What Is the *Terroir* of Synthetic Yeast?

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Abstract Humans and yeast have a long history of productive collaboration in making a global array of fermented foodstuffs including wine, bread, and beer. Synthetic biology is now changing the shape of human-yeast work. The Sc2.0, or "synthetic yeast," project aims to completely reengineer the *Saccharomyces cerevisiae* genome, designing an organism with improved capacities for scientific research and diverse industrial applications. Notably, synthetic yeast has present connections with the wine industry and likely futures in our wider foodscapes. Here I suggest that we imagine this scientific object, synthetic yeast, as an incipient cultural object by asking: what is the *terroir* of synthetic yeast? Terroir invokes tangled relationships among the many variably human and nonhuman, living and nonliving participants in a landscape. Terroir replaces synthetic yeast in its context of production, against scientific narratives that work to create utopian, placeless organisms. Terroir is moreover a world-building tool, not about discovering and describing a place but about constructing and connecting to one. Inquiring about terroir therefore suggests that rather than ask how far humans should go in manipulating nature, we instead ask how humans can continue to cultivate the relationships that constitute our humanity and sustain our environments. Fundamentally, I suggest that the best futures for synthetic yeast are those that connect rather than estrange; in other words, that we continue to value terroir in imagining how synthetic yeast satisfies the more-than-caloric needs of future appetites.

Keywords synthetic biology, yeast, *terroir*, fermentation studies, multispecies studies

Introduction

Tiny microorganisms are huge figures in future foodscapes. In Isaac Asimov's classic *Foundation* and *Empire* series, the central planet Trantor was sustained on giant underground vats of yeast and algae tended by robot labor. Asimov's *I, Robot* depicts the united Far Eastern peoples of a future Earth subsisting almost entirely on yeast, bioengineered and processed into every desirable food. More recently, Joss Whedon's space-cowboy television drama *Firefly* depicts twenty-sixth-century spacefarers relying on standard protein rations with more-than-likely microbial origins. Closer to home, a supermarket freezer near you may stock Quorn, a brand of vegan meat replacement products made with mycoprotein derived from growing fungi in vats that, robots

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notwithstanding, might resemble Asimov's dreams.[1] Genetically modified microorganisms produce vanilla flavoring and other food additives, some already in commercial use, others in development. In addition to these myriad high-value molecules already built into the tractable bodies of bioengineered yeast, scientific work is well underway to construct the first fully synthetic yeast—a platform for infinitely flexible future developments.[2]

Bioengineered yeast foods are an imagined future of the past and a speculative future of the present, but also a present and developing reality. In both science-fictional and scientific discourses such future and futuristic foods are routinely distanced from the cultural webs that accompany present-day eating experiences. These foods are imagined as part of worlds where satisfying hunger means supplying calories, and where the decoupling worldview of synthetic biology and other biotechnologies transfers reliably and desirably to social spaces outside the laboratory. Products of synthetic biology that travel—those with current and anticipated lives outside the lab—extend the decoupling agenda into locations where reducing relations might not suffice to satisfy future appetites.

Synthetic yeast is most often depicted as a technical accomplishment: a product of being able to divide an organism's genome into chunks, synthesize those chunks, stick them together to recreate the organism, and, in so doing, divide the organism via its DNA qua genetic operating system from contextual dependencies that inhibit its mobilization in new technical applications. Here I would like to suggest that depicting synthetic yeast as a cultural actor—not only as having a context of production but as mediating the creation of affective relationships—is a productive counterpart to more typical narratives of synthetic biology: productive because satisfying appetites is not about providing calories alone, but sustaining humanity in its web of codependent relations. I do so by asking: what is the *terroir* of synthetic yeast? Focusing on the cultural location of synthetic yeast, in opposition to narratives that make synthetic yeast placeless, makes it possible to envision how engineered organisms might build relationships rather than increase disconnectedness.[3]

1. Quorn, "Quorn Facts," "Micoprotein Explained," www.quornfacts.com/mycoprotein-explained (accessed December 26, 2017).

2. I use *yeast* and *Saccharomyces cerevisiae* interchangeably to refer to the one among many species of fungi with single-celled growth habits with which humans have the closest and most numerous relations. In colloquial use, "yeast" is reliably *S. cerevisiae* or one of its very taxonomically close cousins, save in the case of "yeast infections," associated with the unrelated yeast *Candida albicans*.

3. This article follows from twenty-two interviews conducted with yeast workers across the consortium, a year of fieldwork cohabitating with a key synthetic yeast laboratory for two days each week and attending related meetings and conferences, and the peer-reviewed and variously colorful literature surrounding the project as well as collective experiences with Jane Calvert in our work as social scientists with the synthetic yeast project.

Coupling Terroir and Synthetic Biology

"Decoupling" is central in synthetic biology.[4] Following ideals for making biology engineerable, synthetic biologists work to decouple gene expression from regulation, design from construction,[5] design from biological reproduction,[6] message from communication medium,[7] and resource cost from product yield.[8] Above all, engineering-minded synthetic biology has worked to decouple function from context so that the identity of the living organism becomes incidental to the desired outcome.[9] Yeast itself challenges this element of biological componentization by its unique position as a microbial companion species with which we have developed extensive, coproductive, and flavorful relations.[10] Synthetic yeast is inevitably implicated in these existing webs by its associations with brewer's and baker's yeast as well as its potential participation in future food production. Consequently, engineering yeast—in comparison with projects involving microorganisms with less conspicuous public profiles—brings up questions about the typically unquestioned necessity and desirability of decoupling place from production and production from consumption. I suggest terroir as a means of tracing synthetic yeast in and through its tangled relations with humans and environments rather than insisting from the outset that something that is already entangled must be disentangled to be understood. Asking after the terroir of synthetic yeast becomes a means of questioning the desirability of extending synthetic biology's disentangling, decoupling program elsewhere through the travels of the creature-products it generates.

Considering terroir is in one sense a speculative exercise about synthetic yeast's potential futures, but it is also a means to delineate a portrait of synthetic yeast, as it is currently being made, from an uncommon angle to make different elements of its character visible. Without speculating about any particular life that synthetic yeast and its offspring might have, I wish to examine some facets of what envisioned futures for synthetic yeast might entail. The resulting picture, in contrast to those typically drawn through synthetic biology lenses, may be better suited to understanding what synthetic yeast is in many of the other places where yeast lives. Neither this portrait nor the work of making it is anti–synthetic yeast or anti–synthetic biology; rather, the picture questions whether there could be a different synthetic biology by looking at possibilities that already exist in the present but that typical frameworks for discussion tend to preclude seeing.

Many followers of microorganisms, animals, and plants have sought such alternatives to the dimensionlessness of scientific descriptions for their organisms of

4. Chen, Galloway, and Smolke, "Synthetic Biology"; Calvert, "Commodification of Emergence"; Endy, "Foundations for Engineering Biology."

5. Mackenzie, "Design in Synthetic Biology."

6. Endy, "Foundations for Engineering Biology."

7. Ortiz and Endy, "Engineered Cell-Cell Communication."

8. Müller, "On Epistemological Black Boxes."

9. Frow, "Making Big Promises Come True?"

10. Haraway, *When Species Meet*; Tsing, "Unruly Edges."

interest;[11] as Jamie Lorimer has commented, "a political ontology of entanglement (and disentanglement) has emerged as something of a leitmotif in recent work in multispecies studies."[12] At the risk of drawing one more term into the panoply of terms used to do the work of reentangling our lives with other organisms, I employ *terroir* because it already does similar work in a yeast-inhabited world where multispecies landscapes are routinely limned in tangled terms and where, therefore, effects of decoupling can be brought into high relief.

Synthetic yeast is already growing into the wine industry, where questions of its terroir—its nature and provenance generally and even terroir specifically as a desirable property of fine wine—will become relevant in terms of how this and other synthetic biology products fit into the legal and cultural codes of acceptable and desirable wine making. Terroir is moreover not applied solely to wine but is a tool for asking about how something created in and through sensory experience connects to, and connects the experiencer to, a complex landscape of relations. Terroir is in this respect sympathetic with other reentangling tools more native to contemporary critical scholarship—a tool for examining "diverse geographies that coexisting humans and animals [or microorganisms] create," such as those traced with domesticated macrofauna—but developed in and for the context of coproductive microbial relationships mediated through sensory experiences.[13] And *terroir* is untranslatable, in part because having been so often and variously translated, all of the various meanings and connotations associated with its common uses are irreducible to any single definition.[14] Communicating in English, *terroir* evokes rather than specifies relations imagined into being through aesthetic experience mediated particularly through smell and taste.

Investigating where yeast sits in changing human-yeast relationships tends to invoke the specter of inappropriate anthropomorphisms against which multispecies studies is often defending itself, whether in the form of adjacent scholarly communities or of its own anthropomorphobia-phobia—fear of fear of anthropomorphism.[15] Tools for thinking about human-yeast work must stem from the human side of those relationships, and even then vocabularies for thinking about the unique subjectivities of yeast are impoverished. When Michelle Bastian, Owain Jones, Niamh Moore, and Emma Roe respond to the same kind of problem in their collection on "more-than-human participatory research," they rebut the notion that concerns about anthropomorphism involve concerns about "bias, inappropriate assumptions or projections" that inevitably apply to

11. H. Lorimer, "Herding Memories."

12. J. Lorimer, "Gut Buddies," 60.

13. H. Lorimer, "Herding Memories," 497.

14. See, for example, Caple and Thyne, "Concept of Terroir"; and Trubek, "Incorporating Terroir."

15. I borrow this term from Claire Marris, who uses *synbiophobia-phobia* to describe the "fear of the public's fear of synthetic biology," which she identifies as motivating some efforts at public engagement to address synthetic biology-related issues. Marris, "Construction of Imaginaries," 83.

all research approaches, not just those in multispecies studies.[16] Their suggestion that we look for how nonhumans might participate in research worlds rather than focus our attention on the lines that might keep them out is well-read through Jean M. Langford's defense of anthropomorphism as an indispensable strategy for coming to appreciate another, similar to how "we apprehend the feelings of other humans only by similar projections."[17] The cooperative, voluntary, working nature of human-yeast relations combine with their domestic familiarity to make observing them with critical distance more difficult. The same factors make apprehending the participation of microbial collaborators even more worthwhile, in terms of continuing to maintain and nourish these relationships as human technology proposes to reshape the world we inhabit together.

The *Saccharomyces cerevisiae* 2.0 Project

Synthetic yeast—*Saccharomyces cerevisiae* 2.0, or Sc2.0 to its intimates—is a synthetic biology project to construct the first complete eukaryotic genome entirely from laboratory-synthesized DNA. Synthetic biology, according to the 2012 "Synthetic Biology Roadmap for the UK," is "the design and engineering of biologically based parts, novel devices and systems as well as the redesign of existing, natural biological systems."[18] More colloquially, many synthetic biologists with whom I speak say that synthetic biology is designing and building with DNA. Neither definition possesses sufficient detail to satisfy some social scientists, who have questioned whether they are looking at a new field or discipline,[19] whether synthetic biology is "engineering,"[20] and whether engineering with DNA necessitates standardizing genetic parts.[21] Some scientists who might be called synthetic biologists argue that "synthetic biology" itself is meaningless, being chiefly a "marketing banner"[22] used to mobilize resources (including excitement) around the continuously developing genetic engineering sciences. Defining synthetic biology is difficult.[23]

Defining any meaningful boundary between synthetic biology and genetic engineering is also difficult, politically fraught, and scientifically fuzzy. The fields share tools and a common "ambition to create novel functions by engineering biological material," but the synthetic biology community has numerous interests in distancing itself.[24] Following what has been widely construed by scientists and policy makers as the

16. Bastian et al., introduction to *Participatory Research*, 7.

17. Langford, "Avian Bedlam," 97.

18. Synthetic Biology Leadership Council, 4.

19. Meyer and Molyneux-Hodgson, "Placing a New Science"; Molyneux-Hodgson and Meyer, "Tales of Emergence."

20. Schyfter, "Drive to Make"; Schyfter and Calvert, "Intentions, Expectations, and Institutions."

21. Endy, "Foundations for Engineering Biology."

22. "What's in a Name?," 1073.

23. Ibid.; Calvert, "Synthetic Biology."

24. O'Malley et al., "Knowledge-Making Distinctions."

failure of the "GM episode,"[25] synthetic biology supporters of various stripes have been eager to separate their work from the public histories of genetic modification. One argument for doing so is that synthetic biology works by far more systematic means and on a larger scale than what has been considered genetic modification; GM was about ad hoc modifications, but synthetic biology is supposed to be about engineering and design.[26]

A prominent cadre of DNA designers takes a parts-based approach, aiming for repositories of human-built DNA sequences with specific well-characterized functions that can easily be assembled into pathways that perform infinitely varied tasks. Loading such pathways onto "chassis" organisms—the analogy is to the stripped-down frame of an automobile, a "framework or foundation that supports other physical components for an engineered structure"[27]—creates "cell factories"[28] to produce useful compounds in service of human needs. Another cadre attempts to build such cell factories from scratch. Rather than stripping unwanted features off of existing organisms, these bottom-up designers aim to build up new organisms from nonliving parts in the form of simplified "protocells" that scientists will ideally understand in full and can therefore fully optimize. A third group is interested in engineering whole genomes.[29] Like the protocellularists, genome engineers concern themselves with whole organisms rather than parts or pathways, but they begin with an existing living cell that they aim to redesign and make more fit for its intended human purpose.

The synthetic yeast project brings genome-driven cell engineering to eukaryotes. Beginning with the nuclear genome of a common laboratory strain of *S. cerevisiae*, the project designers have eliminated "noncoding" DNA that they suspect is unnecessary, added features intended to make the yeast more suitable for addressing scientific questions and developing industry applications, and are then building that designer genome chromosome by chromosome, genetic brick by genetic brick.[30] Such whole-genome construction projects have been undertaken on behalf of viruses and bacteria in the past: poliovirus in 2002,[31] the bacteriophage *phi*-X174 in 2003,[32] *Mycoplasma genitalium* in 2008,[33] and *Mycoplasma mycoides* in 2010.[34] A eukaryotic genome such as yeast, however, represents an undertaking much larger than any of these genomes: roughly 14,000,000 base pairs versus about 7,500 nucleotides for poliovirus or about 1,100,000 base pairs for *M. mycoides*. Also, rather than being the work of a single scientific group, Sc2.0 is being

25. Macilwain, "Rejection of GM Crops."

26. Examples of this argument are reviewed in O'Malley et al., "Knowledge-Making Distinctions."

27. Adams, "Next Generation of Synthetic Biology Chassis," 1328.

28. Pretorius, "Synthetic Genome Engineering"; and many others.

29. O'Malley et al., "Knowledge-Making Distinctions."

30. Dymond et al., "Synthetic Chromosome Arms Function in Yeast"; Enyeart and Ellington, "Synthetic Biology: A Yeast for All Reasons."

31. Cello, Paul, and Wimmer, "Chemical Synthesis of Poliovirus cDNA."

32. Smith et al., "Generating a Synthetic Genome."

33. Gibson et al., "Complete Chemical Synthesis."

34. Gibson et al., "Creation of a Bacterial Cell."

shared across a consortium of eleven labs in Europe, North America, Asia, and Australia. Synthetic yeast is, therefore, a significant scientific milestone in part simply because it is big. The project necessitates synthesizing enormous volumes of DNA, coordinating many distant contributors, and managing data across labs in ways that push against the outer edges of what synthetic biologists have attempted to do.

The synthetic yeast project is also significant because, compared to bacteria, yeast cells are much more similar to human cells and therefore more relevant to biomedical investigations as well as to addressing fundamental scientific questions about eukaryotic cell function. In contradistinction to the bacteria and archaebacteria, yeasts, humans, and other eukaryotes organize their cellular contents into membrane-bound compartments and share many common strategies for managing basic cellular functions. Yeast is conventionally seen as the simplest of these eukaryotes. Yeast is also—as I hear from many of the scientists employed on Sc2.0—"easy." It will not kill you or make you sick. It reproduces quickly. It likes to eat a broth of sweetened protein extract that is cheap and easy to prepare. While yeast doing active experimental work is most often housed at thirty-two degrees Celsius, it happily survives at ordinary room temperature. For longer storage—say, over a holiday weekend that the scientist would prefer not to spend in the lab, or for a few weeks between experiments—yeast can be kept dormant but alive in an ordinary refrigerator at four degrees Celsius.

S. cerevisiae has consequently become the favored model organism for studying all manner of cellular functions, along with many cellular dysfunctions related to human disease—problems with dividing chromosomes equally during cell division, for example, that lead to Down syndrome and other conditions of having more or fewer than the typical number of chromosomes per cell. And consequently, with decades of use, *S. cerevisiae* has become even easier to use as scientists accumulate a well-stocked toolbox for manipulating it. As recently formulated by an Sc2.0 consortium member, "yeast is a workhorse with sound academic and industrial credentials," even a "Swiss army knife" of "unequaled versatility."[35] A completely reengineered *S. cerevisiae* genome would be one more tool in that knife, opening up a wide field of new scientific avenues for yeast research.

The Sc2.0 project is already raising an equally plentiful array of questions for social scientists around species definitions, whole organisms as engineerable materials, and relationships between engineering and design, among many others. The parts-based approach that continues to dominate synthetic biology often appears to be "organism agnostic," with synthetic biologists not caring which cellular "chassis" goes into a project so long as the desired pathway or product comes out.[36] Whole-genome approaches, where the product *is* the cell, might challenge that agnosticism. So too might working with *S. cerevisiae* as a particular organism. Even beyond its ease of use, yeast

35. Pretorius, "Synthetic Genome Engineering," 117, 118.

36. Richardson, "Computer Assisted Design for Synthetic Biology."

attracts affection. Unlike many microscopic creatures, per J. Lorimer's characterization, yeast's relations with humans are anything but awkward. On the contrary, yeasts are uncommonly charismatic, distinguishing themselves to human perception by fermenting flavorful and inebriating food, by behaving as tractable laboratory organisms, and by being available in packets on grocery store shelves.[37]

Moving Synthetic Yeast Out of the Laboratory

S. cerevisiae is responsible for fermenting wine, beer, bread, coffee, chocolate, and all manner of other culturally and nutritionally valuable foods and drinks whose names spring less readily to American English-speaking lips. The edible products of human-yeast collaborations—a fixture of human life for millennia—are central to nutrition, culture, and ritual wherever they are found, and they are found in most places.[38] Looking backward, modern microbiology exists in no little part because of this history. Pasteur began working with brewer's yeast at least in part because it was available and familiar, and he conducted some of his formative work on behalf of the wine and beer industries.[39] Looking forward, synthetic yeast provides a potential route to creating "new and improved" strains for these mundane applications, including microbial collaborators specially bred to raise bread faster, to make wine with less alcohol, or to brew beer with new flavors.[40]

Early in its life, synthetic biology was imagined as a route to cheap and sustainable biofuels. The cost of engineering a bespoke organism, however, proved far out of line with the return to be made on such a low-priced commodity as biodiesel. Attention has since largely shifted to molecules with higher trading value. The publicly traded Swiss-based company Evolva has, for example, developed genetically engineered organisms that produce resveratrol, two major aroma molecules from grapefruit and oranges, vanillin (the signature flavor molecule in vanilla), stevia (a potent calorie-free sweetener), and numerous (many yet publicly undisclosed) other molecules with commercially relevant food applications.[41] The current wave of synthetic biology is characterized by work to create additional standardized, customizable tools forecast to make cells into even more efficient factories for producing a wider variety of high-value compounds in the future, with more speed and less expense.[42]

37. J. Lorimer, "On Auks and Awkwardness"; J. Lorimer, "Nonhuman Charisma"; see also the rest of the special section, "Living with Awkward Creatures," in which this article appears.

38. Cavalieri et al., "Evidence for *S. Cerevisiae* Fermentation."

39. Barnett, "History of Research on Yeasts"; Latour, *Pasteurization of France*.

40. See, for example, Borneman, Schmidt, and Pretorius, "At the Cutting-Edge of Grape and Wine Biotechnology"; brewer Chris Baugh's comments in Herkewitz, "Scientists Create Synthetic Yeast Chromosome"; and numerous other scientific and popular articles about the synthetic yeast project.

41. Evolva, "Products," www.evolva.com/products/ (accessed December 27, 2017).

42. See, for example, Awan, Shaw, and Ellis, "Biosynthesis of Therapeutic Natural Products"; Nikel et al., "From Dirt to Industrial Applications"; and other recent synthetic biology review articles.

Synthetic yeast thus has at least two main potential arenas for application in scientific knowledge and industrial manufacturing. Sc2.0's designers hope that a "refactored" genome will help identify the function of heretofore mysterious genes, better explain connections between chromosome features and the mechanics of cell division, and otherwise serve as a new approach for taking on old and intractable biological questions. Scientific applications tend to be what workers on the project mention first, but always on the horizon is making products to sell rather than scientific knowledge to inform. This forked path to futures in both scientific understanding and industrial production is a common feature of construction work in synthetic biology.[43]

Synthetic yeast has an additional, narrower but notable set of applications heralded by the involvement of the Australian Wine Research Institute (AWRI) and the bridge thereby formed between Sc2.0 and the wine industry.[44] The AWRI is a service organization for the Australian wine industry, providing quality and safety controls and various administrative services, running a highly sophisticated industry help desk, and conducting research with anticipated industry benefit. The AWRI is not constructing one of the essential yeast chromosomes. Instead, they have chosen to assemble an auxiliary component which they hope will improve Sc2.0's utility to the food and beverage industries.

At this point it becomes important to note that the *S. cerevisiae* used in wine making and the *S. cerevisiae* used in synthetic biology laboratories are worlds apart. The species *S. cerevisiae* is "one thing" in the same sense as the species *Canis familiaris* is "one thing"; that single species name denotes (or disguises) many highly varied smaller groups specially adapted to different tasks. Dogs have breeds. *S. cerevisiae* has strains. Yeast strains used for laboratory-based genetics work are distinct in genetic sequence and in behavior from those used in brewing, and the two cannot be interchanged. Bakers similarly have their own stable of strains. Wine in particular cannot be made by just any old yeast picked up off the street but requires a strain specially able to withstand the acidic, nutrient-poor, and intensely sugary or intensely alcoholic environment that grape juice and wine present in turn.[45]

What the AWRI's Sc2.0 team calls their "pan genome" is a collection of genes found in wine making, brewing, and baking strains of *S. cerevisiae* but *not* present in the standard laboratory versions. These genes, putatively related to efficient fermentation, essentially amount to a small new chromosome when assembled end to end. Inserting this pan genome into the standard Sc2.0 strain will, it is hoped, transform the laboratory yeast—which, by virtue of a low tolerance for alcohol, among other limitations, is useless for wine making—into a functionally fermentation-competent organism.

43. Endy, "Foundations for Engineering Biology"; Schyfter and Calvert, "Intentions, Expectations, and Institutions."

44. Pretorius, "Synthetic Genome Engineering."

45. Borneman, Schmidt, and Pretorius, "At the Cutting-Edge of Grape and Wine Biotechnology."

Per legislation from the Organisation International du Vin et des Vignes (OIV), which regulates wine production in the vast majority of the grape-growing world, including Australia, wine production cannot involve genetically modified organisms; synthetic yeast and all other yeast, bacteria, and grape vines produced using techniques *other* than conventional breeding and directed evolution are off the table.[46] Even if the pan genome delivers on its promises, no product of the Sc2.0 project will be able to be developed for commercial wine-making use. Nevertheless, the synthetic yeast will function as a useful model for scientific research into wine-making problems, and if and when international policy regarding genetically modified organisms in wine making changes, the AWRI and the Australian industry would be at the ready and leading the pack.[47]

Wine made with genetically modified yeast exists. As a side project, the Australian synthetic yeast team has made a distinctively raspberry-scented experimental chardonnay by building an *S. cerevisiae* strain with a non-native pathway for producing raspberry ketone.[48] But selling their raspberry-flavored chardonnay would be illegal, and you cannot buy any other synthetic yeast-made wine from even the best-stocked online bottle shop. Questioning the terroir of synthetic yeast is not an exercise in describing the potential flavor characteristics of some imagined future beverage. Rather, it is an application of a strategy from one yeast-inhabited world to examine another, suggesting that these worlds are not and cannot be entirely separate and considering how synthetic yeast might become as they merge. Synthetic biology work cannot be considered solely as an activity that changes the contours of biology but as world-making activity that makes other living organisms into materials that can (and perhaps should) be redesigned to more perfectly match human needs. The current route that synthetic biology projects such as Sc2.0 take toward that possible world, with decoupling as a central principle, involves disentangling biological systems to create components able to be mobilized for human use without their original organism-dependent strings attached. That vision ignores or seeks to erase connections that organisms participate in making as species work together. Synthetic biology work needs to account for these connections rather than extend its decoupling vision without observing what is being erased.

Discussions of synthetic yeast place it squarely in the lab but gesture toward lives it is expected to live elsewhere. In asking about its terroir, I ask what happens when Sc2.0 is perceived as a cultural actor rather than only a scientific accomplishment. Yeast strains bearing synthetic chromosomes—intermediaries en route to a fully synthetic Sc2.0—are at present restricted to appropriately certified scientific laboratories

46. Notably, the United States is *not* a signatory party to the OIV, which means that the use of genetically modified organisms in wine produced and sold in the United States is subject to national legislation and that GM wine is therefore not a complete nonstarter. One genetically modified wine yeast strain, ML01, is indeed already approved for industry use in North America.

47. Borneman, Schmidt, and Pretorius, "At the Cutting-Edge of Grape and Wine Biotechnology."

48. Lee et al., "Heterologous Production of Raspberry Ketone."

by national and international biosecurity regulations. Sc2.0 and its descendants are, however, unlikely to remain so spatially divorced from other yeast-working locations. Even if they do remain spatially isolated, the very existence of the Sc2.0 project changes the discursive landscape in and out of which "yeast" is constructed. Moreover, yeast move. Introducing new genetic material changes the pool available for the promiscuous forms of genetic exchange in which yeast engage. Genetic relationships among yeast strains align with human movements and fermentation practices across continents, with genetically distinct populations associated with North American oak forests and with coffee and chocolate production relating to intercontinental human movements.[49] Human work has changed the shape of global yeast populations; human work, perhaps including synthetic biology, continues to do so. Synthetic biology makes *S. cerevisiae* a subject of and tool for engineering, but yeast is never just a scientific tool; it is necessarily always also a cultural and gastronomic *companion* with whom humans share a table.[50]

Terroir: Synthetic Yeast as an Organism in the World

Several recent analyses have employed complex and nuanced understandings of terroir—for instance, as an "optic" for visualizing the evolution of French culture and identity;[51] in definitions of quality in contemporary commodity versus various local or other "alternative" foodways;[52] structuring Jewish legitimations of space in the West Bank;[53] building value-making in artisan production;[54] or relating to regional French governance strategies.[55] Terroir, in addition to being intriguing on its own merit, has become a useful heuristic for tracing the nonlinear geographies with which scholars across disciplines are increasingly concerned. I employ it here in terms of its use in the "New World," where it is employed more as a means of constructing producer and consumer identity than as a distinctive physical location.

English translations of the untranslatable French word are contentious and many. "Taste of place" is arguably the most common.[56] Among the shortest comes from American wine critic and writer Matt Kramer, who calls terroir "somewhereness."[57] The French Institut National des Appellations d'Origine (INAO) parses terroir, to paraphrase their description, as comprising physical place, climate, the grape variety planted, and human activity.[58] To that list other industry bodies, academic researchers, and aficionados

49. Goddard, "Microbiology"; Ludlow et al., "Independent Origins of Yeast."
50. Haraway, *When Species Meet*.
51. Parker, *Tasting French Terroir*.
52. Trubek, *Taste of Place*.
53. Handel, Rand, and Allegra, "Wine-Washing."
54. Paxson, "Locating Value in Artisan Cheese."
55. Demossier, "Beyond Terroir."
56. Joy, "Terroir: The Truth"; Paxson, "Locating Value in Artisan Cheese"; Trubek, *Taste of Place*.
57. Kramer, "Matt Kramer on Wine."
58. "Guide du demandeur d'une appellation d'origine protégée"; Joy, "Terroir: The Truth."

have been adding the influence of other elements of the wine-making ecosystem: native plants, domesticated animals, soil architecture,[59] politics,[60] and the local microbiome of yeast and bacteria.[61] All contribute to terroir because they contribute to connecting the qualities of a wine with the qualities of the landscape of its production. That landscape, constructed through the mingled contributions of many species, is, as Brice observed in working with an Australian winery, "saturated with more-than-human intercorporeal entanglements." Tangled as they are, tweaking any one thread moves the others.[62]

Terroir is also a heuristic for understanding *provenance*, where synthetic yeast comes from. Following the INAO definition, we could trace the physical places, climate, varieties, and human (and nonhuman) activities of Sc2.0. The project is international but has nationally distinctive loci of activity in the United Kingdom, the United States, China, Australia, and Singapore. As each consortium lab must obtain its own funding to work on Sc2.0, national sources of and motivations for funding influence how each lab frames its core aims and what kinds of related side projects they pursue. The *climate* for scientific research and synthetic biology in those countries and in the individual labs pertains to how the features of Sc2.0 develop. Similarly salient are the motivations and capacities of the humans and other organisms working to produce Sc2.0: *E. coli* bacteria, geneticists, computer scientists, programmers, designers, undergraduate students, and the odd social scientist. Together, these conditions comprise the environment in which Sc2.0 is cultivated and therefore establish how synthetic yeast grows.

The *variety* of yeast chosen as the backbone for the project, and that yeast's parentage, likewise informs the design and outcomes of the project. The original genome behind the new Sc2.0 design belongs to a laboratory strain called BY4741. The human father of BY4741 is Jef Boeke, leader of the Sc2.0 consortium, who led the group that developed BY4743 from its fungal mother, S288C, in 1998.[63] S288C is the daughter of Robert Mortimer and six strains that contributed genetic material to the yeast Mortimer selected for biochemical studies.[64] BY4741 was developed as a "designer deletion strain" to be specially "tractable" for genetic work.[65] Several genes commonly used to track the movement of plasmids—small circular pieces of DNA that can be used to ship new genes into the yeast cell—are deleted from the BY4741 genome, which makes using those plasmids easier. Mortimer selected S288C as a strain highly compliant with

59. Tomasi et al., "Soil Influence on Root Distribution."

60. Josling, "The War on Terroir"; and many others.

61. Bokulich et al., "Associations among Wine Grape Microbiome"; Knight et al., "Regional Microbial Signatures"; Padilla et al., "Yeast Biodiversity from DOQ Priorat."

62. Brice, "Killing in More-than-Human Spaces," 191.

63. Brachman et al., "Designer Deletion Strains."

64. Mortimer and Johnston, "Genealogy of Principal Strains."

65. Brachman et al., "Designer Deletion Strains," 115.

exigencies of biochemistry: it requires few nutrients and readily grows as separate cells in liquid culture.[66] However, S288C also has a dysfunctional version of a protein important to mitochondrial gene expression, limiting its use for many biological studies.[67]

Usual narratives of synthetic biology tend toward erasing rather than emphasizing this sort of context. In remaking organismic functions as standardized parts, "biological complexity" becomes a "challenge" to be "avoided" or "managed"; differences in how genetic parts function across organisms are "engineering costs" and therefore targets for optimization.[68] Successfully overcoming such challenges implies engineering away individual organismic variation "through practices of isolation, measurement, standardization and reconfiguration" so that "biological parts become dissociated from their species provenance and evolutionary histories."[69] These parts can then be loaded into "host cells" with standardized functions that remain predictable and controllable every time the biological engineer takes them off the shelf. "The proposed moral economy for synthetic biology," as Frow explains in her study of valuing the BioBrick, "is intended to disentangle the part from its (biological and institutional) context of production, so that it may circulate freely for others to use."[70] The object of synthetic biological work is not necessarily to erase organismic specificity and contextual complexity itself, but doing so ends up being collateral damage in efficient bioengineering.

Latour's account of scientific knowledge production hinges on immutable mobiles, observations that can be divorced from their original contexts to travel anywhere and remain valid.[71] Describing how agricultural field studies are processed into scientific knowledge, Timothy F. Gieryn observes that field sites "shed" specific contextual references to become "placeless places."[72] Synthetic biology, it could be said, produces placeless organisms. These "utopian," literally "no-place" solutions to feeding the future belong nowhere and can therefore go anywhere. Attempting to depict an engineered organism in its unique and thoroughly nonstandardized context is therefore an exercise in asking what the standardizing work of synthetic biology makes invisible. What disappears?

One such constructed invisibility is the situated, local craft of humans and yeast working together. Aspirations to engineer biology invisibilize much of the craft of the human scientist involved in making these interspecies collaborations successful. Biological engineering has a "'de-skilling' agenda":[73] democratized biohacking, the imagined

66. Mortimer and Johnston, "Genealogy of Principal Strains."

67. *Saccharomyces* Genome Database, "Strain: S288C," www.yeastgenome.org/strain/S288C/overview (accessed December 27, 2017).

68. Endy, "Foundations for Engineering," 450; but the critical point is made throughout social scientific literature on synthetic biology. See, for example, Mackenzie, "Design in Synthetic Biology"; O'Malley et al., "Knowledge-Making Distinctions"; and Roosth, "Biobricks and Crocheted Coral."

69. Frow, "Making Big Promises Come True?," 433.

70. Ibid., 442.

71. Latour, "Visualization and Cognition."

72. Gieryn, "City as Truth-Spot," 6.

73. Schmidt, "Do I Understand What I Can Create?"

future of current citizen science, should theoretically be accessible to anyone; robots will, it is hoped, take over much of the mundane labor of building genetic constructs.[74] Well-configured construction work will permit linking together a logical sequence of off-the-shelf components and inserting them into a cellular operating system that will, in effect, run the genetic program as designed.

This is not how synthetic biology currently works. Genetic parts do not function identically across organisms or even in the same organism when used in different pathways. Host cells are neither standardized nor completely understood. The cell's own systems interfere with human designs in unpredictable ways. Assembling short DNA sequences into larger constructs follows well-defined protocols, but these protocols fail in unpredictable ways, accomplishing their initial aims only with intensive and individualized troubleshooting. The first fifteen "chunks" of a growing synthetic chromosome may link together smoothly, but the sixteenth may not, requiring an experienced scientist to devise a wholly different strategy to work around the yeast cell's inexplicable refusal.

Identifying the nexus of a problem and finding "winner" cells containing successful assemblies means knowing how to judge when a yeast cell or colony looks "sick" or "healthy," ready to participate in an experiment or signaling that something is awry. Attending to terroir as the local productive human-yeast ecology of synthetic biology—a laboratory-grown lichen of humans and yeast living together—makes this skilled work visible and therefore something that can be counted as part of the necessary labors of synthetic biological construction. The lichen is a useful metaphor because yeast synthetic biology is as much dependent on the work of the yeast as on the work of human scientists.

In the synthetic yeast project, increasingly long sections of laboratory-generated DNA are built by giving individual "chunks" to yeast cells and relying on their "incredible" power of homologous recombination to fuse them together in the correct order.[75] While not every individual yeast cell will successfully accomplish any given assembly task, a few members of the population occupying any given test tube usually will. Human scientists rely on their microbial coworkers' being able to do this job reliably, and their labor is written into scientific protocols. While human scientists have devised numerous non–yeast-dependent means of attaching bits of DNA together in the desired order, these non–yeast-based methods tend to have lower success rates. The detailed mechanics of homologous recombination works remain fuzzy as far as microbiology knowledge is concerned.[76] Humans do not know how to do homologous recombination, but yeast do.[77]

74. Balmer, Bulpin, and Molyneux-Hodgson, *Synthetic Biology*; Burgess, "Democratizing Biotech"; Synthetic Biology Leadership Council, "Biodesign for the Bioeconomy."

75. Mitchell et al., "Versatile Genetic Assembly System," 6629; and many other publications in yeast genetics.

76. Symington, "Homologous Recombination."

77. Yeast is thus asked to *labor* to support the research lab economy, per Jennifer Hamilton's definition of "labour" for *Environmental Humanities*, drawing on Donna Haraway's questions in *When Species Meet*.

Tracing terroir makes all of these labors both visible and valuable: first, by acknowledging that synthetic yeast emerges from a multispecies ecology of production; second, by conceptualizing that ecology of production as complex, nonlinear, and codependent. Location, climate, and varieties of organisms must all be felicitous. Yeast and numerous "species" of human workers must cooperate such that the productive landscape invoked by terroir coincides with Timothy Ingold's "congealed taskscape," gelling the skilled work of multiple species.[78] Like the American artisan cheeses concerning Heather Paxson, the provenance of synthetic yeast is built up as it goes along, through human intra-action with the variously living environment.[79] As Ingold and Paxson, along with Donna Haraway, Annemarie Mol, and numerous other ecosystem-minded theorists have articulated, it is less useful to think of organisms as "expressing" a predetermined set of characteristics in an environment than to see how organisms are "generated" in and with environments with which their boundaries are fluid.[80]

Terroir as World Making

Terroir, however, in its contemporary English usage, is not principally about describing a physical place.[81] Wine writers harness terroir to evoke an emotional response, a pleasurable experience of imagining a beautiful landscape and an assessment of higher quality, all mediated by a physical product that embodies the ineffable totality of that landscape. Paxson observes that artisan cheese makers employ terroir less to refer to a historical sense of place than to conjure up the kinds of places they want their cheese making to create.[82] Terroir is thus about experiencing a *connection* to place as an ecology of production, insisting that we imagine a landscape into being through a mediating flavor.[83] Terroir is not about *describing* a place but about *connecting* to one, not about *discovering* a place but about *constructing* one. Terroir is a world-building exercise. Asking about the terroir of synthetic yeast compels asking not how the yeast is but how we make it and reorienting from what is scientifically possible to what is culturally desirable. Terroir becomes a tool for asking what kinds of worlds taste good.

The argument in suggesting that a synthetic organism be understood through the cooperative landscape of its production—not only as tangled connections rather than decoupled components but as an experience of what is culturally nourishing—is that human appetites are better satisfied by building relationships than by increasing disconnection. Humans are only human in relationship with organisms and

78. Ingold, *Perception of the Environment*.

79. Paxson, *The Life of Cheese*.

80. de Laet and Mol, "Zimbabwe Bush Pump"; Haraway, "Anthropocene, Capitalocene, Plantationocene, Chthulucene"; Ingold, *Perception of the Environment*.

81. Demossier, "Beyond Terroir."

82. Paxson, "Locating Value in Artisan Cheese."

83. Ibid.

environments.[84] Insofar as we are human by being in relation with other species, estranging humans from mutually constitutive webs of relating would seem to definitionally make humans less human. In considering how synthetic yeast and other technical achievements become future foods, their connections should remain visible so as to impel attention to—moreover, impel active construction of—the more-than-caloric value of these products, realizing them not just as future foods for the "no places" of utopias but potential solutions to satisfying appetites in utopian places—that is, the "good places"—of future well-being.

A radically different imagined synthetic biological solution to future hunger emphasizes this point. When asked to name a "moonshot" project, a leading Ivy League scientist proposed the photosynthetic human.[85] If humans were, like plants (and algae, and cyanobacteria), equipped with the cellular machinery to convert sunlight and carbon dioxide into sugar and oxygen, one of humanity's most central and enduring problems would be solved or at least fundamentally restructured. Even if humans still consumed nutrients orally, the species would have taken steps toward true independence, toward the individual's not needing to rely on any other organism for this one inescapable requirement for survival. Human photosynthesis might alleviate hunger but might also eliminate some of the webbed social relationships through which we constitute ourselves as persons. In so doing, such technology might engineer away some opportunities to care for, with and within, those multispecies ecosystems.[86]

I am not trying to advocate for some idyllic and unrealistic fantasy future in which everyone drinks sustainably produced local low-alcohol wine in suitable moderation with communally prepared meals, in which humanity is always at peace and environments are always healthy, and in which our species has devised cooperative social means to ensure that we care for humans and nonhumans alike. I *am* saying that as we imagine technologically mediated well-fed futures, we think about locating those science fictions in places where food still builds connections.

Numerous futures imagine yeast (and algae) as providing scalable, cruelty-free protein able to feed an expanded population without killing animals anyone thinks are worth caring about. Needless to say, these visions constitute cruelty narrowly, even without considering cruelty to yeast but in terms of the ramifications of the infrastructures those yeast-fed futures involve. To hold on for a moment to the idea of cruelty toward yeast, however, the violence of being made placeless should not be discounted. Current modes of synthetic biology demand that yeast (and other living things) become chassis able to accept any number of interchangeable modules, easily retrained to suit

84. A central tenet of multispecies studies as reviewed, for example, in Latimer and Miele, "Naturecultures?," and other articles in the same special issue.

85. Singer, "Photosynthetic Fish and Other Oddities."

86. I thank Catie Griessler for making this point and for showing me its connection to synthetic biology at the 2016 Symposium for Australian Gastronomy in Melbourne.

fluid market-driven needs. Yeast are being trained as the kind of flexible workforce that other twenty-first-century workers are often exhorted to become: mobile laborers who can work anywhere, with "transferrable skills," who can be contracted as needed across companies and cities and so make a long-term place nowhere. In a factory or on the knowledge-production lines and cube farms of many glass-walled office buildings, humans are encouraged to labor without acting too much like biological organisms. Youth being trained to competitive scientific and academic culture are instructed that professional success depends on a willingness to be decoupled from one's home. The ideal worker, one could say, becomes a chassis onto which desired roles and functions can be loaded.

The violence of decoupling sensory experience from place as affective syntheses should also not be discounted. In the absence of terroir, violence toward landscapes becomes easier because connections between food and the collaborative landscapes responsible for producing food become easier to ignore. Synthetic biology could be criticized as a tool similar to the American supermarket, promulgating a placeless food culture and contributing to the estrangement of humans from their environments by selling the same plastic-wrapped prechopped broccoli season after season. The habit that supermarket cultures encourage of paying relatively little attention to product origins facilitates creating a market for synthetic yeast and products thereof. Moreover, terroir opposes the kind of utilitarianism that reduces a food's value to its ability to meet nutritional needs or to basic chemically and physically measurable parameters, independent of where it comes from or who has been responsible for its production. As eaters who have been subjected to institutional food can attest, standards for nutritional adequacy do relatively little to encourage the kinds of attentive relationships with food that we increasingly understand as part of eating healthfully in addition to eating well. Terroir has long since ceased to be, if indeed it ever was, solely a description of a product. Necessarily juxtaposed against placeless production schemes, as Paxson observes in cheese making and Amy Trubek and Sarah Bowen observe in the American supermarket system, terroir has become a moral statement.[87]

None of this is to say that synthetic yeast should not be a future food or that foods made from synthetic yeast or other products of synthetic biology are necessarily tools of violence but rather that violence will be done if synthetic biology programmatically estranges organisms—ourselves included—from place and from each other. Worlds are made and remade through actions. Making cells into production factories with little thought for their individuality as organisms, save to squash or erase tendencies that interfere with production, can remake the world as a culturally poorer place. Conceptual tools for thinking about one element of the environment spill over into thinking about other elements, both insofar as environments are webs of connection and because thoughts and behaviors in one direction contribute to structuring thoughts and

87. Paxson, "Locating Value in Artisan Cheese"; Trubek and Bowen, "Creating the Taste of Place."

behaviors elsewhere.[88] I am therefore wary of the ways in which we might make humanity and the environments we share poorer by engineering life to be less lively, by reducing complexity to increase utility, and by making our companions more narrowly functional but less rich.

Conclusion

Asimov describes his Trantor as a subterranean "City" that digested a world, "the culmination of man's mastery over the environment," whose "yeast-culture vats" were manifestations of scientific logic spread out over the landscape. Scientific logics fed enormous numbers of people by "increasing utilization of yeasts and hydroponics"; they also governed the rationalized landscape of the city.[89] Reconceived through the central principles of contemporary synthetic biology, imagined future cities might similarly emphasize rationally designed modularity and be far more aggressive about harnessing biological systems for instrumental human use. Synthetic biology has been heralded as the driver of a new bioindustrial revolution, the engine behind moving from the occasional yeast-grown vanillin and Quorn cutlets to the dramatically reconfigured farms and factories of science fictional utopias.[90] The field's failure to deliver on these promises so far has been attributed at least in part to its failure to divide biological systems into standardized modules and to adequately "characterize and control" context effects.[91] Whether synthetic yeast is ever completed, much less whether naturally brewed raspberry-scented Chardonnay or robot-grown yeastburgers become part of mainstream diets, the prospects and promises of synthetic biology will have already changed the world: by making microorganisms into materials that can be seen as desirable to decouple from their contextual attachments; by changing the landscape in which humans relate to other species.

Seeking the terroir of synthetic yeast, therefore, is useful for at least three reasons. First, it is a suggestion to consider what happens to synthetic yeast when it leaves the laboratory. Second, terroir permits constructing an atypical narrative of synthetic biology that forms a useful counterpart to more typical descriptions, emphasizing the local and the specific against discourses that tend toward the universal and the homogeneous. Third, inquiring after the terroir of synthetic yeast is a world-making activity that compels the question: how do humans *want* to live with yeast (and other organisms) in worlds synthetic biology might construct? Terroir can thus be a source of new rhetorical tools for handling synthetic biology that emphasize care, connectedness, and designing future worlds for collective living.

88. That conceptual schema bleed across contexts to profound effect is a point made in literacy studies through detailing how literate forms of communication shape ways of thinking and knowing, as in Walter J. Ong's *Orality and Literacy*.

89. Asimov, *Caves of Steel*.

90. Peccoud, "Synthetic Biology."

91. Arkin, "A Wise Consistency."

What is the terroir of synthetic yeast? This question is less about what synthetic yeast is and the physical laboratories it occupies than about how it might be made and the kinds of landscapes that it might be used to construct. Imagined synthetic biological solutions to future appetites rely on a series of estrangements, erasing organismic connections and specificities to make life less lively. At the risk of sounding naively optimistic, I would like to ask whether this is necessarily the case. Must building with DNA abstract the becoming-synthetic organism from relationships that synthesize place? Can biotechnology manifest rather than ignore the constructive relationships and intraspecies collaborations that constitute humanity? Could synthetic yeast help feed a future in which food still has terroir?

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