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Microbial repair and ecological justice: A new paradigm for agriculture

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In this paper, we put forward a case for repair by showing how food security, rural economic resilience, ecological restoration, and environmental justice can be achieved through a repaired agricultural microbiome. Microbial repair must reverse the damage done by legacies of agricultural intensification to restore the microbiome's ability to deliver key agricultural and societal functions. This project demands collaboration from diverse food system actors building on different types of knowledge.

Agricultural intensification has helped deliver substantial improvements in food production, but it has come at a great cost to the environment, with associated risks for human health. New approaches to genome bioinformatics (metagenomics) reveal the microbial consequences of modern agriculture, including the ability of the soil microbiome to sequester carbon, regulate the water cycle, and assist in the production of nutrient rich food[1]. In both arable and livestock contexts, there is a growing understanding of the microbial traffic between the farm, the environment and the clinic and, as a result, how the widespread use of antimicrobials drives the evolution of drug-resistant disease strains[2]. In both cases, a 'treadmill' of intensive tillage and agrochemical application denudes soils, plants and animals of the microbial diversity required to replenish fertility and to resist disease[3,4] while further increasing reliance on agrochemical inputs, forcing the agricultural microbiome into a positive feedback cycle of dependence and damage[5].

A common chronological story emerges from across diverse geographic and agronomic contexts, in which the microbial life that once supported agricultural functioning has been harmed by a program of agricultural management predicated on simplicity, acceleration and artificial input substitution[6]. Over the course of this perspective piece, we refer to this as the **antibiotic model**[7]. The term does not (just) relate to usage of antibiotic medicines, but to a general managerial approach predicated on the disruption and destruction of life on and around the farm. Around the world, the agricultural microbiome has been thrown into a state of **dysbiosis**: dysfunctional and pathological microbiome disequilibrium, that gives rise to various **blowbacks**. These are the unintended consequences of past rounds of agricultural modernization[8] and include amplified greenhouse gas emissions, biodiversity loss, anti-microbial resistance, zoonotic disease spillover, and other indirect impacts on human health.

There is a growing awareness amongst scientists, agronomists and policy makers of the challenges of managing these blowbacks and of the need for new approaches to address and ideally repair the underlying agricultural microbial dysbiosis that is causing them. Various commissions and research programs have begun to explore these topics. They focus, for example, on animal agriculture and bacterial zoonosis[9], on the livestock sector and the economic and health costs of antimicrobial resistance in Canada[10], or on the relationship between the soil microbiome and planetary health[11]. While these studies have provided invaluable insight into the character of different microbial-agricultural interactions, they have done so in relation to specific agricultural systems or bioregions. We suggest that additional lessons be generated by seeing them in synthesis—lessons that can be used to underpin empowered and scientifically informed intervention.

Our aim in this perspective is to look across existing research and practice to make the case for **microbial repair**. Our hope is that by identifying how different actors in the food system are facing microbial challenges with similar origins we can encourage them to identified shared remedies underpinned by a common scientific agenda. We first define microbial repair, before examining three of its most salient dimensions. We position this concept as a contribution to established synthetic frameworks —like One Health—that promote microbial health across the nexus of human-animal/plant-environmental relations. As an interdisciplinary collective concerned with humans and the microbiome, our aim is to foreground the shared fates of human and natural systems and to provide a conceptual and scientific rationale to pull together researchers, commercial actors, policy makers, scientists, and producers working in different domains of the food system. Microbial repair is, in this way, a political project concerned with ecological justice, every bit as it is an environmental and scientific one.

Microbial repair

We define microbial repair in the following way

Microbial repair reverses the damage done by an intensive model of agricultural management predicated on agroecological simplification and high

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inputs of fertilizers, pesticides, and antibiotics. This is achieved through the cultivation of resilient microbial ecologies capable of reversing the blowbacks caused by microbial dysbiosis. It demands careful attention to how microbes interact with one another, and with other biotic and abiotic factors to deliver key agricultural functions. It seeks a just and sustainable food system that is healthy for people and the planet.

The concept of repair draws attention to the entropy to which social and ecological systems are exposed[12]. It speaks to the ethic of agricultural care needed to keep them in good working order[13]. Repair sometimes demands the maintenance of a system, and sometimes demands that it be transformed to ensure it can meet new challenges[14]. We use the term in a way that is expansive enough to accommodate different agents and recipients of repair. The repair *of* the agricultural microbiome might be achieved through, for example, crop diversification and soil health care practices. But the benefits and costs of this repair, we suggest, must also to be on the agenda. Proponents of agro-ecology, for instance, advocate for farm management practices that improve the environmental impacts of the farm as a means of redistributing the benefits, wealth, and power that undergirds the food system. Such justice issues might, in other words, be repaired *through* the agricultural microbiome. As we argue in the final section, repair should be orientated towards justice and fairness by paying attention to both the repair *of* and the repair *through* the microbiome.

Repair has overlaps with other terms that circulate in discussions of sustainable agriculture, including restoration, regeneration, and rewilding. These terms share an interest in learning from the past to guide new futures. They describe working with ecological processes rather than ensuring human absence in a way that is guided by historical baselines. Repair, though, is not confined to a retrospective gaze. It embraces new technologies and research to protect the food system from new threats, and to adapt to meet new demands.

Researchers seeking microbial repair have conducted (meta)genomic analysis of soils to understand the micro-organisms that assist in the fixation, mineralization, solubilization, and mobilization of nutrients, and the transfer of those nutrients into plant roots[15]. They have analyzed the composition of bovine rumen to understand how different microbes contribute to the digestion, metabolism, and growth of livestock animals[16]. And they have examined the microbes that enable livestock animals[17], crops[18], and soils[19] to resist disease. These studies aim to transform the food system via the production of novel biofertilizers, biopesticides, and soil and feed additives.

Meanwhile, many of the investigations being conducted into the agricultural microbiome also focus on heritage crops, cultivars, soils, and animal breeds that have evaded the microbial changes and dysbiosis caused by intensive agricultural practices [20–22]. As with human microbiome research[23], Indigenous and traditional agroecosystems are being approached as reservoirs of microbes and data that might enable the curation of a sustainable and healthy food system. Here, food system transformation is achieved through the restoration and maintenance of an erstwhile microbial agroecological order. Table 1 provides some illustrative examples of microbial repair.

An ecological ontology

The term ontology refers to the nature of being, the entities that exist in the world, and the relations between them. It concerns the words, ideas, and organizational structures used to make sense of material reality. We suggest that microbial repair requires a new ontology to conceive of the health of plants, animals and the ecosystems in new and better ways. This first involves a shift from the chemical metrics that predominate in soil science, towards a focus on microbiology, concerned less with the presence or absence of particular molecules, and more with the organisms responsible for their production and metabolism. Second it involves a shift in focus from specific microbes, revealed by the traditional culture-based techniques of microbiology, towards the microbiome, understood as the collective genome and ecology of interacting organisms.

Table 1 | Illustrative examples of agricultural microbial repair

Intervention	System	Details	Repair of	Repair through
Probiotic feed additives (e.g., *Lactobacillus*)[58]	Broiler chickens	Feed additive	Improved immune response, quicker body mass growth.	Potential reduction in reliance on antibiotics in broiler systems, impacts on antimicrobial resistance. However, designed for use in an unchanged economic system (vertical integration, power concentration).
Streptomyces[59]	Cropping agriculture	Seed coating	Biofertilization of crops, less synthetic fertilizers needed.	Reduced downstream pollution pressures. However, designed for use in an unchanged economic system (intensive agriculture).
Agroecological and/or permaculture crop diversification[60]	Cropping agriculture, mixed farming	Replace monocrop systems with diverse rotations of different cash crops, legumes, herbal leys etc.	Improved soil health, lower reliance on chemical inputs to manage fertility and disease pressures.	Higher rural employment, better engagement with seasonality, locality, and traditional mixed farm practices. However, risks of lower yields and knock-on impacts on food security.
No till or reduced-till[61]	Cropping agriculture, mixed farming	Reduces the depth and frequency of tillage	Improves system connectivity by reducing disturbance of beneficial fungal hyphae; improved soil health and carbon sequestration.	Reduce downstream pollution through reduced fertilizer usage. Potential need for increased herbicidal applications, particularly glyphosate. Applicable for large intensive cropping systems, or smaller units.
Agroforestry[62], silvo-pasture[63]	Mixed, cropping, or livestock agriculture	Use of trees and forestry to diversify production portfolio and create public goods.	Local biodiversity functionality, improved pest resistance, increase carbon sequestration.	Higher rural employment, better engagement with seasonality, locality, and traditional mixed farm practices. However, risks of lower yields and knock-on impacts on food security.
3-Nitrooxypropanol[64]	Beef	Feed additive	Reduced methanogenesis rates, lower GHGs emissions from the herd.	Improved farm economics, reduced inputs. However, emissions reductions can be used to undermine efforts to reduce meat/dairy in diets and are designed for use in intensive husbandry systems.

This moves away from a Pasteurian focus on specific pathogens or beneficial probiotic organisms, towards an interest in microbial interactions over different temporal durations and spatial scales. Crucially, it requires an attention to the pathological consequences of microbial absence, as well as the excessive presence of specific microbes, tracing how the loss of keystone organisms can lead to the deleterious loss of function as well as generating hotspots for the emergence of new pathogens[24]. While this represents a major and novel scientific challenge, promising work is emerging in this area developing indicators of abundance and absence to predict future agroecological vulnerabilities[25].

Third, a focus on the agricultural microbiome leads to a recognition of myriad ways in which different elements in the food system are connected. Microbiome research is revealing how biodiverse rich soils have positive impacts that ripple out across entire landscapes[26,27], how healthy soils create nutritionally dense foodstuffs[28], how the enteric livestock animal microbiome shapes the fertilizing potential of the manure produced[29], and how livestock antibiotic use shapes human exposures to antimicrobial resistance[2]. This research shows how the things (plants, fields, humans, livestock animals) that populate the modern agricultural imaginary are not isolated entities. Through the microbiome, they are best understood as connected materializations of ecological processes[30]. This processual philosophy of connectivity informs the ecological ontology of relations, interactions, and entanglements that is necessary for conceiving of microbial repair [31,32].

An agenda for agricultural microbial repair thus requires us to address fundamental philosophical questions about the interdependence of human and agroecological systems, to reconfigure the conceptual architecture of modern agronomy (predicated on neat divisions between isolated elements in a system) that defined a previous generation of agricultural research and development. It thus requires new ways of producing knowledge.

The science of repair

This novel relational ontology emerges from a shift in the methods employed to produce knowledge in the agricultural sciences and allied disciplines[33]. The agricultural intensification that unfolded over the course of the 20th century was underpinned by a reductionist scientific framework (what is sometimes referred to as an 'epistemology') geared towards the identification of inputs, cultivars, and management practices capable of producing more food[34], as well as the pathogens that threatened yields. It focused on discrete elements within a system and sought knowledge on the fundamental building blocks of agricultural production[35]. For example, under these research conditions, nitrogen, phosphorus and potassium values became a proxy for soil fertility, livestock metabolism was understood as a function of feed-conversion ratios, and the absence of weeds was understood as the evidence of a healthy crop. Applied science sought to optimize these elements, severed from their relations, via the sustained application of biocides, fertilizers, and antibiotics[5]. This epistemology helped drive substantial increases in global food production but it has become central to the agricultural microbial dysbiosis we know today.

To repair this dysbiosis, new scientific principles are needed predicated on *holistic* and *site-specific* knowledge and associated modelling tools and experimental systems. In the first instance, repair demands knowledge about the interactions of diverse microbial processes. With the advent of metagenomics (along with transcriptomics, metabolomics, and proteomics) scientists now have the tools to understand the rich and complex microbial relations that deliver agroecological functionality (pest resistance, fertility, crop growth etc.). By offering higher resolution insight into the microbial life that underpins agricultural production, integrative 'omics research methods can deliver a holistic knowledge framework[36].

While researchers seek to identify particular microbes (e.g. a bacterium that reduces enteric methane production in bovine rumen), they are also interested in how individual microbes relate to one another, and how their interactions drive (or inhibit) agricultural functionality. These integrative and interactionist principles will be vital for the repair of the agricultural microbiome [37,38]. The shift towards the term *soil health* and away from terms like *soil fertility* or *soil quality* reflects this holistic scientific mindset[39] and should be expanded to describe the repair of the agricultural microbiome more generally.

Owing to the complexity and variability of the microbiome, particularly in agricultural soils, there is growing recognition that the same intervention is liable to lead to very different outcomes in different contexts[40]. As a result, the microbiomes of different soils, animals, and plants all need different things to be repaired well [4,41]. While insights into very specific microbes are helping to produce generic and scalable inputs like biopesticides and biofertilizers[42], the repair of the microbiome also necessitates greater attention to site-specific needs. Advances in metagenomics, which allow functional assessment of microbes that exist in vivo agroecosystems, rather than just those that can be grown and experimented on in vitro lab settings, are helping to fulfil these site-specific research demands[43].

The contextual insights generated through in vivo research (done, for example, in the fields where the science will be applied) will best enable microbial repair if they can be deployed in conjunction with tailored agricultural extension services and within peer-to-peer learning networks of local farmers[44]. These approaches to co-producing microbiological knowledge can help ground research in local contexts and democratize its implementation by working alongside farmers, land managers, vets, and other practitioner scientists[45]. Experiences and insights[46], particularly from projects based in Latin and South America[47], help demonstrate how space can be carved out for the creation, valorization, protection, and potential dissemination of Indigenous and other non-Western approaches to agricultural management.

Just repair

Existing research into the agricultural microbiome has largely focused on the relationships between the agriculture and human healthc[1], on microbially-informed practices for reducing the food system impacts on biophysical systems[11], and on the microbes needed to help agriculture feed a growing world population[48]. Such research is crucial and is needed to realize the repair *of* the agricultural microbiome and also to encourage food system actors to pay greater attention to how the microbiome might be reimagined to allow for a fairer and more equitable food system. Microbial repair should encompass more than just the attainment of environmentally efficient and healthy food production systems. It should be understood in its broader historical, political and economic contexts. These broken aspects of the food system can, in other words, be repaired *through* the agricultural microbiome.

We need to ensure, for example, that the technologies being developed to modulate the agricultural microbiome are available to a large number of practitioners, including those poorer farmers in the poorer parts of the world usually excluded from access to capital, to fair market relations, and to new agricultural technologies[49]. Particularly given the highly uneven burdens of agricultural production, repair is not just the repair of the microbiome, but of the highly uneven ways that the world's farmers share the responsibilities, benefits, and harms of agricultural production. It is helpful that the word *repair* shares common etymological roots with the term *reparations*. Reparations, like those being called for in relation to biodiversity loss, climate change, and colonialism[50] demand engagement with environmental histories, and how the past continues to haunt the present. While these diverse social and political concerns represent an extra set of considerations to be made in the design and delivery of relevant interventions (economic, policy, technological), they need to be—and already are being[51]—addressed to ensure that microbial fixes do not reproduce a set of unjust food system outcomes.

In the case of agriculture and the microbiome, repair needs to confront how histories of colonialism and industrialization shape the uneven environmental and health burdens generated by the modern food system, which are largely borne by poorer and other underserved communities[52]. While research into Indigenous agroecological microbiomes may lead to valuable insights into the cultivars, soils, breeds, feedstuffs, and soil additives needed for a sustainable food system, they also risk biopiracy and the (re) creation of neocolonial relations in the food system[53]. Projects for microbial repair could learn from the growing discussion of the need for regulations to ensure that bioprospecting forays into agricultural settings in the Global South resist extractive neo-colonial logics and work instead towards goals such as food sovereignty and global economic justice[54].

Past research identifies persistent problems with the type of 'technofix' solutions[55] proposed for the repair *of* the microbiome. A holistic and just program of repair through the microbiome must be attentive to the hidden costs and political agendas of the solutions being offered by different actors in the food system. Like agroecology[56], repair is thus a political movement, every bit as it is an environmental and scientific project. For this reason, we call on researchers and scientists to extend long-standing discussions about the development of globally even environmental and labor protections to the new agricultural microbiome frontier; to work towards global trade relations that are attentive to the microbial consequences of agricultural production, and to ensure equitable access to new agricultural microbial technologies.

The future of repair

Thinking with microbes makes manifest the entanglements of human, animal and plant bodies, connected through the promiscuous traffic in microbial organisms. It demonstrates the tight coupling of agroecological and human futures[57] and points to the microbial origins of quality food and to a wide array of plant and animal diseases. It suggests that:

- Approaches to food system governance must be recalibrated to acknowledge the pathological consequences of both missing microbes, as well as of excessive presence.
- More integrative research is needed to understand how microbes contribute to agricultural system functionality.
- New ontologies, epistemologies, policies and practical interventions are needed to secure the microbial foundations of our food system.
- Attention needs to be paid to the political drivers and justice outcomes of microbial dysbiosis and repair.
- The repair *of* the agricultural microbiome must be attentive to how the social injustices of the food system can be repaired *through* the microbiome.

Data Availability

No datasets were generated or analysed during the current study.

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Author contributions
G.C. Conducted initial literature review; wrote first full draft of the manuscript; incorporated successive rounds of comments from other authors. B.F. Formed structure of the argument; inputted expert commentary on successive drafts of the manuscript, particularly with regards state of the art science in microbiology. N.N. Formed structure of the argument; inputted expert commentary on successive drafts of the manuscript, particularly with regards state of the art science in microbiology.JL Shaped the structure of the manuscript's argumentation, competed a major redraft for the second version of the manuscript. All authors read and approved the final manuscript

Competing interests
The authors declare no competing interests.

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