Who knows what a microbe is? The variable texture of microbial identity in agricultural products, regulations, and fields

Abstract

Microbial products are becoming common alternatives for pesticides and fertilizers in light of the unsustainability of chemical products. What the microbes in these products are, though—that is, how they are enacted—varies across regulatory, research and development, and growing spaces, and that variation matters to how they are regulated. From document analyses, interviews, and ethnographic work with scientists, growers, and policy actors, we find that these microbes are epistemically uneven, sometimes with pinned-down identities, and sometimes with loosely woven textures with holes. Amid calls to tailor regulations specifically for these products, we suggest that regulations predicated on discrete identities and predictable and controllable functions will fail to account for all users' experiences, and that regulation may need to learn to live with the lacy texture of microbes across contexts.

Introduction

Conventional agriculture runs on inputs—not just oil into tractors, but also into soil. The petro-derived fertilizers that drove the "green revolution" continue to shape agricultural soils, still largely conceived as inert substrates. Nitrogen, phosphorus, potassium and pesticides are poured into and onto soils to support crop growth and yield, with "yield" defined in the short-term through a single season's production and profit rather than through the land's long-term fertility. Meanwhile, regenerative, biodynamic, and other sustainability-minded forms of agriculture have long approached fields as richly multispecies endeavours of plants, animals, insects, and the microscopic life inhabiting and making up the soil itself. While the idea of microbial inoculants has been around in US agriculture for more than a century, it is now more prevalent in conventional systems, where multispecies considerations of agriculture (agroecology) have become part of company narratives toward more self-sustaining soils and more sustainable futures. "Soil health" is becoming a centrepiece in sustainability conversations, even within Big Ag (Krzwoszynska and Marchesi, 2020), and noticing the importance of microbial worlds has become a prominent discourse in social science, whether in discussions of soil and agriculture (e.g., Lyons, 2020; Puig de la Bellacasa, 2017 & 2019) or the human body and other geographies (e.g., Lorimer, 2020, Greenhough et al., 2020). "Healthy" bodies and soils are coming to be understood as integrated ecosystems—as homes for many living things or even as living things themselves-- not merely inert matrices to support crops. Our interest in this paper is to investigate how microbial identity is understood in a rapidly expanding industry and how, specifically, *what a microbe is*, is enacted by different groups (R&D scientists, regulators, and growers) as beneficial agricultural inputs.

In this context, the green revolution's chemical inputs are now understood to be both unsustainable and potentially toxic to soil life (Pingali, 2012, Banjeree et al., 2019). But, because yields need to be sustained and/or increased and soil health has often been compromised, inputs cannot easily be eliminated. Instead, product makers are turning towards creating replacements that support longer views of agricultural sustainability. Simultaneously, scientific and societal appreciation for the value of microbes in supporting the health of many environments has expanded, as have technologies for understanding and employing them (Paxson & Helmreich, 2014). Consequently, agricultural products containing microbes or microbially derived compounds are increasingly being explored in conventional field cropping systems to support crop growth, suppress pests, and sustain soil ecosystems. Most agricultural giants such as Bayer (which acquired Monsanto in 2018) and Corteva (a subsidiary of Dow Chemical) now sport microbial product amendment lines. Although such amendments are only occasionally one-to-one replacements for non-living chemical products, in the absence of regulations developed specifically for microbe-based products, microbes tend to be subject to regulations similar to their chemical predecessors.

In this study, we ask: how is microbial identity enacted when living microbial products are slotted into regulatory frameworks designed for non-living chemical products? How do research-and-development (R&D) scientists, growers, regulators, and regulations make sense of the microbes in these products? And where might tensions exist between microbial products and the expectations applied to them? We draw on 23 interviews with scientists employed at companies that make these products, agriculturalists who use them, and stakeholders working in and around agricultural policymaking in the United States. We asked about the microbes with which they work, the types of products to which those microbes contribute, and their perspectives on current and potential future regulatory architectures for those products. We then contextualised what they said in the wider academic, grey, and industry literature about the role of microbes in growing crops. In addition, we conducted a more in-depth ethnographic project at a small agricultural microbial company. This project is the focus of a different paper in preparation, but the data certainly inform the discussion here.

What we found were different enactments of microbial identity in each sector. In the realm of policy, regulations require pinned-down, discrete microbial (genetic and functional) identities. In turn, scientists working for the companies that produce these products must *choose* how (by what method) to pin an identity onto microbes, in addition to choosing which genetic or functional identities to include in a product. In contrast, growers gather data about microbial identity differently; that is, through their sense-able presences as expressed through the complex interactions that comprise a field—that is, as a gestalt rather than as a species or even a function. Moreover, they do so through assembling those observations across time, characterizing a microbe as a pattern or an effect rather than a discrete thing such as a species name or a genome sequence. This ontoepistemic disconnect between microbial identities on labels and microbial identities in fields suggests that regulatory frameworks—even if configured for microbes as microbes, rather than as chemical-equivalents—will likely be unable to account for how microbial identity is enacted in any practical sense.

But more than that, our analysis points to a possibility that because microbes are indeterminate in multiple ways, *no one* may know what a microbe is *across* these shifting contexts—from lab to production line to agricultural field, for example—because microbial identity varies unpredictably and unevenly across them. Further, this lack of coherence might not be resolved simply by learning more about agricultural microbes, or by implementing one standardised view. That is, the gap between what a microbe is on a label and what a microbe is in a field is not a "productive" form of not-knowing that enables scientists to continue pursuing further epistemic certainty indefintely (Lehman 2021; Reinecke and Bimm 2022). Rather, we argue that sites or regions of microbial unknowability may be a feature of more-than-human agricultural landscapes that current regulatory frameworks have difficulty acknowledging. We wonder about the capacity of these frameworks to allow microbes to be as uneven as the texture of agricultural microbial enactments are themselves.

The uneven texture of microbial enactments

Copious scholarship in the tradition of actor-network theory and material-semiotics tells us that our epistemic makings of what "things" are—microbes per se—are not only constructed *in* practice, but also are assembled differently *through* multiple practices, such that further work is required to assemble these into a shared sense of a stable thing (e.g., Mol 2003). As such, rather than thinking of things as continuous, congruous, and smooth across their enactments, we might be better off thinking about the texture of things across enactments as being a variable, dynamic, uneven, and inconsistent fabric. Some ideas of things are dense, relatively immobile, solid, more shared across practices and more stable. Others are patchy, uneven, loosely woven with holes, invisibilities, and inconsistencies; they are "slippery" as are, for example, enactments of wild and farmed salmon (Law and Lien, 2011). Because things are assembled and these assemblages are textured like fabrics, perspective matters; the location in the fabric matters; "the same thing" may not be the same thing to everyone, everywhere, everywhen, and therefore what we know about microbes is always factish, or provisional (Latour, 2012; Flachs, 2019). A microbe on a product label might be a taxonomic genus or a quantity of spores, whereas in a lab that "same microbe" may be a phenotype under a microscope or petri dish, and in a field, in that "same microbe" might appear through other cues such as plants with healthy roots.

Figure 1: Lacy fabric: discrete flowers in a field of holes

In asking "who knows what a microbe is?", we take inspiration from Annemarie Mol's question: "who knows what a woman is?" (Mol, 2015). Mol's point is to demonstrate that a woman is not a very tightly woven thing; different disciplines (and ways of knowing beyond academia) have very different ideas about the answer to the question of what a woman is and are linked to who is doing the knowing, how the knowing is done, and whom the knowing is for. We want to make a similar move here. Microbes are like women. While some microbiologists learn about microbes by growing them in isolated cultures, others do so by sequencing community DNA from samples of soil or seawater, with the potential for strikingly different conclusions about which microbes exist and what they can do. Since microbial product regulation relies on knowledge claims about microbes, we need to get at the texture of the fabric—how different enactments of microbes are assembled—to understand the work that regulations might or might not be able to do.

Further, these variable epistemic enactments and subsequent assemblages of what things *are,* are not easily separable from their ontological properties. As has been demonstrated elsewhere across the growing critical microbe-studies literature, microbes are also ontologically complex and hard to pin down (O'Malley, 2014); taxonomic designations, for example, such as species, do a poor job of containing them (Ward et al, 2008; Murray et al., 2021) and the metabolic and phenotypic aspects of microbes that we use to characterize them *functionally*, change readily across time and space (e.g., Nguyen et al., 2021). We therefore began this analysis of agricultural microbiome products with the expectation that the fabric of how microbes are known in agricultural products would not be smooth and solid. After investigating practices that enact microbes across agricultural-product contexts (regulation, R&D, and agricultural practice), we have come to think of them as them lacy: woven so that in some places discrete notions of what microbes are, are formed—blossoms or flourishes in the fabric; moments of discrete knownness through labels or lab results—but in between these, a sort of gauze; a slippery fabric filled with holes (Figure 1). Microbes as we know them—that is, human enactments of microbial life in various contexts—feel like islands of knowing, flowers in the gauze, but are only ever single states of microbe-ness from single vantage points. Try to pin down a microbe and they're inclined to slip—something we see even in regulatory frameworks designed around an assumption of fixedness.

Commented [A1]: This reminds me very much of Susan Leigh Star's work on boundary objects and "interpretative flexibility"

This sense of microbial not-quiteness and the multiplicitous interpretations of microbes by various stakeholders make microbes rich and delightful subjects for critical analysis, but troublesome subjects for regulation. Regulatory bodies such as the US Food and Drug Administration (FDA) and the US Environmental Protection Agency (EPA) *do* make regulations around microbes. However, the regulations they make can cause plenty of trouble for, for example, artisan cheesemakers, whose ways of knowing what good cheese is—meticulous production practices, evaluation via visual and olfactory cues, etc.—don't always align with how the FDA knows what constitutes a safe food product (Paxson, 2008). Regulations around agricultural microbial products similarly attempt to sort "good" or safe microbes from "bad" or dangerous ones through enactments of microbes that do not necessarily align with how agriculturalists judge microbes. Further, R&D scientists' inside knowledge of their microbial product's capabilities also only partially aligns with the judgements that regulations require. Herein lies the trouble: making regulatory enactments of microbes meaningful to scientist and grower enactments of microbes requires a lot of work, and sometimes does not work at all. Much of the challenge seems to lie in the difference between the solid-ish moments of "knowing" (e.g., obtained by lab results and presented on labels) and the quite varied textures of how growers know microbes once they are in the field. So, our question becomes: who knows what a microbe is? When, where and how do they know it? In the next section, we discuss the ways in which microbes are slippery to begin with, and in the subsequent sections we discuss the modes of enacting microbes in regulations and R&D. Finally, we think about how growers enact microbes and what discrepancies among these perspectives this means for our abilities (or inabilities) to even know what a microbe is?

Microbial identity: slippage in taxonomic and functional classifications lead to epistemic inconsistencies

Humans come to know microbes through diverse practices, many of which do not extend from modern Western microbiology (e.g., Giraldo-Herrera, 2018; Hey, 2019; Muenster, 2018). However, for the purposes of regulations and R&D settings in the US, we can say that microbes tend to be formally or officially categorised either taxonomically (e.g., phylum, species, strain) or functionally (e.g., "Nitrogen-fixer" or "Phosphorous-solubiliser"). Because one works in capacities as identified by humans and one works in genetic or morphological differences, these two systems of knowing microbes do not always produce the same distinctions, in ways that set up other kinds of epistemic inconsistencies.

Taxonomic classification is a prevalent way of knowing biological life, but also a long-standing problem for microbes. It is well-known that the concept of species doesn't work well for bacteria, yeast, and fungi (e.g., Doolittle & Papke, 2006; Staley, 2006). Microbes are prone to exchanging genetic material “horizontally” with other cells in ways that often disrupt two core taxonomic principles: the assumption that any one creature has one and only one fixed genome throughout its lifetime, and the idea of a “species barrier” that means members of different species are less likely to mate, combine their genomic material, and produce viable offspring. Microbes also trouble ideas of phylogenetic “trees” with tidily branching paths that begin with common ancestors and feather out into families of more recently differentiated cousins. Instead, maps of microbial relations are highly rhizomatic and reticulate.

Nevertheless, in the absence of a yet widely accepted alternative way to handle taxonomy (though see Hedlund & Whitman, 2022), microbes remain known via species, delineated by genetic material. Species designations also underpin most agricultural microbial regulation. One common point of reference are designations made by the Animal and Plant Health Inspection Service (APHIS) which uses the prevalent pathogen lists (e.g., prevalentbacteria.org, prevalentfungi.org) to delineate species that may be moved across state lines with and without permits, such as native or naturalised plant pests or biocontrol agents (aphis.usda.gov, 2020). The federal Health & Human Services and the US Department of Agriculture (USDA) also maintain the “Select Agent Program” which, in 2021, contained 233 microorganismal species (including viruses) that are considered severe threats “to public health and safety and to animal health or products” (selectagents.gov, 2021). Corporate researchers who want to include such species in commercial products would be hard pressed to demonstrate the safety of these “outlaw” microbes, though there are occasional exceptions, one of which, a *Burkholderia* species, will be detailed below. If there is enough literature supporting the safety of a particular strain, some microbes become generally recognised as safe and are easier to pass through both federal and state regulations (as discussed later). However, far more microbes occupy regulatory grey zones, that is, neither generally recognised as safe nor outlawed—either because they remain taxonomically ambiguous (such as in the case of microbes newly “discovered” through bioprospecting) or because their range of potential behaviours cannot be cleanly predicted.

Functional classification of microbes, or the grouping together of microbes by their metabolic capacities or effects on organisms or ecosystems, is also quite prevalent in R&D settings. In practice, species designations are not always the most useful way to classify microbes in agriculture for reasons that have nothing to do with taxonomic messiness; rather it is that multiple kinds of microbes may perform the same agronomic job (in ecologies this is sometimes called functional redundancy). Researchers and other humans who work with microbes often talk about them in terms of their signature function or capacity, that is, the *capabilities* that professions or industries value most among the repertoire of what a given microbe can do. For practical purposes in agriculture, it may be less useful to know a taxonomic designation such as species or strain names and more salient to know that a microbial community includes a nitrogen-fixer, phosphorous-solubiliser, or a fungicidal bacteria.

The conflation of species identity and functional capacity creates a tension for regulating and using microbe-based agricultural products because a species name on the label does not always stably align with a single set of functions that this species will reliably perform. Labels are required to describe what a product does, but what a product does may change with how and where it is used. Microbes, like other living things, respond to their environments. Moreover, they may also undergo genetic changes as they reproduce and dwell with others, so that the microbe that goes into the bottle may not be identical to the microbe that proliferates in the field in either genome-based taxonomic or functional terms.

This imperfect alignment between taxonomy and function becomes important for companies that must defend, simultaneously, the safety and efficacy of their products. Companies, in keeping with contemporary practice in other industries and research areas, may establish microbial taxonomic identity by sequencing only a small portion of a strain's DNA (a portion often known as 16S) However, this portion of the DNA may, indeed, is likely—to remain stable even as other changes occur that matter to a microbe's phenotype or functional capacity (Terzaghi and O'Hara, 1990). Consequently, when microbes are identified via 16S, taxonomic and functional identities may not move in lockstep.

Not all ways of knowing microbes revolve around species. Growers and extension scientists gather data differently and may know microbes through observation of crop health or soil texture or changes that occur in crops and soils over seasons and decades. Microbes influence nutritional status or field quality in ways that can be perceived sensorily: green plants, rapid growth rates, rich black soils, vigorous root growth shown off on agricultural microbe social media, or gestalt senses of crop-soil complex "health". In agricultural praxis, knowing what is effective often comes through accumulated experience over time and across contexts, looking for patterns across mulitple "reaction norms" or range of observed variation of a crop, a field, or of a microbe-containing agricultural product (Figure 2). Growers and plant breeders have long understood that there is no such thing as a ubiquitously good crop variety, that is, one which is always good in all years, fields, conditions, etc. Further, the challenge of predicting crop performance has grown only more difficult in the weird environments produced by climate change (Iizumi & Ramankutty, 2016; van Etten et al, 2019). Decisions about what varieties to plant are often made based on long-term, cumulative, and often intuitive knowledge and then bet-hedging against unpredictability. In the past, in large-scale contemporary monocultures, the slopes of linear crop reaction norms that have helped predict performance and major crop-environment interactions have been relatively well-characterised. More to the point, crops planted anew each year from commercial seed do not mutate, exchange genes, or otherwise evolve within or across generations. Microbes, which do mutate, exchange, and evolve rapidly, are less linearly predictable than plants; they also have shorter histories of deliberate human observation. For microbes, there

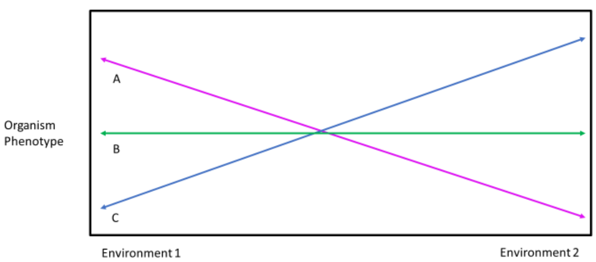

*Figure 2.**Reaction Norms**. Growers **expect** that living things will vary across environments. Reaction norms are a commonly employed visual in agriculture to describe variability of living things, e.g., crops across environments. "Environments" can be considered as any number of contexts such as fields, locations, years, or different conditions such as high and low rainfall.*

are more spaces of unknowability that cannot necessarily be predicted across time, environment, and context; a difficult place from which to regulate.

What regulators know a microbe to be

We begin with how regulations "know" microbes or, in other words, with how microbes are enacted through microbial product categories. Regulations dictate microbial product categories (e.g., biopesticide) for labels and markets. Defining these categories is central to enactment of commercial agricultural microbes. Mirroring the categories employed for synthetic chemical products, microbe-containing products are most often classified either under biopesticides or biofertilizers/biostimulants. Because different categories of agricultural products are regulated by different agencies, producers think about which regulating body they will face before making discrete claims about individual products and the ingredients they contain. Those claims may be only tenuously connected to the potential activities of the microbes inside the bottle in that many microbes do many things and only one of those functions need be listed on a label. Therefore, regulations apply to what a company *claims* a product does—and companies are not obliged to openly claim that their microbes have all the functions they may know them to have.

In the United States, any agricultural product that claims to kill things (to work as a pesticide) is subject to regulations set by the federal Environmental Protection Agency (EPA).[i] This includes chemical and biopesticides: fungicides that kill fungi, herbicides that kill plants, insecticides that kill insects, and so on. Once "pesticidal intent" is claimed, a product's risk is evaluated on the basis of its individual *ingredients*. Microbes, in this case, are an ingredient. For every taxonomically distinguished microbe in a -cidal product, a company must provide evidence that that microbe is safe for non-target organisms (it kills only the organisms it is meant to). For microbes already characterised for agricultural use, adequate evidence can come from an existing body of literature. For unfamiliar microbes, companies must make statements about both taxonomy and provide proof of non-toxicity, either of which may raise a rationale for refusing product approval.

In contrast, products which claim life-*stimulating* effects—biofertilizers and biostimulants—are not typically regulated by the EPA, but by individual state governments as each sees fit.[ii] Such products encompass a range of plant nutrition-supporting functions beyond basic fertilizers such as avoiding, correcting, or preventing nutrition-based plant disorders (e.g., blossom end rot, or chlorosis, etc.); improving soil or seed nutrient conditions for better root growth; supporting or improving organic matter biodegradation; optimizing soil conditions for increased "plant vigour" or "abiotic stress resistance"; improving overall plant nutrition or nutrient uptake; and so on (EPA Regulations, 2023). The modes of action through which microbes may perform these functions are similarly varied. The EPA also judges certain modes of (non-pesticidal) biostimulant action (known as plant growth regulators (PGRs)) to fall under its authority as "enhancing, promoting, or stimulating fruit growth and development; inhibiting or promoting sprouting; inducing, promoting, retarding, or suppressing seed germination; and enhancing or promoting "crop, fruit, or produce colour, development, quality, or shape". So, not only are the positioning of a microbial pesticide and its subsequent regulation defined by the claims of the producer, the modes of microbial action which subject a product to EPA regulations are slippery. It can be quite tricky to distinguish a product that promotes vigorous plants from a product that promotes things attached to vigour such as fruit development or quality because these effects often travel together. Therefore, where, by whom and for which qualities a microbe is identified and regulated is slippery fabric to begin with.

The EPA requires that microbes employed in products under its jurisdiction be "deposit[ed] in a nationally recognised culture collection. For a microbial species to be recognised as a species with an internationally authoritative species name, it must be held in pure culture in two separate, internationally recognised culture collections. (This requirement raises issues for microbes that cannot be cultured or depend on the presence of another organism for survival, and the global microbial taxonomy community is reconsidering and revising it.) In fact, the microbial product (and intellectual property) worlds often operate at the level of *strain*, a finer distinction than species. Bacteria evolve quickly and thus exhibit a high degree of genetic variability. Maintenance of a particular strain within a species becomes a way for product developers to attempt to ensure more specific functionality and ownership of particular genetic variants within species. EPA regulations state that "each new isolate for which registration is sought have a unique identifier following the taxonomic name of the microorganism, and the registration application must be supported by data" both to indicate that the strain is what the company claims it to be, and that it is the same or different than strains that have been registered and used before. The EPA has this to say about confirming microbial product identity:

> The product analysis data requirements for microbial pest control agents (MPCAs) parallel those for conventional chemical pesticides...However, due to the unique nature, composition, and mode of action of the MPCAs, there are some important differences. For example, protozoa, bacteria, fungi, and viruses should be identified to the extent possible by taxonomic position, serotype, composition, and strain, or by any other appropriate specific means. This information would take the place of chemical name and structure information for conventional chemical pesticides. In addition, the Agency must be reasonably assured that the methods used and the data submitted are capable of demonstrating that the microbial pesticide used in the field is the same as that which was tested for safety. (EPA website, biopesticide registration section, 2021).

There is much ambiguity to take note of here; the EPA requires microbes be identified *to the extent possible* suggests that even in formal regulatory documents there may be implicit recognition, if not direct articulation of the difficulty of knowing what a microbe is. Regarding other squishy language in this passage, interviewees tell us that in practice, what the EPA means by "reasonable assurance" is determined on a case-by-case basis. But, at least in some cases, this means that proof the pesticide tested is the same as the pesticide applied requires a comparison of genetic or metabolite data from the field to the original lab tests.

The EPA (and some state-level regulatory bodies) will not approve some species under any circumstances because they cause harm or are related to pathogens that cause harm to human, animal, or plant life. For example, the genus *Burkholderia* is (in-theory) off-limits because some members are responsible for a variety of human, domestic animal, and plant diseases, including several species considered to be potential biological warfare agents (Compant et al, 2008). In other taxa, judgements are made at the strain level, as is the case for members of the species *Pseudomonas aeruginosa*. *Pseudomonas* is a close taxonomic cousin of *Burkholderia*, enough so that some species have been moved back and forth between those two groups over time and taxonomic disagreements. *P. aeruginosa* is ubiquitous in soil, water, and built environments. However, some strains are opportunistic pathogens responsible for life-threatening lung infections in people with cystic fibrosis. We interviewed researchers from one company that sought approval for a *Burkholderia*-containing biopesticide product with confirmation of non-pathogenicity obtained directly from the Cystic Fibrosis Foundation. Even so, the EPA required that live microbes be replaced with heat-killed ones. This was possible in this case because the active ingredient was a microbial metabolite retained in the final product, but an additional step and deal-breaker for living microbial products. In the end, a live organism was literally reshaped to look like a chemical product.

Such judgements are even slipperier because pathogenicity is often not a property of a microbe but of a context. Many sometimes-pathogens are routinely present in environments where they do not cause disease, only becoming a problem when environmental disruption gives them room to grow. *P. aeruginosa* is probably dwelling with you right now, wherever you are reading this paper. Unless you have a respiratory disorder, this should cause you no concern; the human respiratory tract is typically efficient at trapping and sweeping inhaled bacteria into the back of the throat where they can be harmlessly swallowed. If you have cystic fibrosis, however, or a disorder that changes how trapping mucus and sweeping cilia function to keep your respiratory tract clean, inhaled *P. aeruginosa* cells can stay put in the lower reaches of your lungs, reproduce, and build antibiotic-resistant biofilms. *P. aeruginosa* only forms biofilms when gathered as a sizable community or "quorum" of cells, making them a non-issue when small numbers of cells are regularly cleared out. *P. aeruginosa* becomes a different kind of microbe in the lungs of someone with cystic fibrosis, with distinctive and situationally pathogenic characteristics. *Clostridium difficile* is another well-known example of a microbe that *becomes* pathogenic, rather than *being* a pathogen; ordinarily present in small numbers in every human gut, it causes disease and even death when sustained antibiotic exposure kills large segments of someone's normal flora, leaving an unusually large ecological niche for the antibiotic-resistant "C diff" to fill.

Examples of such contextual pathogens abound in agriculture. For example, most microbial species that cause the multi-etiology disease known as "root rot," such as *Alternaria*, *Botrytis*, and *Fusarium*, routinely live in agricultural soils. But, it takes it takes damp or otherwise conducive environmental conditions for disease to occur. Certainly, recommending any of these species as a microbial amendment would be hard going, just as arguing for *C. difficile* as a probiotic would be. However, if disease were diagnosed on mere presence of a potential pathogen, then every field and every human would be diseased, even when they clearly are not suffering symptoms. And not all cases are as clear-cut. As we will see in the following section, one of the most favoured agricultural microbes, *Bacillus subtilis*, can occupy different places in the lacy fabric as "beneficial" or "-cidal" depending both on context and the epistemic point of view from which it is enacted.

For products that do not belong to the EPA remit, individual state agencies must choose how to regulate them. Many state-level regulations are concerned with accurate labeling: does the product contain the microbe (and the amount of microbe) on the label and do what the company claims? However, the evidence that companies must provide to address that concern varies. Under relatively strict Oregon regulations, the term "biostimulant" is considered one of several "undefined" and "misleading" terms not allowed on packaging.[iii] What are then called biofertilizers or require comprehensive lists of ingredients and their derivations, plus heavy metal testing reports detailing how the testing was done. Some ingredients, including certain acids and "waste-derived" products, require additional data. Live microbes trigger additional content-verification requirements: an "agricultural amendment product label" (Figure 3), detailing the "number of viable organisms" by weight or volume (typically reported as spores or colony forming units, CFUs) plus a warning statement for all microorganisms established by the American Biological Safety Association (ABSA) to carry an "elevated risk" of human pathogenicity (Oregon Department of Agriculture, 2023). There is, again, a list of bad actors. While each of these modes of pinning down microbial identity comes with its own set of epistemic negotiations, by the time they come to bear upon product regulation, the evidence poured into each taxonomic delineation or list or set of literature has been reduced to a point, a discrete microbial identity that falls to one side or the other of a line that separates acceptable from unacceptable.

At the opposite extreme, Texas operates on what is effectively an honour system. Several interlocuters told us that registering a biostimulant in Texas requires nothing more than mailing in a payment. Therefore, the same microbe—name, genome, and documented function—may be transformed from threatening to non-threatening simply by crossing state lines. Yet whether ingredients raise concerns or not, companies must apply for product approval, separately, from each state in which they wish to be allowed to sell that product—a significant regulatory burden that shapes the claims they choose to make and where they choose to make them in ways independent of the *potential* capabilities of the microbes they contain.

What R&D scientists know a microbe to be

As we have described, microbial products are primarily regulated based on claims made, and secondarily on ingredients listed. The decision about whether to make a particular claim or not represents a branching point and presents challenges for manufacturers of biological products. For example, a company might observe that microbes used in a product have both killing and stimulating properties. By choosing to claim that the product functions as a biostimulant, they may avoid EPA regulations entirely and only seek approval from those states in which they plan to market it. The very same product could also be marketed as a biopesticide, without anything changing other

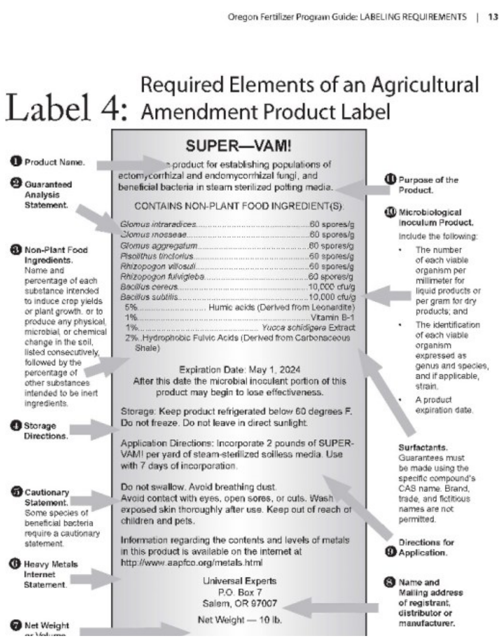

Figure 3. Oregon Department of Agriculture, sample label for microbial product.

than the words on the label and regulating agency.

The cost of seeking EPA approval for a new biopesticide can be substantial (particularly for multi-microbe, i.e., multi-ingredient products), so small companies with limited resources may favour seeking approval for products as biostimulants to avoid that burden. They can do so without modifying the composition of the product because the same microbes may have multiple functions or may do different things in different environments. This is to say, outside of regulatory contexts, the distinctions between biostimulants and biopesticides—the difference between which facilitates life and that which facilitates death—may not be clear. Indeed, it may not exist at all.

Among entrepreneurs and scientists, however, microbial multiplicity is often a selling point: one product can do more than one thing. For example, *Bacillus subtilis* is well-known and loved for its plant growth-stimulating functions because (depending on the strain) it makes soil phosphorus more soluble and available for plant roots to absorb, "fixes" inorganic nitrogen into plant-available organic nitrogen compounds or induces other plant growth-positive functions such as producing growth hormones.[iv] But *B. subtilis* also secretes metabolites that damage fungal cell walls and performs other potential "-cidal" activities (Li et al., 2021). Scientists employed at biologicals companies, as well as technicians and growers who use *B. subtilis*-containing products, observe that they protect against common diseases caused by fungi such as *Pythium* and *Phytophthora*. Though scientific evidence remains correlative and not causative on this point, some also believe that *B. subtilis* affects plant health in broader ecosystemic ways by affecting the community structures of other soil microbiota; as numbers of *B. subtilis* increase in an ecosystem, numbers of other contextually pathogenic microorganisms decrease. *B. subtilis* appears to support "healthy" soil microbial ecosystems, which in turn give fungi with pathogenic potential fewer opportunities to reproduce and take over in disease-causing numbers. By affecting fungal abundance, *B. subtilis* may appear to have fungicidal properties without ever committing fungicide at all.

Such modes or mechanisms of promoting soil or crop health also do not align well with regulatory assumptions largely inherited from chemical products. If a company wishes approval for a biopesticide, that product must pass regulations that assume that its -*cidal* effects occur through killing other organisms, even if the product's anti-fungal activity suppresses fungal growth through ways other than killing. Some companies can and sometimes do position a product as having both stimulant and -cidal effects. Yet many smaller companies with fewer resources rarely bother with that expense, preferring instead to compensate for mandated reductionist labels through nuanced conversation with consumers about multiple benefits. However, while microbial multiplicity and context-responsiveness can be attractive to the right consumers, these attributes can also be stumbling blocks in an industry where products have often been followed by the "snake oil" accusation and purveyors would prefer to advertise products concisely to both consumers and R&D investors; unpredictability does not tend to be attractive in capitalist enterprises. In our interviews, representatives from large companies who *can* afford the regulatory expenses for multiple product positionings often argued for even stricter regulations as the solution for that reputation. But we wonder something slightly different: whether it is possible for any amount of regulation to contend with microbial functional identities if they are never one thing to begin with.

The troublesomeness of microbial multiplicity is true for taxonomic identities as well. As previously mentioned, data confirming species or strain are usually only required for novel or previously uncharacterised microbes. But what is a characterised microbe and where and when is it characterised? The trickiness of microbial identity is a source of regulatory instability for multiple reasons. For one, taxonomists sometimes revise classifications such that a microbe might be in a clade (a group with a presumed shared evolutionary history) recognised in the literature as generally safe one day and become a member of a more risky clade the next. For another, taxonomy is troublesome because living things evolve, and the microbe applied or what the microbe becomes in the field may not be identical to the microbe put into the bottle and cleared by regulatory processes. The implicit hope expressed by most R&D scientists for the fate of most agricultural microbial products is, of course, that they will survive, at least temporarily, in fields. However, much remains unknown about the persistence of product microbes or their long-term effects in soils because researchers have largely focused on functional traits rather than ecological traits related to a microbe's ability to establish in the field (Kaminsky et al., 2019).

What we *do* know is that microbes take up genetic material from their environments and often mutate as they reproduce. We know they routinely change which genes they *express*, and we know phenotypes and associated expression profiles in the field will differ from those tested in the lab. Taxonomic identity may or may not relate to functional identity, even beyond the functional multiplicity mentioned above. Put most simply, microbial identity may become something we have no way to predict; something that can only ever be enacted in a discrete way very briefly, at a particular place, in a single moment in time, and from a certain perspective.

Company R&D scientists are not thrilled by this kind of slipperiness because it complicates both marketing and intellectual property claims. It also complicates asking questions about what the long-term outcomes of microbial products will be, a topic in which regulators and growers have mutual interest. No one was willing to talk about risks on the record, but they were acknowledged by a small number of scientists, and some risks have been brought up in the literature for instance, by Jack et al. (2021) in a paper entitled "Microbial Inoculants: Silver Bullet or Microbial Jurassic Park?" Some companies compensate for other kinds of functional uncertainties by designing "redundant" products—microbial mixes containing multiple species with the same theoretical capabilities (e.g., nitrogen-fixing)—in hope that if one species fails to "do its job" in a particular environment, another will. "We are trying to compensate for environmental variability" one scientist told us about a biostimulant that contains twenty-one species of microbe. "We just want to make sure it works in as many soil types as possible." Functional redundancy also plays a role in how R&D scientists think about bioprospecting; if multiple microbes perform the same job, choosing one for a product can be a matter of choosing which one is easiest and cheapest to grow. In some ways, this reflects the way that growers tend to enact microbial identities: they don't particularly care who does the N-fixing or the pathogen suppression, they just need it to get done and their empirical observations of their fields are how they know if it does or does not.

What growers know a microbe to be

What growers need to know about microbial products is, at times, quite different than what either regulators or R&D scientists need to know. (It should be noted that "grower" is a far from homogeneous category; the supervisor of an industrial-scale corn farm has a much different job and a much different set of empirical tools than an organic, local, multi-crop community-supported agriculture (CSA) farmer. That said, when we refer to "growers" in this paper, we are speaking of data collected from individuals growing many different crops, but who all have frequent, critical-to-success, hands-on interactions with agricultural fields.) Federal regulations require knowing whether a microbe is a member of a presumed-safe species with no toxic effects. State regulations typically focus on a product's contents, safety to varying degrees, and the accuracy of its labelling. R&D scientists need to know whether they can correlate a microbe's genetic signature with a stable function under model conditions, and that a particular microbe fits within permissible regulatory categories. But the key question for an end-user has less to do with pinning down whom a microbe is and what it does, and more to do with how microbial actions manifest in the success of agroecological systems over time. What growers need to know is: How do microbes affect my fields and crops over days, weeks, seasons, and years?

No label can fully answer this question. Labels best describe what microbe-based products have been demonstrated to do in certain model and experimental conditions, and it is axiomatic in biology that lab conditions are not the field—let alone *your* particular field. On the contrary, as Maureen O'Malley (2015) observes, it may be especially the case for microbes that "laboratory environments often select organisms for capacities they do not exhibit in the wild," suggesting it is more likely than not that what a microbe does in the field will be misaligned with what a lab-determined label can report.

Growers are savvy though, so, while regulators may strive to pin down islands of certainty in a sea of microbial slipperiness—discrete flowers in the gauzy lace—people who grow plants *expect* that living things will not always behave the same. Over time, they have come to *expect* unpredictability, and very few solid moments of knowing in an otherwise uncertain fabric. Growing is always gambling, we were told, but microbes are a form of bet-hedging in the same way that selecting the best seed variety for your field is bet-hedging. In fact, thinking about the contents of a microbial product as similar to the contents of a seed packet is helpful. A seed packet label suggests some properties of the contents but is also not necessarily a deterministic prediction of the results of planting them. You may plant a certain variety of tomato or pepper but depending on the year or the place –the variation in rain, wind, sun, soil, and other organism encounters— a plant may have larger leaves, fewer flowers, or fruits that vary in size, hue, or sweetness, or may even fail entirely. In these regular dealings with the dynamism of living organisms, many growers are already prepared to see microbes, who are likely to be even more variable than seeds, in the same fluctuating light. That is not to say that company scientists ignore the "how does this product affect fields" question; obviously, if they are to be successful, it concerns them, too. But there is no single model field to be understood, and so this knowledge must be accumulated differently. Field R&D, which seems to sit somewhere in between the lab and grower experiences is a critical component of long-term commercial success, something that company scientists tell us will increase exponentially as the industry expands and tell us about the more distant futures of microbial identities. What we do know is that outside of some aggressively managed agricultural settings, most soil is replete with relatively stable microbial communities (Fierer & Jackson, 2006). New microbes introduced into robust communities may integrate or alternatively, fail to establish and die out relatively quickly (Debray et al, 2022). (It should be noted that many agricultural microbial communities are not considered robust, but rather, are labeled "dysbiotic" after years of harmful conventional practices.)

Most growers do not directly care about whether an externally applied microbe integrates into a robust soil microbial ecology, but they do care about whether to expect a temporary or lasting effect on health or productivity. Answers to these questions do not usually come through a product label or a lab result.[v] Within a season, the growers we spoke with enact their ideas of microbial inoculants empirically. This might look to them like greenness, leafiness, stalk robustness, heavy seed heads, seed size, resilience in the face of drought, absence of disease, or the ever-important, livelihood-related metric of yield. Across seasons, this might look like darker, more tractable soil or greater consistency in yields. Many grower readings of microbial inoculants are even less discrete. A hemp grower in Colorado told us that things had just "gone better" since he had been inoculating his fields. Microbes are identified by growers through their experience—their discrete *and* gauzy observations of the collective phenotypes of the whole system of living things within which they are in *long-term* relations, including crops and other microbes.

Another grower spoke to us about the difficulty of trying to produce an organic crop on a field which had been in conventional wheat rotations for more than a decade. If they saw any sustained rainfall, these acres had a strong tendency towards outbreaks of root rot. Application of beneficial microbes backed it off more than once. An outbreak looked like rapidly spreading wilting, early signs of ultimately fatal collapse of plant vascular systems. Recovery after field inoculation with microbes meant that as long as a plant was not too far gone, they would stand straight again as their vascular system regained functionality. The absence of a robust soil microbiome and presence of introduced microbes certainly matters to growers, but in this case and others, microbial mattering was not read through label identities or functional mechanisms. Rather, the importance of microbial identity to growers was enacted through their observation of plant posture, through phenotypes that indicated regained future possibilities of health and crop productivity.

When microbes are applied without corresponding practices that sustain soils or as of single-microbe product "fixes" that treat microbes like chemicals, microbial products are likely to act like chemicals too. That is, offering a one-time salve rather than any long-term salvation. Here, again, comes a challenge for aligning pinned-down regulatory identities with how growers know microbes. Growers look for larger organism and system phenotypes over varying timeframes. Growers expect inconsistencies. They expect living products—seeds, plants, and increasingly microbes—to exhibit a range of behaviours across years and changing environmental conditions. Short-term fixes are still fixes, and welcome, but not guarantees of what to expect next time and not necessarily as valuable as practices that move systems away from dysbiosis over the long-term. Growers know and will continue to come-to-know microbes through the patterns of lacey microbial fabric that they can make sense of over time. Rather than pinning down discrete enactment or flower in the lace, as a label might try to, growers are looking for only relative stability in how variable and uncertain threads weave together in the bigger picture of cultivation over years, decades, or even centuries. Whether a microbe is life-stimulating or -cidal or both, whether it makes yield go up or disease go down, and whether it is ultimately beneficial, harmful, or irrelevant is all a function of the agroecosystem pattern in which the microbe is somehow woven, but in which *what it is* and *what it does* is never precisely pinned down. While more data about how externally applied microbes behave across healthy and dysbiotic fields might better trace those microbial threads, they are very unlikely to change the metrics that growers apply to evaluating the texture of the fabric over time.

Discussion: Who knows what a microbe is?

Existing regulations demand and thus partially invent discrete microbial identities in efforts to predict and control their outcomes. But while this framework can be applied to microbes to generate lab results and labels with taxonomic status and prospective functions, these discrete ways that microbes can be known—the discrete flowers in the lacy fabric of microbes—are unlikely to have much to do with what microbes become as they move out into the more slippery parts of the fabric, the variable field contexts and long-term lives of agroecosystems where they become known in other ways, or become, perhaps in many ways, unknowable. The texture of microbial enactments is uneven, containing discrete identifiable moments amid lots of slippery gauze, so that trying to know microbes in *only* discrete ways limits what we can do with them. Yet in contrast to discrete labels and de-contextualised lab results, growers have no choice but to work in variable fields with dynamic living organisms. They must accumulate their knowledge about what microbes are differently, which means developing their own gestalt metrics, but also, critically, that these metrics hold space for what cannot be known and/or predicted about them.

Growers have no choice but to treat microbes as complex and uncertain if they want to work with them. This manifests in at least two main ways. First, growers come to know microbes through multispecies readings of the agroecosystem. If plants grow well, or are resilient through drought or disease, growers know microbes through that gestalt. They come to understand microbes through whole systems or nested systems such as soil quality or plant health. Second, growers come to know microbes over time. Whether it is a crop variety or a microbe, growers cannot rely on living things being reliable. Growers accumulate intuition about what “works” over time and variable contexts are forced to make knowledge through complex co-productions in which patterns may become more predictable, even while individual elements within that pattern cannot be predicted or controlled.

Marketers, scientists, growers, executives, regulators, and lobbyists alike all say: we need more data on microbial agricultural products. The operating assumption across the community of interested parties is that contemporary Western humans have only just begun to work deliberately with microbes to support agriculture; consequently, uncertainties that currently characterise their regulation and use are a function of not yet knowing enough about how microbes behave in soil or in association with crops. On the basis of the investigation that we have described here, we would like to make a different suggestion. We agree wholeheartedly that microbes have been understudied and warrant more attention. Additional study may even help resolve them into more consistently regulatable entities. However, we are unconvinced that attempting to fit microbes into regulatory and other epistemic frameworks in which they are assumed to have fixed identities is practically helpful. Further, it is not an approach that accomplishes much toward understanding microbes in the complex, ecological, systemic senses in which they are most important to agroecosystems. More data, even from field trials under varied conditions, will not fully resolve this mismatch between a need for certainty and a reliance on intuition over time.

Microbial products fit poorly into regulatory frameworks not just because they are poorly understood, but because they challenge boundaries among products, environments, and contexts insofar as regulations assume microbial identity in ways that have not yet been (perhaps can never be) fully stabilised. It is our position that because regulatory frameworks make sense of microbes *only* in discrete ways that regulations may be *incapable* of making sense of what a microbe can be in the field. That is, in this epistemic space of regulations, though microbes are known in certain ways, they may be *unknowable* in the ways that ultimately matter to growers or in a larger ecological sense. It may eventually be possible that regulations can come to know them through observations that can encompass more multiplicity and dynamism, but what that might look like remains an open question.

One way to make sense of microbial complexity is to locate that complexity in ways of knowing rather than in microbes themselves. Talia Dan-Cohen (2016) distinguishes “ontological complexity,” as a function of an object, from “epistemological complexity,” produced through mismatches between an object and the paradigms or approaches applied to understand it. Epistemological complexity, in her account, describes the aspects of an object left unaccounted for by particular ways of studying it. Epistemological complexity may therefore *increase* when scientists gather more data because more discrete ways of understanding something may lead to more misalignments among those ways and not fewer. Distinguishing these two kinds of unknowability enables Dan-Cohen to explain how some early synthetic biologists might have been more successful in engineering biological systems *because* they were naïve about biology, not in spite of their naïveté; to them, biological systems looked simple because they had not yet made them complex.

We could describe soil-dwelling microbes as both ontologically and epistemologically complex. However, distinguishing the two implies that essential properties of an object of study can be identified independent of the epistemological approaches used to study them. Especially for microbes, the two cannot help but be tightly linked. While all observations are always mediated, ways of knowing microbes are less thoroughly stabilised than ways of knowing macro-things such as horses or tomato plants. Mediation matters more here because, as we have gestured to in this article, ways of knowing microbes—practices that contribute to assembling microbes are less ignorable than practices that assemble many other things. In short, we must describe microbes in agricultural products as onto-epistemologically complex. "The same" microbe is made to be different things across varied contexts with no single, stable conceptual infrastructure to align them. Microbial unknowability is co-produced in the space among actors.

What does the laciness of agricultural microbes mean for regulating them? Some recent studies of ambiguity or non-knowledge have highlighted how not-knowing can be productively employed to sustain research fields, as in Reinecke and Bimm's (2022) analysis of Martian exobiologists' strategic maintenance of ambiguity to support continued funding for the search for life on Mars, even in the absence of any evidence for life on Mars. In contrast, Jessica Lehman's study of the study of ocean variability concluded that "increased data led not to a straightforwardly more accurate picture of the ocean but rather to fundamental uncertainty about how the ocean operates." Lehman calls these uncertainties "productive limits" because while they limit, they also "demand a response" that manifests as ongoing genesis of ways of understanding uncertainty and the social infrastructure that strives to contend with it, albeit unevenly (Lehman, 2020).

Our case differs from Lehman's because microbial laciness is not necessarily tied to the texture of the *human* social order through which microbes become known, but also often to the multispecies social order of how humans and microbes relate. Dominant epistemic frameworks are inadequate not just because of not what humans do with respect to other humans, but because of the mismatch between authoritative human ways of knowing and microbial modes of action. Microbes exceed and challenge categories established for non-living things (such as chemicals) that they are presumed to be like. They exceed and challenge categories for macroscale living things (such as plants) because their identities evolve differently. In addition to these limits of understanding being productive in terms of motivating efforts to learn, we see R&D scientists leaving open the possibility that microbial identities, functions, and capabilities exceed scientific ways to make sense of them.

Conclusion

How might a regulatory system grapple with microbial unknowability? Ways of knowing microbes cannot be perfectly aligned, and all are partial. Consequently, it won't do for regulators, or R&D scientists, or corporate lobbyists, or even growers to assert their own microbial heuristic as a standard by which the entire community should be organised. Instead, if the texture of microbial assemblages is uneven, then perhaps frameworks for regulating them should be, too. On the one hand, this suggestion is consistent with the patchiness of current practice. On the other, it may be in tension with movements to standardise agricultural microbial products and microbiome research and practice more generally. Regulations might come to be better informed by what growers already know about working with the uncertainty of living things, and perhaps metrics of microbial life taken in variable fields and knowledge gained over time will be a part of this. However, any regulation concerned with prediction and control will always be in tension with microbial life.

Organizations including the Biological Products Industry Alliance and the Biostimulant Council (comprised of representatives from both biologicals-focused and conventional fertilizer corporations) are working to craft and advance specific legislation to regulate “microbials” as more and different than replacements for chemicals. Progress is slow—a concern for many of our interviewees, but perhaps also an indication of the challenges of categorizing microbes and microbial products. Assembling a coherent and distinct idea of a biological-thing-as-regulated-product seems to require significant and contentious work. Ultimately, our findings suggest that the goal of that work might be best conceived not as trying to firmly pin down what these microbes are, but how regulations designed to ensure safety and efficacy can best account for how microbial fabric cannot be pinned down.

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[i] Those products that are not pesticidal but are considered plant growth regulators” (PGR) are regulated, like pesticides, under FIFRA (the Federal Insecticide, Fungicide and Rodenticide Act).

[ii] These mechanisms are potentially in flux. A bill which could eliminate EPA jurisdiction over biological products altogether, introduced in spring 2022, currently sits in the House “Subcommittee on Biotechnology, Horticulture and Research.”

[iii] Words Oregon considers “undefined” and “misleading”: balanced, health, stimulant, probiotic & catalyst.

[iv] While many strains of *B. subtilis* are known to be as beneficial, a few have been shown to cause disease in immunocompromised humans; and multi-antibacterial-resistant strains have turned up in hospitals: yet another example of the contextual identities of microbes.

[v] Not surprisingly, there are an increasing number of companies offering to “test” for certain microbes or “whole microbiomes” in agricultural systems. How these companies go about establishing “microbial identity” could be the subject of an entire article altogether.

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