Can Microbes Be Active Participants in Research? Developing a Methodology for Collaborating with Plastic-Eating Microbes

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Abstract The emergence of *Ideonella sakaiensis*, a microorganism with the capacity to metabolize the widely used plastic polyethylene terephthalate (PET), raises important questions about how human and nonhuman agency are related in responding to pressing environmental issues. The article explores how the agency and expertise of *I. sakaiensis* is a constitutive but often overlooked collaborator in scientific research into plastic biodegradation, and it attempts to develop a methodology for enrolling microorganisms as active research participants from the outset. Knowledge coproduced with microbial others, and specifically those microbes with the capacity to detoxify anthropogenic pollutants, may inform and enact inclusive and prescient responses to ongoing environmental degradation. Accordingly, drawing from theoretical orientations in more-than-human participatory research and animals' geographies, the article asks how microorganisms might express their own directives, preferences, and constraints on the research process, and how, in turn, we might listen and be directed by them. Although the ontological and ethical commitments of the environmental humanities are well suited for welcoming microbes as partners in deliberative processes, the challenges of communicating with them across vast scalar and bodily differences suggests a need to engage with techniques traditionally considered the disciplinary property of the natural sciences. Some of these concepts are contextualized with respect to a research project currently being undertaken at the River Lea in East London and the attempt to enroll *I. sakaiensis* as a collaborator in responding to plastic pollution in the river.

Keywords microbes, more-than-human participation, bioremediation, multi-species, plastic

In her ethnographic study of the Yeast 2.0 project, Erika Szymanski reconceptualizes synthetic biology as a participative process in which yeast and microorganisms communicate across species boundaries with their human handlers.[1] The metaphor of

1. The Yeast 2.0 project is an attempt to synthesize a complete artificial yeast genome. The iteration *2.0* refers to how, through engineering-like processes, synthetic biologists aim to streamline, rationalize, minimize,

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participant breaks from the customary subject-object ontology of basic research, evoking material-scientific practice as a "dance of agency" and an attunement between different forms of material existence.[2] Pointing to the role of language in constraining, enabling, and creating new forms of relationships with nonhuman others, Szymanski suggests that "more active metaphors [i.e., participant] for microorganisms can . . . be seen as methods for doing multispecies research as well as for doing synthetic biology."[3] The challenge of this article is precisely that—to suggest, provoke, and argue for enrolling microorganisms as active participants in research projects within multispecies studies and the environmental humanities more broadly.

Synthetic biology, and the goal of synthesizing a complete artificial genome is perhaps apotheotic of the drive toward a total mastery over the biological world, but the explorations of microbial life as they churn over our accumulating detritus evokes the image of a vast, uncontrolled experiment in which human involvement is minimal.[4] As microorganisms encounter anthropogenic pollutants in all manner of inhospitable environments, they are rapidly evolving to metabolize and detoxify these contaminants, producing the ground from which other forms of life may flourish. It is the suggestion of this article that these processes, which are collectively referred to as "bioremediation" by the scientific-industrial establishment, might figure as productive sites for human-microbe collaboration on shared matters of concern.

Pollutant-degrading microorganisms express their own forms of molecular and embodied expertise in encountering and transforming environments, forms of expertise that may be shut down through conventional biotechnological approaches.[5] Accordingly, this article discusses how such microorganisms are already significant contributors to scientific research, and how we might reconfigure experimentation to follow rather than constrain their agency, to be led by their directives, preferences, and constraints on the research process. In so doing, the article aims toward developing a practical methodology for interspecies communication with environmental microorganisms, and the formation of human-microbe relationships focused on issues of environmental pollution and remediation.

At the same time, it is the expertise and methods of microbiology as a scientific practice that have furnished us with the understanding of microbial life that I am suggesting places it as a prime collaborator in pressing ecological issues. That is why this article, and the methodologies I suggest for human-microbe collaboration, sit—potentially

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and "free up" the genome of yeast for downstream biotechnology and research applications. Szymanski, "Who Are the Users of Synthetic DNA?"

2. Pickering, *Mangle*.

3. Szymanski, "Who Are the Users of Synthetic DNA?," 2.

4. Clark and Hird, "Deep Shit"; Clark and Hird, "Microontologies"; Hird and Yusoff, "Subtending Relations"; Hird and Yusoff, "Lines of Shite."

5. Szymanski, "Who Are the Users of Synthetic DNA?"

uneasily—between the social and natural sciences and between the environmental humanities and environmental microbiology.

I begin this article by introducing the recent discovery of *Ideonella sakaiensis*, a microorganism that has the capacity to degrade the widely used plastic, polyethylene terephthalate (PET). I explore how the agency and expertise of *I. sakaiensis* is already a constitutive, but often overlooked, collaborator in research into plastic biodegradation and raise the question of how such microbes might be enrolled as collaborators and research participants from the outset. This question is contextualized with reference to theoretical and methodological developments in the fields of animals' geographies and more-than-human participation. I finish by discussing a research project I am currently undertaking at the River Lea in East London to engage *I. sakaiensis* as a collaborator and partner in responding to the issue of plastic pollution in the river.

Plastic-Eating Microbes and Human-Microbe Relations in the Context of Bioremediation

In 2016 researchers from Japan identified a bacterial species with an appetite for the commonly used plastic polyethylene terephthalate (PET).[6] *Ideonella sakaiensis* was found lurking in the "ecosystems of excess" and "feral" ecologies outside a plastic recycling facility in Sakai, and, unlike the organisms of the human microbiome or the SARS-CoV-2 virus, this plastic-eating microbe lives constitutively outside the human body (and the bodies of other organisms) and barely in any relation with the human at all.[7] If we follow emergent microbial life beyond the confines of our own bodies, we are often led to the deep and dark ecosystems of landfills, wastewater, and tailings ponds to learn that the province of human-microbial coexistence is "slender" at best.[8] To put this in the context of plastic-eating microorganisms, we might reflect on how it was the metabolism of microbes in the first place that created the oil reserves from which contemporary plastics are synthesized, and it is likely to be microbes that will recirculate the locked-in matter energy of plastic into global biogeochemical flows in the coming millennia.[9] Microbial production of space occurs not only in the horizontal plane of networked bodies and topological spaces, but also throughout the vertical strata of the earth and into the deep time of the biogeochemical conditions that ground our contemporary existence. If zoonotic viruses, the human microbiome, and growing antimicrobial resistance speak to the immediate concerns of embodiment, health, disease, and human-nonhuman entanglement,[10] then the provocation of plastic-degrading microorganisms is their calling out

6. Yoshida et al., "Bacterium That Degrades."

7. Yoldaş, "Ecosystem of Excess"; Tsing, "Getting by in Terrifying Times." Although plastic-degrading microbes "involve human agency at some vital point," it is important to note that "substantial sequences of [their] story unfold[s] in domains in which human presence is negligible or non-existent." Clark and Hird, "Microontologies," 255.

8. Clark and Hird, "Microontologies," 256.

9. Aitken et al., "Anaerobic Hydrocarbon Biodegradation"; Davis, "Plastic: Accumulation without Metabolism."

10. Lorimer, "Parasites, Ghosts, and Mutualists."

to a future in which humans might not even be present; they speak equally to the ecological, the environmental, and the geological.

Ongoing scientific engagement with *I. sakaiensis* has been overwhelmingly framed within the context of catastrophic levels of plastic pollution and of developing urgent responses to it. This work, however, has primarily taken the form of human scientists working "on" these microorganisms, attempting to dissect and engineer their metabolism and to optimize their plastic-degrading abilities. But if, through its corporeal and metabolic expertise, *I. sakaiensis* has innovated a process that has stumped human attempts for decades, then it might be quite reasonable to question the assumptions structuring this kind of approach. How does the agency and expertise of the microbes themselves show up in and direct these experiments?

The original *Science* paper describing *I. sakaiensis* identifies the molecular processes driving its hunger for plastic as being linked to two enzymes expressed by this microbe; firstly, a PETase enzyme secreted by the cells hydrolyzes the ester bonds between adjacent monomers in the polymeric molecule to release mono-2-hydroxyethyl terephthalate (MHET). MHET is then taken up inside the microbes and hydrolyzed into ethylene glycol and terephthalic acid, the two molecules out of which PET is synthesized in commercial settings. Soon after Shosuke Yoshida and colleagues published their 2016 paper numerous other groups began to investigate these enzymes and, in one of the more highly cited and reported works that followed, researchers used X-ray crystallography to determine the structure of *I. sakaiensis*'s PETase protein in an attempt to understand how it binds PET in its active site and catalyzes its hydrolysis.[11] Then the researchers designed an experiment to engineer *I. sakaiensis*'s PETase to reduce its affinity for PET, but when they made the proposed changes to the enzyme structure, they were surprised to observe that the resultant protein had an increased efficiency at degrading PET because this had made the active site more flexible and better able to accommodate the polymer.[12]

Active site engineering is deployed as a rational approach that attempts to make precise, specific and quantifiable changes to an enzyme's substrate profile and kinetics, but as the work of Austin and colleagues make clear, rational changes to enzyme structure may result in "irrational" or unexpected outcomes. In particular, this experimental manipulation relied on the expertise of human scientists as they attempted to reconstruct the molecular-phylogenetic relationship of PETase, but what emerged from it was an outcome stemming from *I. sakaiensis*'s own form of expertise. This kind of situation recalls Szymanski's suggestion that

11. Austin et al., "Characterization and Engineering."

12. The researchers made the specific changes because of a hypothetical evolutionary relationship they proposed between the PETase of *I. sakaiensis* and the cutinase and lipase enzymes of other microbes. They introduced mutations to make the PETase active site more similar to that of cutinase and lipase enzymes. Austin et al., "Characterization and Engineering."

> by inviting microorganisms to be organisms with different knowledges and capacities than scientists . . . microorganisms are allowed the possibility of response. In listening for those responses, scientists retain the possibility of being surprised by, learning from, and making use of capacities which they do not own, do not control, and do not need to know how to perform. Enacting microorganisms as mechanical structures [for instance, through the discourses of synthetic biology], in contrast, limits scientists to seeing what they already know.[13]

These "different knowledges" and in particular the surprise outcome of Austin and colleagues' work doesn't necessarily suggest the absence or insufficiency of human expertise in manipulating enzymatic structures, but instead the presence of a form of microbial capacity that is distinct from scientific knowledge. This distinction is foregrounded by the fact that the structure of *I. sakaiensis*'s PETase—as well as its broader metabolic versatility—stood in contrast to the researcher's reference to a model of its activity. Scientific expertise and theoretical models of enzyme evolution were disrupted by the capacities of *I. sakaiensis*, which expresses a form of embodied, molecular, and genetic expertise. In other words the processes of rational enzyme engineering deployed by scientists follow on from, and depend on, the rational exploits of bacterial organisms as they encounter and attune to plastic waste in their environments.[14]

The surprise outcome of these experiments increased the profile and reception of the research because *I. sakaiensis*'s expertise, and its corresponding contribution to the research, aligned with the researchers' desired outcomes in the longer term, that is, the optimization of the PETase enzyme's efficiency at degrading PET. That it did so through disrupting scientific models and hypotheses was coded as serendipity, rather than an explicitly microbial capacity or contribution. Indeed this kind of surprise outcome relies on a whole other set of relations and translations that have already been set up between scientists and *I. sakaiensis*, and this outcome itself was immediately enrolled to further support the scientists' project. If we follow the core insights of actor-network theory (ANT) to analyze human-microbe interactions in scientific research, we can see that *I. sakaiensis*'s expertise is consistently constrained and manipulated to align with the agency, goals, and plans (and hypotheses and models) of human researchers.[15]

Beyond *I. sakaiensis*, many other organisms express enzymes with moderate PETase activity, an observation that has led researchers to speculate that within metagenomic databases[16] there are many undiscovered enzymes that have potential PETase

13. Szymanski, "Who Are the Users of Synthetic DNA?," 10–11.

14. Here I follow Vicki Kirby's suggestion that the molecular exploration of their world by microbes is a form of writing and rememoration—a rational and deliberative process. Kirby, "Tracing Life."

15. Through a series of negotiations, manipulations, and constraints, or "translations" in the terminology of ANT, scientists got *I. sakaiensis* to comply with their demands. See Callon, "Some Elements," for an overview of the "four moments" of translation—problematization, *interessement*, enrollment, and mobilization.

16. Databases composed of billions of base pairs of microbial genetic sequence from various environmental microbiomes.

activity. To search for these candidate genes, researchers "mine" these databases, and their tools for doing so are the reference sequences of PETase genes provided by organisms such as *I. sakaiensis* and *Thermobifida fusca*.[17] Statistical models and mathematical analyses compare the gene sequence of these reference PETases to other genes in these databases, and they return candidate genes that are likely to express PET hydrolysis activity. These genes are then often expressed in *E. coli* or other biotechnological "workhorses," purified, and their activities against PET studied. The discovery of novel genes, or novel functions of previously known genes are in this way linked not only to the labor of microorganisms, as the material precondition of biochemical experimentation, but also to the molecular expertise and capacities of plastic-degrading microorganisms that serve as a model and reference point for identifying and rationalizing these experiments. In this sense, *I. sakaiensis* is a central, yet often overlooked, interlocutor in this "inherently collaborative" metagenomic science, and it contributes to "novel knowledge on the phylogenetic relationships, the recent evolution, and the global distribution of PET hydrolases."[18]

This, of course, is a core tenet of ANT: the idea that scientific knowledge emerges from the interaction of a set of actors who are related in a stable network focused on a specific goal, and where "the word actor—or actant" in these networks is extended "to *non-human*, *non-individual* entities."[19] Although in the experiments discussed above there is an important contribution from microorganisms and their associated capacities, this contribution is not singular and self-contained (as the human is imagined to be), but distributed among various technical objects, digital artifacts, and conceptual schema—as well as the corporeal, metabolic, genetic, and evolutionary existence of microorganisms. These entities are enrolled into the scientists' projects, "punctualized" and "black-boxed," and as such their input often recedes into the background.[20]

Defining Collaboration: More-than-Human Participation and Animals' Geographies

Retroactively reading the agency of microbes into experimental science that exists squarely within the confines of microbiology is one thing—and something that readily emerges from a general STS (science and technology studies) understanding. But to take Szymanski's suggestion, it is another to ask how understanding and enacting microbial agency as collaborative from the outset might shift our practices and engagements with microbes, especially in the context of multi-species and environmental studies. While ANT uses the principle of symmetry to describe the processes of network formation

17. Danso et al., "New Insights."

18. Lee and Bietz, "Barriers," 3; Danso et al., "New Insights," 1.

19. Latour, "On Actor-Network Theory," 369. See Callon, "Some Elements," for an example and explanation of the processes by which networks are formed and are dissolved.

20. Heeks, "Development Studies Research," 5; "Punctualization" or "black boxing" actors is a process that "place[s] [actors] into a taken-for granted and trusted categorization" within a network and relies on their agency without calling it into question. Such processes are characteristic of stable and persistent networks.

between human and nonhuman actants, the aim of this approach would be to wield ANT's analytic symmetry as a methodological orientation. Indeed, although the idea of multi-species coproduction might well apply to the studies reviewed above, this refers "to the more general idea that human and nonhuman agents are intertwined in shared worlds, with both involved in the production of these worlds."[21] Participatory research (PR), on the other hand, provides a framework in which nonhumans might be enrolled as active participants, and in which coproduction offers not only "an analytical framework for approaching the object of study" but a "method of engaging with fellow enquirers."[22]

The point of more-than-human participatory research (MtH-PR), then, is to think about how "one might invite specific nonhumans into the research process at the outset, rather than identifying nonhuman agency in human worlds as a research output."[23] PR is generally focused on including marginalized groups of people in the research process in order to respond to and address issues that they are facing, and Michelle Bastian and colleagues extend this motivation to working with nonhuman others. This approach becomes especially relevant in the context of extensive disruptions to nonhumans' worlds and the implications that traditional research has for them. This work in engaging nonhumans as collaborators is "driven by the need to take environmental devastation seriously, and to develop research methods that might better support more sustainable ways of living together."[24]

There is a peculiar paradox or tension, however, in thinking about how MtH-PR might be applied to the case of microbial life. If microbes are "amply capable" of composing, recomposing, and decomposing worlds "on their own"[25] and in ways that often escape—and undermine—our own abilities, then isn't it us who are excluded from their worlds? Collaboration and participation with those microorganisms might be less about us enrolling them as active participants in our projects than about getting more consciously involved in their world-transforming activities, about asking questions of their capacities and agency without attempting to direct it in specific directions and through instrumentalist epistemologies. What I am suggesting is that *I. sakaiensis* is an organism with expertise and capacities that might help us think about and respond—both speculatively and practically—to specific environmental issues, an organism that might help

21. Bastian et al., "Introduction," 9; see also Noorani and Brigstocke, "More-than-Human Participatory Research."

22. Bastian et al., "Introduction," 9.

23. Bastian et al., "Introduction," 9.

24. Bastian et al., "Introduction," 2.

25. Clark and Hird, "Microontologies," 256. This also raises questions about the analytic mode of ANT and its insistence on symmetry between human and nonhuman actors. Latour's seminal *Pasteurization of France* discusses how humans and microbes have made and remade each other, but Clark's claim is that microbes made human life and human technoscience possible in the first place. Clark, "What Can Go Wrong." See also Ingold, "When ANT Meets SPIDER."

us renegotiate our troubling relationship with the earth while also forcing us to keep notions of our own agency in check. Responding to the agency of these organisms, responding to their responses to a polluted earth, I suggest, might inform ways of surviving—and thriving—on a damaged planet.

We might begin this task by figuring out how to listen and attune to microbes, by figuring out where and what their voice is, and being open to these questions despite how "ironic" or "challenging" they might first appear.[26] Developing a research framework for microbial participation might be strengthened by reference to the developing field of animals' geographies, an area of research that seeks to study and understand animals' lives and lifeworlds as they unfold outside human mediation and imposed spatial orderings, and that attempt to get at human-nonhuman interactions from the animals' "side."[27] As Leah Gibbs observes, "While animal geographies scholarship is diverse, it continues to be dominated by an empirical focus on terrestrial mammals."[28] Pointing to recent research at the sites of the almost-animal and para-animal, including on microorganisms, Gibbs calls for a "move beyond the animal" in animals' geographies, an orientation that is echoed by Timothy Hodgetts and Jamie Lorimer's aim to "pluralize" the category of both "animal" and "geography."[29] Lorimer, Hodgetts, and Maan Barua's own frameworks for studying and developing "animals' geographies" and "animals' atmospheres,"[30] while contextualized primarily with reference to the terrestrial mammals to which Gibbs refers, may be instructive in this regard. They point to attempts in attuning to animal presence and evoking animal agency as central in studying animals' geographies, while their methodological paper suggests that developing interspecies communication and mobilizing genomic methods might also help us craft a view of animals' geographies. In concert with the wider more-than-human turn in human and cultural geography, "this is more than giving an increasing voice to more-than-humans; it is about making space for new 'voices' and using the experience as a stimulus for reflection . . . and for future actions of attending."[31]

Interacting with microorganisms, attuning to and evoking their agency, requires a specific set of methodologies and tools. Although some important processes have explicit microbial components—for instance fermentation, decomposition,[32] and certain forms of illness—microbes are, for the most part, invisible; we cannot directly observe their behavior as the ethologist might observe her animal of study, and it is in this sense that attuning to microbes requires that we "sense" and "amplify" their agency.[33] Beginning with the task of culturing, growing, and caring for microbial organisms, our

26. Bastian, "Towards a More-than-Human Participatory Research," 20.
27. Gibbs, "Animal geographies I."
28. Gibbs, "Animal geographies I," 773.
29. Hodgetts and Lorimer, "Methodologies for Animals' Geographies," 286.
30. Lorimer, Hodgetts, and Barua, "Animals' Atmospheres."
31. Dowling, Lloyd, and Suchet-Pearson, "Qualitative Methods II," 827.
32. Abrahamsson and Bertoni, "Compost Politics."
33. Whatmore, "Materialist Returns," 606.

engagement with them can be mediated through certain microscopic, biochemical, and metabolic tests.[34] We might also think about how these kinds of techniques could be developed in conversation with the genomic methods that Hodgetts and Lorimer outline and that provide a detailed view of the composition of particular bacterial communities.[35]

It is potentially through such techniques that we may approach the question of interspecies communication with microbial life. Microorganisms participate in extensive communication with each other and across species boundaries with larger multicellular organisms. This communication often takes the form of chemical messages called quorum sensing (the archetypal model of microbe-microbe communication) and allows a large community of microorganisms to sense and respond to population density, tune their metabolic responses, and effectively act as a coordinated multicellular unit. Chemical messaging between microbes and larger organisms such as humans can give rise to embodied forms of communication that interact with and sculpt personal and medical practices.[36]

But how might we go about communicating with environmental microbes that live outside the confines of the human body? Although we might speculate on newly forming embodied symbioses between larger organisms and plastic-degrading microbes that would allow those organisms to sense and respond to microplastic pollution,[37] our encounters with these microbes in the short term are more likely to proceed via mediated approaches that involve culturing, growing, and caring for them outside the body. For example, performative engagements with microbes have attempted to cross the human-microbe divide via artistic, chemical, and biological tools. One recent project, the Co-corporeality project,[38] has created an interface called "E-FEED/ER" that translates human emotional responses into bacterial growth via administration of nutrients and other factors. Other artists have created sensory links between humans and fungi that realize "non-linguistic forms of awareness and exchange—sonic, electronic and metabolic" between humans and nonhumans.[39] In the next section I aim to think about how different forms of interspecies communication might be adopted and geared toward enrolling microbes as participants within a research project focused on responding to plastic pollution.

34. It is important to point out that I am not suggesting such tests are a window onto an objective microbial world. My review of these techniques is expressed in the spirit of rendering ourselves sensitive to microbial presence and agency. Their deployment is "diagrammatic" rather than representational, in the sense elaborated by Hinchcliffe et al. ("Urban Wild Things")—that is, not simple representations of the microbial world but a form of writing that they themselves contribute to.

35. For instance, metagenomic techniques can be used to sequence the DNA of all microbes present in a particular environmental niche.

36. Beck, "Microbiomes"; Greenhough, "Where Species Meet and Mingle."

37. Jang et al., "Impact of the Insect Gut Microbiota," 34–36. See also Koppel et al., "Chemical Transformation."

38. Co-corporeality, "E-FEED/ER."

39. Rapp, "On Mycohuman Performances," 2.

Engaging with *Ideonella sakaiensis* in Responding to Plastic Pollution in the River Lea

To begin putting some of these concepts into practice, I have recently begun a project at the River Lea, a highly engineered and canalized river network that courses throughout East London. Plastic pollution is an ongoing problem in the River Lea, as it is in many UK rivers. A Greenpeace report from 2019 that documented the levels of microplastics in UK rivers displays numerous photos from the River Lea that serve to represent an "invisible" problem and emphasize the ubiquity of plastic and microplastic pollution in UK rivers.[40] In entering the high-profile issue of pollution in UK waterways, my aim is to explore how *I. sakaiensis* might be engaged as a collaborator in responding to this issue. In line with the more-than-human participatory research discussed above, my ongoing goal in this work is to "explore how a broader account of community—one that recognizes [and enrolls] the active participation of nonhumans—might not only challenge understandings of how research can be co-designed and co-produced"[41] but also be a pragmatic and equitable response to the issues of plastic pollution.

This project has centered around a number of visits to the river and attempts to attune to the site's specific historical context and ongoing issues with plastic waste. In walking along the towpaths and footways of the River Lea, its canalized navigation, tributaries, and cuts, my goal was to be led by the presence of plastic waste, and to tune into discarded plastic as a site for colonization by microorganisms. Plastic waste is composed of a spectrum from large, identifiable objects—such as bags and bottles—to weathered fragments and microplastics. All these objects serve as colonization sites for microorganisms. Microplastics can be sampled through simple filter constructions,[42] but in my initial fieldwork I have been focusing on larger, more readily observable plastic waste. The river's history is closely intertwined with the industrialization of the West Ham region in the sixteenth and seventeenth centuries, during which time it was affected by heavy pollution from adjacent "noxious industries."[43] Although the river and surrounding Lea Valley area are now best described as postindustrial—primarily a site of leisure and tourist activities—and the heavy industry has moved out, pollution has not.

As I walked along the river I saw coots nesting and living among plastic waste that had become embedded in the planters on the side of the canal. Some recognizable items were visible, while others were at different points of disintegration. Plastic items would collect in mini constellations in the center of the river and aggregate between moored boats and the bank of the canal, entangled with reeds, macro-algae, and other discarded items. My meanderings down the river eventually brought me to a point known as Old

40. Greenpeace, "Upstream: Microplastics in UK Rivers."

41. More-than-Human Participatory Research, "About."

42. For instance "BabyLegs," which "is an aquatic trawl (net system) for monitoring microplastic pollution and biological composition of surface water." BabyLegs is easily built from "a floatation device [e.g., a plastic bottle] attached to a set of children's tights. . . . The fine-knit mesh of the tights traps microscopic bits of biological materials as well as nurdles and other plastics found within the water." Public Lab, "BabyLegs."

43. Clifford, "River Lea in West Ham," 49.

Ford Lock, a double lock and weir that is built on the site of a natural ford in the river that has been used for crossing since the Roman period. Only one side of the lock is used for moving boats today, while the other serves as a transfer point for cargo—often plastic waste—carried in large container barges. On this latter side all kinds of waste objects accumulate and fester, and the site serves as a veritable laboratory for biotic intra-action, community formation, and evolution. The lock is both an accumulation point for unintended (plastic) debris, and a conduit, or transfer site, for the purposeful mobilization and terrestrial transfers of (plastic) waste, which led me to focus on this site for the remainder of the project.

Microbial Choices, Communities, and Outcomes

How to enroll *I. sakaiensis* as a participant in responding to the issue of plastic pollution in the River Lea? The next steps in my research are focused on culturing, attuning to, and caring for *I. sakaiensis* in the laboratory. This microorganism can be grown in a relatively simple growth medium, and under these conditions it will also metabolize PET as its sole carbon source. After initial experiments in culturing *I. sakaiensis*, I plan to begin identifying plastic waste in the lock and transferring it to these cultures in the lab. Moving plastic from the context of the river to a specific bacterial culture combines the agencies of humans and microorganisms, providing opportunities for *I. sakaiensis* to begin metabolizing the waste. *I. sakaiensis* has the capacity to visually degrade PET sheets, which will serve as a readily observable proxy for their agency.[44] By bringing *I. sakaiensis* into contact with plastic debris that is ordinarily out of its reach (this bacteria has not yet been identified in UK waterways), the capacities of humans and microbes combine in the process of biodegradation (and potentially ecosystem regeneration), a process that equally means caring for *I. sakaiensis*, attending to their growth and behavior, and remaining attentive to the potential for other organisms to take hold in the culture.

In extending participation to these microbial interlocutors, my goal is to begin asking *I. sakaiensis* questions such as "what do you need?," "what do you like?," and "what would you prefer?" Szymanski suggests that communication between humans and microbes in the lab often "happens by way of [microbial] growth rate." According to Szymanski, microbes "communicate their satisfaction or dissatisfaction" with certain conditions "by growing at a normal rate, by growing more slowly, by refusing to grow at all, or by dying."[45] These questions are mediated via the various environmental conditions—such as the growth medium—that human handlers provide microorganisms with in the practice of culturing them, while the answers to such questions are reflected in the growth rate and metabolism of the microbes.

Asking microbes the question of what conditions they prefer might be achieved by offering different environments from which the organisms can choose and then

44. Microscopic analysis can aid in visualizing the metabolism of PET by *I. sakaiensis*. See Yoshida et al., "Bacterium That Degrades," supplementary materials.

45. Szymanski, "Who Are the Users of Synthetic DNA?," 12.

following their responses to these conditions. In configuring these experiments to follow the choices and responses of the microbes, the ongoing evolution of the project will be influenced by their decisions. Responding to the issue of plastic pollution in the river will, in this way, emerge through the ongoing interaction and collaboration between humans and plastic-degrading microbes.

The formation of actor networks usually entails the punctualization of certain actors in the process of working toward specific goals and outcomes. This often means speaking for nonhuman nodes in the network, of predicting, constraining, and manipulating their agency. If these nonhumans fail to act a certain way, if they speak "for themselves,"[46] scientific experimentation is disrupted. But as Michel Callon remarks in his seminal study on the scallops of St. Brieuc Bay, "It is . . . difficult to speak in the name of entities that do not possess an articulate language."[47] In these experiments with *I. sakaiensis* we are not setting up a network with a specific goal in mind; rather, the network is being formed to allow *I. sakaiensis* to speak for itself, an orientation that welcomes disruption and that keeps goals and outcomes open and negotiable.

So moving beyond the relative binary of growth rate and its equation to questions such as "what do you like?" and "where does it hurt?" can we become more "nuanced in our modes of listening"[48] to microbial others? What other questions might we pose to them, and through what means might we interpret the answers to these questions (if, indeed, they are answered at all)? If our microbial companions grow differently under certain conditions, for instance, is that because they are doing something else that we have not yet understood? Rather than categorizing microbial behavior within fixed reference frames, we might learn that slow or "abnormal" growth reveals certain facets of their agency, as well as answers to questions we have posed to them unknowingly; part of the issue, then, is figuring out what these questions are. One suggestion for getting into these more detailed questions might be to follow the sequence and structure of the PETase gene as we begin to culture and communicate with *I. sakaiensis*. Does the gene sequence remain the same, or does it undergo various changes? In these ongoing experiments with microbial life, microbiology and scientific expertise become critical and provide a "human intermediar[y]" that helps "facilitate engagements"[49] with microbes.

In thinking how scientific expertise might help us engage and communicate with *I. sakaiensis*, I am led to the idea that *I. sakaiensis* itself may help us communicate with

46. Callon, "Some Elements," 210.

47. Callon, "Some Elements," 210. Callon studied the formation of an actor network between natural and cultural entities by following three scientists as they attempted to form relationships with fishermen and scallops in Brittany, France. The scientists were attempting to import to France a Japanese technique for scallop fishing in which scallop larvae were cultivated in closed nets prior to shell formation. Callon discusses how the network was betrayed by certain components; the scallops and fishermen "detached" themselves from the network within which the scientists had attempted to enroll and mobilize them.

48. Szymanski, "Who Are the Users of Synthetic DNA?," 12.

49. Bastian, "Towards a More-than-Human Participatory Research," 21.

the wider plastic-associated microbiome. Microbial existence in general is decentered, mutable, and an emphatically social affair; these organisms incessantly exchange DNA, metabolites, and other chemical messengers in complex interspecies relationships. Collaboration between humans and microbes, then, is never going to unfold as relationships between "pure" entities or separated individuals; neither humans nor microbes live in isolation. Discarded plastic is a home for heterogeneous microbial communities that form dense multi-species communities, a fact that was reflected in the plastic I had located in the lock. Moving from the scale of the river network to the micro-spatial detail of plastic waste revealed rich textures and spatialities that provided sites for microbial colonization: folds, creases, and indentations cut through and across colors that made up the visual decoration on some of the items (fig. 1). These plastic surfaces were colonized by small plant-like organisms (fig. 2)—a species of algae—which indicates a finer level of bio-attachment, that of microbes invisible to the naked eye.[50]

Heather Paxson and Stefan Helmreich[51] have pointed to the emerging fascination with microbial ecosystems as both descriptive and prescriptive models of human-nature relations. Although their analysis centers on the ideological dimensions of such "models" of nature, I would suggest that the process of (multi-species) community formation as microbes encounter and colonize plastic waste can be thought of as both a model for, and inciting factor to, the formation of larger more-than-human communities around the issue of plastic waste. In the first instance, the emergence of plastic-associated and plastic-degrading microorganisms has brought together researchers from different academic disciplines, as well as various stakeholders concerned with issues of plastic pollution.[52]

But moving to the micro-logical domain of their embodied corporeal, metabolic, and social agency and expertise, rather than solely their representational (and instrumental) capacity in assembling (and governing) human actors, I am now thinking about how *I. sakaiensis* has the potential to serve as an interspecies mediator between the human world and the world of the plastic-associated microorganisms from the lock. Because *I. sakaiensis* can be cultured in the lab on the one hand, and yet has the capacity to communicate and interact with other microorganisms on the other, it can relay messages between these two worlds; as *I. sakaiensis* interprets, responds to, and communicates with indigenous plastic-associated microbes, it translates these messages back to us at the macro scale through changes in growth and metabolism of plastic.[53] Similar to

50. Smith, Stanton, and Law, "Plastic Habitats."

51. Paxson and Helmreich, "Perils and Promises of Microbial Abundance."

52. This includes biotechnology companies who are interested in capitalizing on the potentials of microbial-mediated plastic bioremediation.

53. Here I use the term *translation* in the sense proposed by Michael Cronin, an interspecies "eco-translation" between distinct yet overlapping lifeworlds; Cronin, *Eco-Translation*, 73–87. While my usage has some connection to the ANT usage, this form of translation is more about the interpretation of signs across species borders, rather than the gelling of actors into a network organized toward a specific goal or interest.

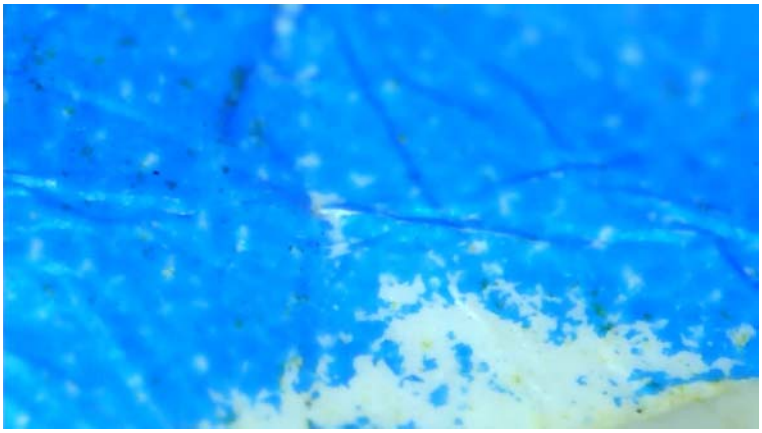

Figure 1. Microscopic image of plastic waste with creases, folds, and weathering identified in the Old Ford Locks. Photograph by the author.

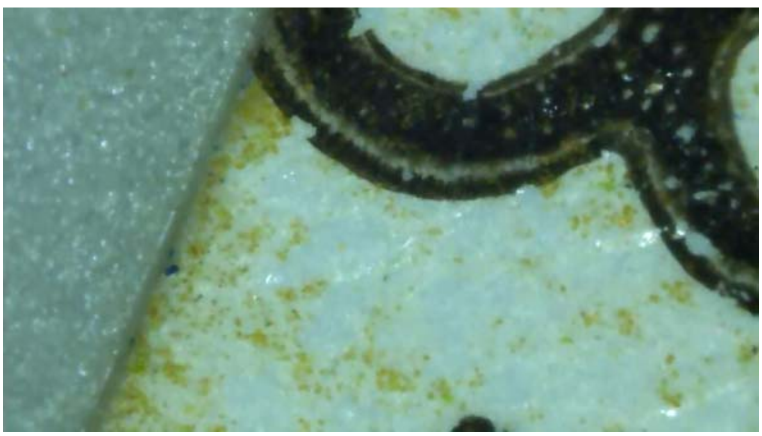

Figure 2. Microscopic image of plastic waste with algae attachment identified in the Old Ford Locks. Photograph by the author.

the experiments outlined above, *I. sakaiensis* can begin to choose the microbial companions that are important to its growth and metabolism, a choice that we might be able to follow through techniques like serial dilution culture and metagenomics. *I. sakaiensis* opens up a line of communication between us and these other plastic-associated microorganisms as we begin to follow its decisions and agency in the evolution of the project.

Just as "canine collaborators"[54] serve as an interspecies mediator between humans and sheep in the act of herding, in this experimental scenario *I. sakaiensis* becomes a hinge point between the human and nonhuman worlds: partially domesticated, partially feral, culturable in laboratory conditions and legible to its human handlers, yet able to interact with other microbial species through unknown exchanges and interactions. We might think of *I. sakaiensis* playing the role of a point of first contact in a multispecies ethnographic research process, a community leader that mediates between lifeworlds that are radically distinct from each other and yet equally assembled around the process and issue of plastic pollution, while also mediating between the lab and fieldwork.

54. Donati, "Herding Is His Favourite Thing"; Despret and Meuret, "Cosmoecological Sheep."

In attempting to form these kinds of engagements, however, how do we decide what is an interesting or important outcome? Although collaboration might combine the agencies of humans and microorganisms, a sticking point in conceptualizing what directions this collaboration might take is the general understanding of bioremediation as a goal-driven process governed by targets and outcomes that are often anthropocentric and taken as self-evident. But in adopting the principles of participation and coproduction might we ask the microbes themselves what kinds of outcomes they are interested in? There is a sense in which the outcomes that are of interest to microorganisms might be at odds with the interests of researchers, especially those working within the confines of academic and industrial biotechnology. Changes in phenotype that allow microorganisms to exploit new resources for growth, or that circumvent the goals of human researchers, might be dismissed when interpreted from the vantage point of control and precision, but for the organisms themselves such changes might be beneficial and desired. These kinds of considerations suggest we walk a fine line between collaboration, negotiation, and the potential risks involved in allowing certain microorganisms a "free rein," especially in the context of pathogenic and antimicrobial-resistant bacteria—and raise difficult questions about what nonhuman participation means.[55] In terms of the plastic-eating microorganism *I. sakaiensis*, there is the ever-present potential that they might become something that doesn't align with what we hope they might, especially in the context of plastic pollution and its remediation.

Conclusions

How then, might we meet "with the microcosmos"?[56] If microbial agency unfolds in deep time and over phenomenal orders of spatial magnitude, our own current engagements with microbes are driven by an increasing sense of urgency. While biotechnology has gone so far in harnessing the power of the microbial world, a cursory glance at the ever-growing data deluge of microbiome research suggests that our purposeful interventions into their worlds—driven by a rhetoric of precision and control—can only go so far; microbial ecology is situated and inherently resists attempts at universalization.[57] It is within this situatedness, and the ongoing relationships between humans and microbes—and others, human, nonhuman, inhuman—that meeting, participation, and collaboration unfold.

Seen and enacted as a participant and collaborator in the issue of plastic waste, the metabolism of *I. sakaiensis*, and the wider plastisphere ecology could "generate alternative and speculative engagements with pollution."[58] These approaches, however, must

55. For instance, see Bastian, "Towards a More-than-Human Participatory Research," 32–33, on the potential perils of participation and the idea of "pseudo-participation."

56. Hird, "Meeting with the Microcosmos."

57. Stengers, *Another Science*, 94.

58. Amaral-Zettler, Zettler, and Mincer, "Ecology of the Plastisphere"; Gabrys, "Sensing Lichens," 354.

be careful not to reify *I. sakaiensis* and other plastic-eating microbes by, for example, reading their agency through the frame of a liberal rationality. The ontology of microorganisms challenges basic assumptions of individuality that would frame these instincts, and it provides us with a more relational, ecological, and processual view of organisms and their interactions.[59] Moreover, these collaborative efforts, I have suggested, sit somewhat uneasily between the methods of the natural sciences and the environmental humanities. Speculative methods for meeting with microbes mean engaging techniques and expertise from microbial ecology to culture and sense microbial life.

These ideas for enrolling microorganisms as participants in research are limited in their scope; they realize interactions between humans and microorganisms within a specific domain and eliminate other organisms and factors that might be important to microbes, such as creating and maintaining relationships with larger organisms like insects. The suggestions raised in this article also necessarily draw from my own experience in the natural sciences,[60] my interest in the technical work of microbiology, and the effort to extend the insights of the environmental humanities to the theory and practice of bioremediation. It is this situatedness that has informed my particular expression of what human-microbe participation might look like and where I am hoping to go with it. Recent calls for "fermentation"[61] as a material and metaphorical method and practice for feminism, for instance, as well as a wider trend toward studying and practicing aesthetic and embodied encounters with microorganisms, are also important and provocative approaches in this regard. I hope my own particular methods and ideas might find a place among these other forms of encounters and contribute to a plurality of approaches that attempt, in one way or another, to broach the human-microbe divide.

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59. Dupré and O'Malley, "Metagenomics."

60. My PhD and postdoctoral research to date have been within the field of cell biology as applied to modeling and studying neurodegenerative processes.

61. Fournier, "Fermenting Feminism."

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