote diverse microbial habitat and
880 short-term storage of landscaping materials (d); revegetation with diverse native plants to

881 promote functional diversity (e); the concept of habitat connectivity via contiguous natural
882 corridors to promote long-term multispecies health (f).

883

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