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PERSPECTIVE

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Rekindling old friendships in new landscapes: The environment–microbiome–health axis in the realms of landscape research

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Abstract

1. Humans are spending less time in biodiverse environments, and according to the Old Friends and Biodiversity hypotheses, this has led to fewer interactions with diverse immunoregulatory micro-organisms or 'old friends'.
2. Non-communicable diseases such as asthma and inflammatory bowel disease are on the rise, and the development and progression of these 'modern' diseases may be attributed in part, to the breakdown of this evolutionary relationship between humans and environmental microbiota.
3. There is a growing interest in the environment–microbiome–health axis as a mechanism to explain some of the health benefits linked to spending time in nature.
4. This may provide a platform for proposing a new, holistic and transdisciplinary approach to public and environmental health.
5. The field of landscape research—which combines social and natural sciences—responds to emerging socioecological issues and can make a significant contribution towards this approach.
6. This paper explores innovative, landscape research-based approaches to understanding the complex relationships between the environment, the microbiome and human health.
7. Transdisciplinarity will play an important role moving forward. This forms a major discussion point in this paper, along with future research directions, key research questions and novel concepts supported by recent technological advancements.
8. The development of a new field of study—*Microbioscape Research* as a crossover between microbiome science and landscape research—is also discussed.

KEYWORDS

biodiversity hypothesis, environmental microbiome, greenspace, landscape research, microbiome, microbiome-inspired green infrastructure, non-communicable disease, Old Friends hypothesis

1 | INTRODUCTION

The Old Friends hypothesis (Rook, Martinelli, & Brunet, 2003), a revision of the Hygiene hypothesis (Strachan, 1989), puts forward a mechanism to explain the rise in immunological dysfunction and allergic disorders in highly urbanized populations. The hypothesis is based on the premise that humans have co-evolved with a diversity of microbiota (or 'old friends') in biodiverse environments, and this relationship was essential to the evolution of resilient immune systems (Rook & Brunet, 2005; Rook, Raison, & Lowry, 2014). The hypothesis supports the relatively recent view that humans are 'holobionts'—that is, a host plus trillions of micro-organisms working symbiotically to form a functional ecological unit (Robinson, Mills, & Breed, 2018; Salvucci, 2016). There is an increasing body of evidence pointing to the involvement of the microbiome (the collection of micro-organisms and their genetic material in a given environment) in the health and well-being of humans—for example, in processes such as emotional regulation, nutrient processing and the modulation of inflammatory diseases (Bicknell, Liebert, Johnstone, & Kiat, 2019; Koppel, Maini Rekdal, & Balskus, 2017; Schirmer et al., 2016; Thomas et al., 2017).

Several authors have suggested that a diverse microbiome plays an important role in the maintenance of favourable health (Flies et al., 2017; Gibbons, 2019; Heiman & Greenway, 2016; World Health Organization, 2015). This has parallels with broader ecological observations that suggest ecosystems with higher biodiversity can be more stable and resilient (Lohbeck, Bongers, Martinez-Ramos, & Poorter, 2016; Mori, Furukawa, & Sasaki, 2013; Ptacnik et al., 2008; Tilman, Reich, & Knops, 2006). However, it is important to note that fragile ecosystems can also be attributed to functional relationship failures and other factors (Dobson et al., 2006; Donohue et al., 2017).

It has recently been argued that reduced contact with micro-organisms from biodiverse environments (Haahtela et al., 2013), along with increases in stressors associated with urbanized lifestyles (e.g. antibiotic overuse, exposure to pollution and poor nutritional intake), has led to a 'dysbiotic drift' (Logan, 2015). Indeed, *dysbiosis* or 'life in distress' is considered by some researchers to manifest as an imbalance in the microbial assemblages in the human body to a state that is detrimental to health (Logan, Jacka, & Prescott, 2016; Schepper et al., 2017; Sokol et al., 2019). However, it is important to note that the complexities of characterizing 'dysbiotic' patterns are considerable and the concept remains controversial.

Since the advent of Germ theory (*c.* 1860s), a strong focus has been on the negative impacts of pathogenic micro-organisms, and the potentially vital role that symbiotic environmental micro-organisms play in regulating our health has been neglected. This historic approach to public health (and to micro-organisms) may have inadvertently contributed to an epidemiological transition, characterized by the current rise in non-communicable diseases (NCDs; Flandroy et al., 2018; Rook et al., 2014). Furthermore, it is suggested that urbanization perpetuates the spread of emerging pathogens, for example, through antimicrobial resistance, land-use change and overcrowded populations (Ayukekbong, Ntemgwa, & Atabe, 2017; Hassell, Begon, Ward, & Fèvre, 2017). Alongside these theories, it is important to acknowledge other aetiological models that take into account the dynamic complexities of social phenomena (e.g. housing and education) such as the social determinants of health and the developmental origins of health and disease—which recognize the importance of the microbiome and other exposures across the life-course (Haugen, Schug, Collman, & Heindel, 2015; Taylor et al., 2016).

The renewed interest in the microbiome—and more broadly, the exposome, that is, the measure of all exposures throughout the life-course—provides a platform for proposing a new, more holistic and transdisciplinary approach to public health. Consequently, it is important to work across disciplines with the aim of uncovering the mechanisms at play in the environment–microbiome–health axis (the relationship between the environment, the microbiome and the health of humans). Recent calls have been made to initiate this via concerted, widespread, interdisciplinary research (Flies et al., 2017). For example, Mills et al. (2017) propose the Microbiome Rewilding hypothesis, which calls for researchers to understand whether 'rewilding' biodiversity (including environmental microbiota) in urban environments could benefit public health while promoting resilient ecosystems. In this paper, we extend these broader calls to landscape research.

Landscape is 'an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors' (European Landscape Convention, 2019, p. 2). Landscape research is well established as a transdisciplinary field of study that addresses a range of social and environmental challenges (Swaffield & Deming, 2011; Vicenzotti, Jorgensen, Qviström, & Swaffield, 2016). In particular, landscape research deals with the cultural, social, ecological and spatial factors that shape urban areas and promote interactions with green and blue spaces (semi-natural terrestrial or aquatic environments). As an integrative field of study, landscape research offers landscape literacy: the ability to 'read' and interpret the cultural, social, spatial and material aspects of place. This includes a strong understanding of how to plan, design and manage urban places. In this paper, we argue that landscape research can make an important contribution towards rekindling the 'old friendships' between humans, biodiverse environments and microbiota.

An interdisciplinary framework is used to consider future environmental microbiome research and practice and to propose a new field of study—*Microbioscape Research*. This proposal reflects a new way of thinking about the characterization and visualization of the environmental microbiome and its relationship with people and nature. Although the methodology for this approach stems from a traditional materialist ontology, it could also be applied to incorporate other perspectives such as new materialism (perspectives that re-think subjectivity, question anthropocentrism and emphasize the materiality of both the natural and sociospheres; Connolly, 2013; Fox & Alldred, 2016).

The discussions within this paper are divided into three themes. The process of selecting these themes was informed by past reviews of landscape research, highlighting the diversity and evolution of this interdisciplinary field (Powers & Walker, 2009; Vicenzotti et al., 2016). This is not an exhaustive list; however, each theme was identified as being highly relevant to the environment–microbiome–health axis.

The three themes are as follows:

1. *Human and Environmental Relationships* (landscape usage and meaning, health and well-being);
2. *Landscape Planning and Ecology* (planning, surveys and ecological design); and
3. *Communication and Visualizations* (mapping, modelling and visualization).

2 | THEME 1: HUMAN AND ENVIRONMENTAL RELATIONSHIPS

Health intervention discourse is active and growing in landscape research (Ernstson, 2013; Vicenzotti et al., 2016). This reflects an evolving framework that addresses emerging social challenges, including changes in human health and well-being. A robust understanding of socioecological dynamics is required to discern the complexities of the human–environment–health relationship. These qualities are present in the landscape research discipline and are arguably transferable to environment–microbiome–health axis research. Environmental justice and nature-based interventions (discussed in the following subsections) have strong socioecological foci, and could provide useful lenses to study the environmental–microbiome–health axis.

2.1 | Environmental justice

One aspect of environmental justice is the consideration for the basic needs of communities in terms of equity of natural resources (Schlosberg, 2013). This is an issue with far-reaching implications for the human–environment relationship. It is recognized as playing a central role in the 'upstream determinants of health' (Prescott & Logan, 2016). A prime example of environmental *injustice* is the disparity in the quality and accessibility of urban greenspaces (Rutt & Gulsrud, 2016). Indeed, several studies have revealed that urban greenspace distribution can disproportionately favour particular social groups—for example, those with a higher socioeconomic status and those from white ethnic backgrounds (Wolch, Byrne, & Newell, 2014; Wüstemann, Kalisch, & Kolbe, 2017). Other studies suggest that it is not necessarily greenspace distribution or spatial proximity, but quality, composition and access that differ between areas of higher and lower deprivation (Jones, Hillsdon, & Coombes, 2009; Mears, Brindley, Maheswaran, & Jorgensen, 2019; Roe, Aspinall, & Ward Thompson, 2016). Therefore, some urban groups and individuals may also be less exposed to diverse microbiota of natural environments due to distribution, access, composition and/or quality issues. As such, the potential health benefits associated with environmental microbiome exposure may also be unequally distributed.

People with lower socioeconomic status tend to eat higher proportions of ultra-processed foods and may face additional barriers to accessing affordable fruit and vegetables (Moran, Khandpur, Polacsek, & Rimm, 2019; Schnabel et al., 2019). Growing evidence suggests that this has detrimental effects on health, and associated changes in the microbiome may be involved (Zinöcker & Lindseth, 2018). Therefore, a lack of access to quality greenspaces may further impoverish the human microbiome and increase health inequalities. As the diet can have a substantial and rapid influence on the gut microbiome (David et al., 2014; Zhang, Ju, & Zuo, 2018), it could be beneficial to increase opportunities for people to get involved in growing healthy foods and harvesting activities that promote contact with diverse microbiota in natural environments, for example, in community gardens.

Furthermore, it is important to consider environmental justice in the context of pathogenic microbiota: for example, do certain environments contain higher proportions of non-beneficial assemblages? Liddicoat et al. (2019) found that disturbed land may favour opportunistic bacteria (including pathogenic strains), albeit in a non-urban setting, and Talamantes, Behseta, and Zender (2007) found anthropogenically disturbed land can release pathogenic fungal spores. Moreover, densely urbanized environments can prevent the transfer of diverse microbiota indoors (Parajuli et al., 2018), and indoor environments can harbour higher proportions of human associated pathogens (Kembel et al., 2012). As such, creating socially inclusive, high-quality biodiverse greenspaces may also help to reduce contact with pathogens.

It has been suggested that spatial proximity to greenspaces and associated microbiota may play an important role in NCDs. For example, Ruokolainen et al. (2015) showed that greenspace proximity was inversely associated with atopic sensitization in children, and surrounding land-use explained variations in commensal skin microbiota. Similar conclusions were reached by Hanski et al. (2012), who demonstrated significant associations between surrounding biodiversity, residents with allergic dispositions and diversity of gammaproteobacteria. They found residents living with higher surrounding biodiversity supported a higher diversity of immunoregulatory gammaproteobacteria. Therefore, establishing equity in the provision of high-quality and biodiverse greenspaces could play an important role in the process of optimizing interactions with beneficial microbiota.

It is important to note that there is still a dearth of evidence to demonstrate microbiome plasticity in later life. Ruggles et al. (2018) provided evidence for stability in the adult human gut microbiome in the face of environmental disturbance (e.g. human translocation to different habitats and dietary changes). This apparent ecological stability in the adult gut microbiome is corroborated in previous studies (Faith et al., 2013; Rodríguez et al., 2015). However, several authors now suggest that the gut microbiome in adults may be more plastic than previously thought. For example, Martinson et al. (2019) recently provided evidence for plasticity of the bacterial family Enterobacteriaceae in the adult human gut microbiome, and Schmidt et al. (2019) challenged the notion of an oral-gut barrier by showing that one in three microbial cells from the oral environment passes through the digestive tract to settle and 'constantly replenish' the gut of healthy humans. As such, additional research focusing on the timing, magnitude and stability (and transmission routes) of environmental microbiome effects on post-infant human health is required.

Environmental justice could be a useful lens for landscape researchers and others to study place and inclusion, understand social and ecological trade-offs, and promote equitable distribution of biodiverse urban greenspaces with strategic considerations for the role of the microbiome. Another useful lens could be nature-based interventions.

2.2 | Nature-based interventions for health and well-being

Building on a rich foundation of nature and human health research (De Vries, Verheij, Groenewegen, & Spreeuwenberg, 2003; Groenewegen, Van den Berg, Vries, & Verheij, 2006; Takano, Nakamura, & Watanabe, 2002), improving the health and well-being of communities through landscape interventions is another area that has received widespread attention. This is a fundamental topic in the *Human–Environment Relationship* theme. For example, the 'social prescribing' movement, which connects patients in primary care with a range of non-clinical services in the local community, takes a holistic approach to address the complex needs of people, often through landscape and community-focused interventions (Bragg & Atkins, 2016; Kings Fund, 2018). Furthermore, there is a continued interest in the role of nature-based health interventions (a subset of social prescribing) as a means of enhancing human health through interactions with natural environments (Bloomfield, 2017; Bragg & Atkins, 2016; Burls, 2007; Maller, Townsend, Pryor, Brown, & St Leger, 2006). Interactions with natural environments include interactions with a range of microbial communities, but the potential beneficial impacts on health have received limited attention. However, our growing understanding of the relationship between the microbiome and human health makes this topic highly relevant. Furthermore, advances in microbiome science offer opportunities to consider human and environmental microbial interactions as part of nature-based intervention research.

There is also an opportunity to address interconnected human–environment relationship issues such as ecosystem resilience and public health, with explicit considerations for the environment–microbiome–health axis through integrative strategies. Raymond et al. (2017) outline a 'co-benefits' framework for promoting nature-based solutions with the aim of generating benefits for humans and the environment (Figure 1). Furthermore, the need for integrative strategies is highlighted by the *planetary health* conceptual framework, which is a systems thinking approach that applies considerations for the inextricable links between human and environmental health (including at the planetary scale; Gabrysch, 2018; Ostfeld, 2017; Prescott & Logan, 2017, 2018).

Green prescribing schemes (prescribed nature-based interventions, which build on the 1990's concept of prescribing exercise and dietary-based interventions) have the potential to provide co-benefits for public and environmental health through integrative approaches (Gribben, Goodyear-Smith, Grobbelaar, O'Neill, & Walker, 2000; Robinson & Breed, 2019; Swinburn, Walter, Arroll, Tilyard, & Russell, 1998). Green prescribing schemes can include therapeutic horticulture, biodiversity conservation activities or simply social activities in greenspaces, which could potentially enhance interactions between humans and environmental microbiota. Further research in this area is needed (see Box 1, e.g. research questions), but using biological markers could

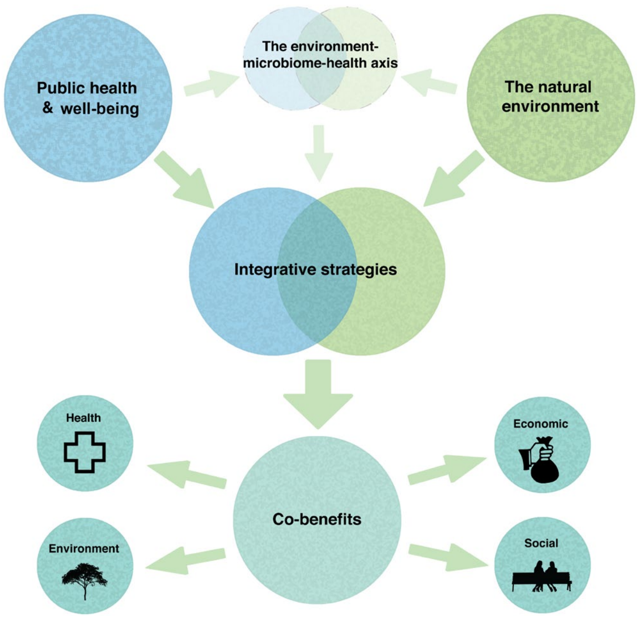

FIGURE 1 Integrative strategies and their potential co-benefits for humans and the environment. Considering the environment–microbiome–health axis could be important (created by authors, adapted from Robinson & Breed, 2019)

BOX 1 Examples of theme-specific research questions

- *Can environmental microbiome research be incorporated into integrative strategies to meet both public and planetary health objectives?*
- *How do the aesthetics of different landscapes entice people to have the social and environmental interactions they need to enhance and regulate their microbiome?*

provide valuable objective evidence of the health benefits of interacting with natural environments. Next, we will consider the second landscape research theme—Landscape Planning and Ecology—and its relevance to the environment–microbiome–health axis.

3 | THEME 2: LANDSCAPE PLANNING AND ECOLOGY

Through planning, design and management, landscape architects can have an important influence on the ecology of urban environments (Rottle & Yocom, 2017). This includes selecting, shaping and managing natural elements based on their functional (proximal and distal) roles in the landscape. Understanding how planning, design and management can influence urban microbial ecology through landscape research is highly relevant to the current conceptual framework.

Relatively, recent advances in molecular biology have enable high-throughput sequencing of microbial DNA, revolutionizing our ability to understand the diversity and dynamics of microbial communities (Wooley & Ye, 2010; Zhang, Wang, Wu, & Kumari, 2019). By revealing the unseen but integral components of ecosystems, this technology provides an opportunity to gain greater insights into the composition and functional roles of microbiota, and to investigate how these interface with nature-based features and humans in urban (and other) environments. The next sections will consider how landscape design, planning and ecology could play a role in environment–microbiome–health research and practice.

3.1 | Innovation in planting schemes and urban design

An emerging objective for those involved in urban ecological design is to understand whether green infrastructure could be designed and managed to generate microbiome-associated health benefits (Robinson et al., 2018; Watkins, Robinson, Breed, Parker, & Weinstein, 2020). This will require a comprehensive understanding of the various physical, spatial and biological factors that affect the composition, function and transmission of environmental microbiota in urban landscapes, and of the social factors that influence interactions (Figure 2). Fulthorpe, MacIvor, Jia, and Yasui (2018) discuss the importance of green roofs as an ecosystem service provider, and the importance of plant–microbe interactions, presenting a list of hypotheses for the positive role of environmental microbiota. These include drought tolerance, pathogen protection and phytohormone production. Here, we present a new addition to this list of hypotheses for green roof scientists to consider:

> *Green roofs can be designed to promote beneficial interactions between humans and environmental microbiota*

Investigating the functional roles of green infrastructure and choosing planting designs supported by empirical evidence already play a fundamental role in landscape research (Cameron, 2016). For example, Blanusa, Monteiro, Kemp, and Cameron (2016) investigated different green roof planting schemes to promote urban

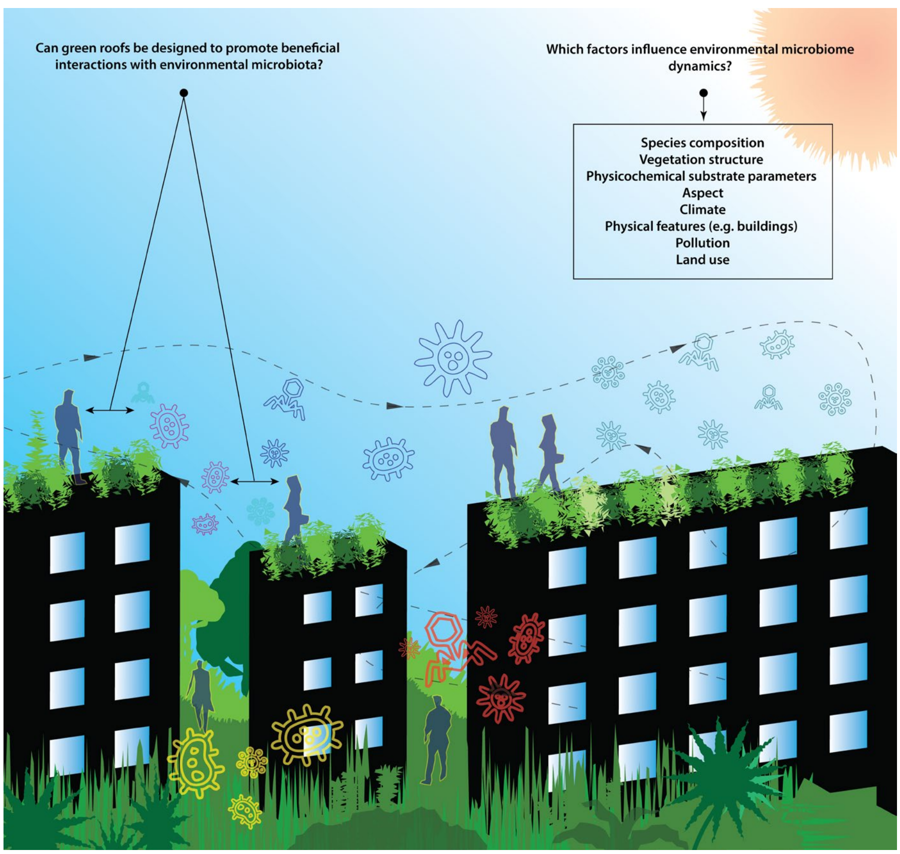

FIGURE 2 Can green roofs be designed to promote beneficial interactions between humans and diverse microbial assemblages, specific immunoregulatory taxa, or 'old friends'? (created by authors)

resilience under various scenarios. The authors suggest that a strong case should be made for the indirect benefits of more complex planting designs, particular those with a greater diversity of morphological characteristics and physiological regulatory factors. Suggested benefits include localized air cooling, greater rainfall and pollutant capture, and thermoregulation. Building on these suggestions, researchers could also investigate whether there are direct and indirect public health benefits to be made through optimizing human–environmental microbiome interactions.

3.2 | Alternative green infrastructural concepts

There are numerous other types of multifunctional greenspaces in urban areas. These range from rain gardens to urban parks; hedgerows to wildflower verges; wildlife overpasses to community allotments. All of these act as natural reservoirs of micro-organisms emitting rich clouds of immunoregulatory biochemical compounds (Rook, 2018, in Van den Bosch & Bird, 2018, p. 62). Considering the environment–microbiome–health axis in future green infrastructure designs could potentially have a profound impact on human health. In addition to species composition, spatial and social considerations are likely to play a role in maximizing the impact of what we call 'microbiome-inspired green infrastructure' (MIGI; Robinson et al., 2018; Watkins & Robinson, 2019; Watkins et al., 2020). For example, it will be essential to understand how size, proximity, aspect and urban physical features affect microbiome dynamics. Community needs assessments could also help inform the design and management of any green features aimed at optimizing interactions with environmental microbiota. Moreover, extending beyond the domain of localized impacts, determining whether interconnected systems of MIGI can improve the microbial network fragility of larger urban areas such as 'megacities' (which have been linked to human diseases; Kim et al., 2018) could also be an important line of enquiry. However, it is also important to recognize that the complexities of microbial ecology and our current limited understanding of microbiome–human health dynamics pose a considerable challenge to this research. Further studies which integrate landscape ecology with fine-scale metagenomics (the study of genetic material from environmental samples) and metatranscriptomics (the study of gene expression in natural environments) such as those in Mehta et al. (2018) would likely bring considerable value to this field of research.

3.3 | Ecological restoration, microbiome rewilding and 'types of nature'

There is evidence to suggest that allowing ecological processes to develop in the absence of anthropogenic pressures, through passive and active restoration processes, could potentially 'rewild' environmental microbiomes (Gellie, Mills, Breed, & Lowe, 2017; Liddicoat et al., 2019). Mills et al. (2017) propose the *Microbiome Rewilding hypothesis*, which outlines a case for restoring urban ecosystems and their microbial communities to a state that benefits human health. This has the potential co-benefit of promoting resilient natural ecosystems and could complement the designed greenspaces. The theory behind microbiome rewilding leads to further questions as to whether it can be extended to other 'types of nature' in urban environments: from remnant vegetation ('old wilderness'), designed/managed habitats ('functional urban greening') to extant and/or emerging urban wildscapes ('new wilderness'; Korawik & Körner, 2005).

Urban wildscapes are 'wilderness' landscapes in urban areas that have naturally established and developed in the absence of human management (Jorgensen & Keenan, 2012). Urban wildscapes include 'wastelands', vacant lots and former industrial sites typically dominated by ruderal vegetation. Several authors have discussed the value of urban wildscapes, highlighting important contributions to climate change adaptation, supporting biodiversity and promoting social inclusion (Aurora, Simpson, Small, & Bender, 2009; Kitha & Lyth, 2011; Rupprecht, Byrne, Ueda, & Lo, 2015). The process of natural succession in urban wildscapes has ecological parallels with rewilding, which points to the plausibility that they could support an important 'rewilded' microbial resource. Urban wildscapes are ubiquitous and provide the potential benefit of enhancing the urban microbiome with limited human input. Interestingly, a recent study showed significant differences in airborne microbiome composition (aerobiome) between non-vegetated parking lots and nearby greenspaces (Mhuireach et al., 2016). As such, the process of natural succession from a non-vegetated site to a vegetated urban wildscape may alter the composition of the aerobiome. Further research is needed to determine whether these potential changes exist and whether they translate to beneficial outcomes for human health.

Landscape planning can include locating optimal wildscapes in proximity to managed areas, and understanding social needs to optimize interactions between humans and potentially beneficial microbiota. 'Design' can include framing wildscapes in a way that makes them acceptable to/usable by a broader range of people. Many researchers in this area have transferable knowledge of landscape, community and functional ecology. Working across disciplines, these skills can be applied to investigate environmental microbiota of urban wildscapes and other 'types of nature'—including the 'designed and managed' type. This could potentially lead to important public health benefits (see Box 2 for potential research questions). The final section will consider how the Communication and Visualization research theme is relevant to the environment–microbiome–health axis.

BOX 2 Examples of theme-specific research questions

- *Can multifunctional greenspaces be designed to promote beneficial interactions with diverse environmental microbiota, specific taxa or 'old friends'?*
- *Can a network of urban wildscapes enhance the aerobiome (airborne microbiota)?*

4 | THEME 3: COMMUNICATION AND VISUALIZATION

The requirement for innovative modelling, visualizations and geospatial analyses has increased as landscape research has expanded to address societal issues (Lovett, Appleton, Warren-Kretzschmar, & Von Haaren, 2015). Innovative data integration has the potential to generate new knowledge in environment–microbiome–health axis research, and can play an important role in communicating complex datasets and concepts to broad audiences. This section discusses the crossovers between innovative modelling, visualization techniques and microbiome datasets.

4.1 | 4D modelling and microbial cartography

Wissen, Schroth, Lange, and Schmid (2008) suggest that 3D visualizations can help to ensure landscape conditions are communicated in an intelligible manner, using visual and non-visual landscape information. This is pertinent to environment–microbiome–health axis research as both visual (e.g. vegetation, buildings, geomorphological features) and non-visual (e.g. microbial communities, biochemical compounds, meteorological factors) landscape data can produce informative models for the environment and health sectors. Three-dimensional modelling offers benefits to the representation of complex spatial, temporal and compositional data. This is important when collaborating with a diversity of stakeholders (often non-designers)—where clear visual interpretations of current findings and future projections are necessary (Lindquist, Lange, & Kang, 2016).

Kapono et al. (2018) recently conceptualized '3D molecular cartography'. The researchers highlighted human–environmental interactions using microbial and metabolic sampling methods and 3D modelling techniques. They were able to map different molecular signatures in indoor environments. Extending this idea to the environment–microbiome–health axis, the nomenclature can be adapted to *4D microbial* cartography (4DMC) and the concept adapted to create 4D models (three dimensions plus a temporal dimension) for mapping and analysing environmental microbiome dynamics. Due to the complexities of microbial ecology, providing a molecular reading of the landscape and explicitly linking these to human health dynamics is currently unrealistic. However, 4D microbial cartography could potentially provide a valuable starting point by generating intelligible outputs of microbial dynamics in the landscape and communicating these to transdisciplinary audiences.

Using either terrestrial scanners or unmanned aerial vehicles with photogrammetry technology (a process also known as Structure from Motion or 'SfM'), 3D models of habitats can be created at different scales. The latter method could be combined with light detection and ranging (LiDAR; i.e. laser-based technology) for detailed outputs. Once the 3D model is created, microbiome sampling is conducted and the sequenced datasets integrated to produce an interactive visualization of microbial spatiotemporal dynamics (Protsyuk et al., 2018; Figure 3). An integrative system for modelling and visualizing these data with changeable layers to display the distribution of certain taxonomic groups and heatmaps of diversity is currently being developed.

Flexible scenarios can be built, compared and analysed by integrating 4D models with other spatial, temporal and compositional datasets. Crucially, the integrated 4D models can help to create context, realistic representations, and enable interactive data exploration. This allows representations of current and future (invisible) elements of the landscape to be visualized and could be used to help understand exposures/interactions.

4.2 | The Microbioscape

As alluded to above, technologies and disciplines can now be combined to gain a better understanding of the structure, distribution, and functional roles and relationships of microbial communities within and across different landscapes. Affordable DNA sequencing

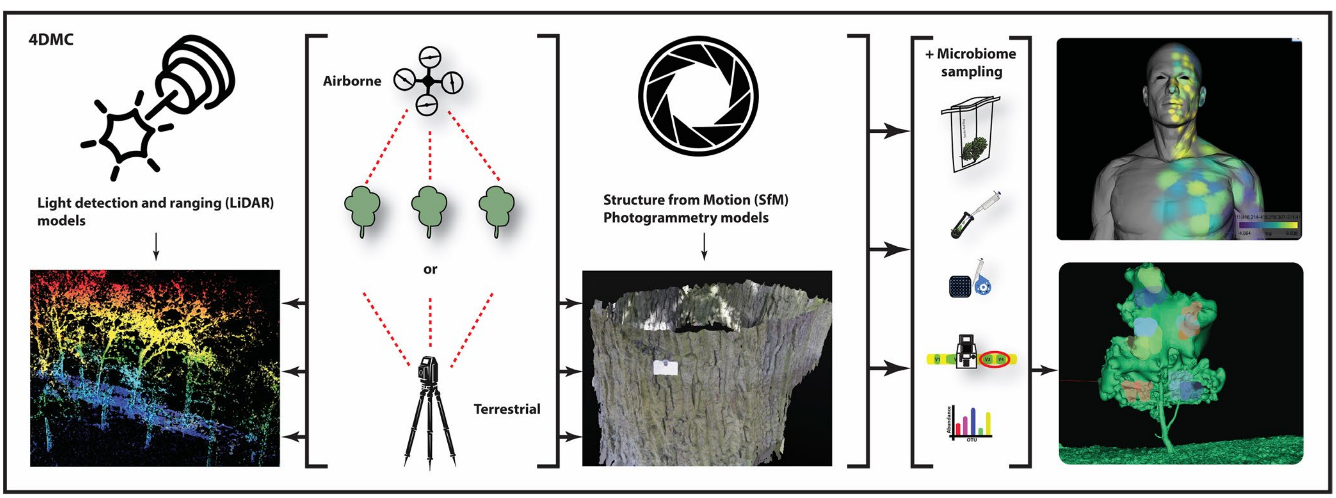

FIGURE 3 Four-Dimensional Microbial Cartography could contribute to the monitoring of environmental microbial dynamics. The top right image (human) is taken from the open-source 'ili software, as per Kapono et al. (2018; created by authors, from Watkins et al., 2020)

technology is now widely available to characterize the environmental microbiome on a larger scale than was previously possible. For example, the Earth Microbiome Project, an initiative launched to characterize 'global microbial taxonomic and functional diversity' highlights the scale of the potential (Earth Microbiome Project, 2018). Using innovative sequencing technology and working across disciplines, landscape researchers could help to pioneer a new concept, hereby termed the *Microbioscape*, and with it, a new interdisciplinary field of study—*Microbioscape Research*. Below is a preliminary definition of this proposed field of study:

> *Microbioscape research is the investigation and application of innovative research methods to characterize and visualize the structure, composition and distribution of environmental microbial communities and their relationships with their hosts. Furthermore, Microbioscape research aims to understand the social implications and functional ecology of these communities, focusing on their importance for people, place and nature.*

Microbioscape research can add an important dimension to landscape literacy and the ability to 'read' and interpret landscape functions and characteristics. With the availability of advanced technology to characterize microbial communities, the previously unseen constituents of natural environments can now become visible (represented) through modelling and visualization interfaces. Developing skills in microbial cartography, 4D modelling, GIS and other spatially orientated technology will play important roles in Microbioscape research. These are roles that landscape researchers and ecologists are well placed to develop. Microbioscape research could also incorporate other ontologies such as new materialism, for example, to explore how *'relational networks or assemblages of the animate and inanimate'* may produce the world (Fox & Alldred, 2015, p. 1; Monforte, 2018). This could lead to additional lines of socioecological enquiry and novel approaches to understanding the environment–microbiome–health axis in the future.

To establish the Microbioscape as a field of research, a strong interdisciplinary (socio-spatio-ecological) approach will be needed. Microbioscape research could make an important contribution towards understanding the environment–microbiome–health axis (see Box 3 for potential research questions).

BOX 3 Examples of theme-specific research questions

- *Can environmental microbiomes be characterized and visualized in a way that more effectively informs landscape planning and design for human/ecosystem health?*
- *Which spatial and design characteristics will provide the optimal conditions for beneficial microbial distribution?*

5 | CONCLUSIONS

A growing body of evidence supports the presence of a health-regulating relationship between humans, biodiverse environments and microbial 'old friends'. This highlights the importance of a concerted research effort to enhance our understanding of the mechanisms and dynamics at play in this relationship. Emphasis on 'co-benefits' is also important, and a transdisciplinary approach is needed to address the interrelated issues of human and environmental health. There is potential to extend the scope of landscape research well beyond the domains of current knowledge to combine microbial ecology and social research. Generating new strategies for human and environment health with explicit considerations for the environmental microbiome and understanding social needs is possible. However, it is important to acknowledge the complexities involved in microbial ecology and in studying the relationships between the environment, the microbiome and human health.

Ultimately, it is hoped this paper stimulates new discourse and lines of enquiry in the area of environment–microbiome–health axis research, and a response of working across disciplines to better understand the relationships involved. In the future, the development of Microbioscape research as a crossover field between microbiome science and landscape research has the potential to inform optimal (health promoting) urban designs, and potentially uncover some of the mechanisms that influence the development and progression of NCDs. Developing Microbioscape research aims to bring together researchers to transcend disciplinary boundaries and help establish integrative strategies for the benefit of people and nature.

CONFLICT OF INTEREST

The authors confirm there are no conflicts of interest.

AUTHORS' CONTRIBUTIONS

J.M.R. conceived the ideas and produced the figures; J.M.R. and A.J. collated and reviewed the literature; J.M.R. led the writing of the manuscript and A.J. critically reviewed the manuscript for important intellectual content. Both authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

There are no data associated with this manuscript.

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SUPPORTING INFORMATION

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