DIRECTIONS FOR DEGRADATION: MULTISPECIES ENTANGLEMENTS WITH 3D PRINTED BIOMATERIALS

Fiona Bell
Department of Computer Science
University of New Mexico
Albuquerque, USA
fbell1@unm.edu

Leah Buechley
Department of Computer Science
University of New Mexico
Albuquerque, USA
buechley@unm.edu

ABSTRACT

As design practitioners begin to consider methods for sustainably disposing of what is made, we explore potential directions for designing with the multispecies-driven degradation of 3D printed biomaterial objects. We present three past encounters with multispecies agents—plants, insects, fungi—that degraded biomaterial samples in our lab. Based on these encounters, we speculate on near-future engagements that such organisms might have with our printed biomaterial objects, where an object is transformed through degradation over time. In these scenarios, we pose multispecies agents as co-designers and co-fabricators of objects, exemplifying how we might reconfigure entangled relationships between human and more-than-human agents in the making-with process and how we might leverage our situated position as human makers to enable planetary flourishing.

AUTHORS KEYWORDS

More-Than-Human Design, Degradation, Biomaterials, Biodesign, Clay 3D Printing, Speculative Design

CSS CONCEPTS

• Human-centered computing~Interaction design

HTTF '24 October 21--23, 2024,Santa Cruz, CA, USA© 2024 Copyright is held by the owner/author(s).
ACM ISBN 979-8-4007-1042-1/24/10
https://doi.org/10.1145/3686169.3686181

INTRODUCTION

In this pictorial, we explore *degradation* as a natural process of making-with the more-than-human world. We as humans often associate degradation with a reduction in quality, condition, and value. This stems from the scientific definition of degradation, which refers to the literal breaking down of matter into smaller parts [33]. Despite its often negative connotations, degradation is inextricably entangled with *growth* and *flourishing*. This is most broadly exemplified by the environmental cycles (e.g., water cycle, carbon cycle, nitrogen cycle, etc.) that maintain balance in our ecosystem—whereby matter is degraded into base elements that are then released back into the environment to support the continued growth of living beings. On a smaller scale, this might look like the carbon and nitrogen in dead leaves being consumed (i.e., degraded) by bacteria and fungi. Given how entangled, and interdependent these relationships are, degradation (and reciprocal growth) is key to planetary wellbeing.

We ground our explorations of degradation in more-than-human and posthumanist design philosophies [19, 27, 30, 59], which provide an alternative to human-centered design approaches by decentering humans and repositioning nonhumans as active agents within the design process [22, 40, 45]. In doing so, more-than-human design broadly grapples with design's role in the Anthropocene by radically challenging traditional HCI methodologies and theories to foster more sustainable relationships with our more-than-human world [18, 51, 56].

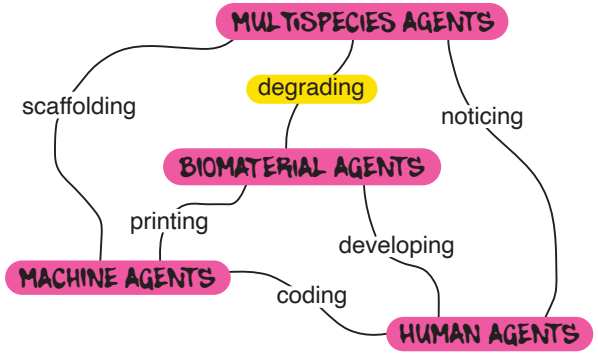
Through this more-than-human lens, we situate degradation as a more-than-human action of making-with, in which the breaking down of matter is a transformative step towards the creation of new matter. Degradation can be caused by a variety of agents such

as wind, precipitation, radiation, and living organisms (both humans and nonhumans). However, for this pictorial, we narrow the scope to degradation driven by *multispecies agents* [26]—nonhuman living organisms such as plants, insects, and fungi. We further focus on how multispecies agents degrade *biomaterials*—materials for human-led making and design practices that are derived from biological matter; they are initially grown from living organisms and are eventually degraded by living organisms [7].

Recently, there has been a surge of new biomaterials developed as environmentally sustainable alternatives to non-degradable materials. Prominent biomaterials in Human-Computer Interaction (HCI) include: algae-based bioplastics [2, 31, 49], microbial cellulose-based bioleathers [3, 37-39], and mycelium-based biocomposites [21, 23, 55, 58]. There have also been several biomaterials designed specifically for 3D printing. One of the most commonly known printable biomaterials is polylactic acid (PLA), which is derived from corn. However, PLA requires specialized composting facilities to degrade (facilities that many cities do not have easy access to), making PLA less sustainable than initially perceived [32]. Accordingly, researchers and designers have begun to develop printable biomaterials that degrade rapidly in the natural environment without the need for industrial composting facilities. Such biomaterials have been derived from pecan shell flour [17], mussel shells [43], spent coffee grounds [42], and bamboo fibers [46].

Our own design research efforts have focused on the creation of paste-like biomaterials designed for printing with low-cost, off-the-shelf, clay 3D printers [4, 16, 41]. In experimenting with biomaterial recipes made respectively from compost, corn flour, and orange peels, we began to notice how various biomaterial samples were degraded by a variety of multispecies agents. These encounters were unexpected, but welcome. Given the digital predictability of 3D printing—precision and repeatability being the key arguments for why digital fabrication is a compelling and important tool—the unexpected entanglements that we uncovered brought newfound inspiration to our making practice.

These multispecies encounters further sensitized us to the other agents present within the making of our 3D printed biomaterial objects: us as *human agents* in charge of designing the object through code, developing the biomaterial recipe, and noticing degradation; nonhuman living organisms as *multispecies agents* in charge of degrading the printed biomaterial objects; and 3D printers as *machine agents* in charge of fabricating the designed object. We found these agents revolved around a fourth agent, *biomaterial agents*, which make up the physical scaffold of the printed object and mediates between the human, machine, and multispecies agents. Together, these agents *make-with* each other—referring to Haraway's notion of sympoiesis: "*a word proper to complex, dynamic, responsive, situated, historical systems...a word for worlding-with, in company*", where *"nothing makes itself; nothing is really autopoietic or self organizing"* [27]. We sketch out a web of these agents to clarify how we perceive their relationships, noting that this web is much more complex and holds many other agents in reality.



We as human agents envision making-with biomaterials, 3D printers, and nonhuman living organisms to co-design and co-fabricate objects; but for this pictorial, we focus primarily on the *making-with relationship of degradation between biomaterial and multispecies agents via human-designed, 3D printed, objects.* Based on our past experiments with biomaterials and the correlating encounters with nonhuman living organisms, we speculate on a collection of near-future scenarios and objects that present both *practical* and *fantastical* next steps for our current research. For each scenario, we assemble a collage that is paired with a short description of the object, questions that the object provoked, and a collection of *design dimensions*—design scale, biomaterial agent, machine agent, multispecies agent, initial form, and time—that help us characterize both technical and conceptual aspects of the speculation.

DESIGN DIMENSION	DEFINITION
design scale	— the situated size of the design intervention
biomaterial agent	— biomaterial that is developed, printed, and degraded
machine agent	— type of 3D printer
multispecies agent	— nonhuman living organism(s) that degrade the object
initial form	— form of the object that is coded and printed
time	— measurement of continued, relational degradation

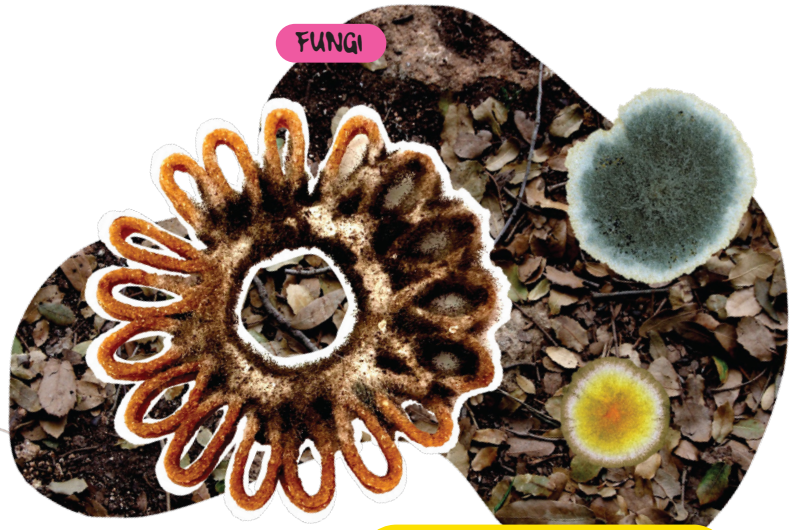
Ultimately, we use this work to imagine how we might go beyond designing *for* our more-than-human world through creating sustainable biomaterial objects, by designing *with* our more-than-human world through engaging multispecies agents as active makers in our relational design practice. We do not aim to find "answers" or "solutions" with this work, but instead considerately w(o/a)nder about future directions for more-than-human making-with via degradation. In doing so, we call for readers to attend to both the beauties and tensions that these highly situated and entangled speculations present; speculations that trouble boundaries between digital and biological, making and unmaking, degrading and growing, imposing control and relinquishing control, aesthetically pleasing and viscerally gross. By surfacing these matters, we hope to promote kinship, humility, and respect when making both for and with our more-than-human world.

PAST ENCOUNTERS

We base our speculations on three past multispecies encounters we experienced when developing biomaterials for clay 3D printing [4]. These situated encounters occurred during the development of new biomaterials, in which nonhuman living organisms intervened with various test samples. These samples exemplify how biomaterials mediate between human, machine, and multispecies agents.

In the creation of a biomaterial made from composted food waste [6], we noticed that the compost itself contained several living organisms—such as worms, maggots, and, notably, different types of fruit and vegetable seeds. We found that some grass seeds began to sprout from one of our biomaterial samples when lightly watered and kept in a warm, light location.

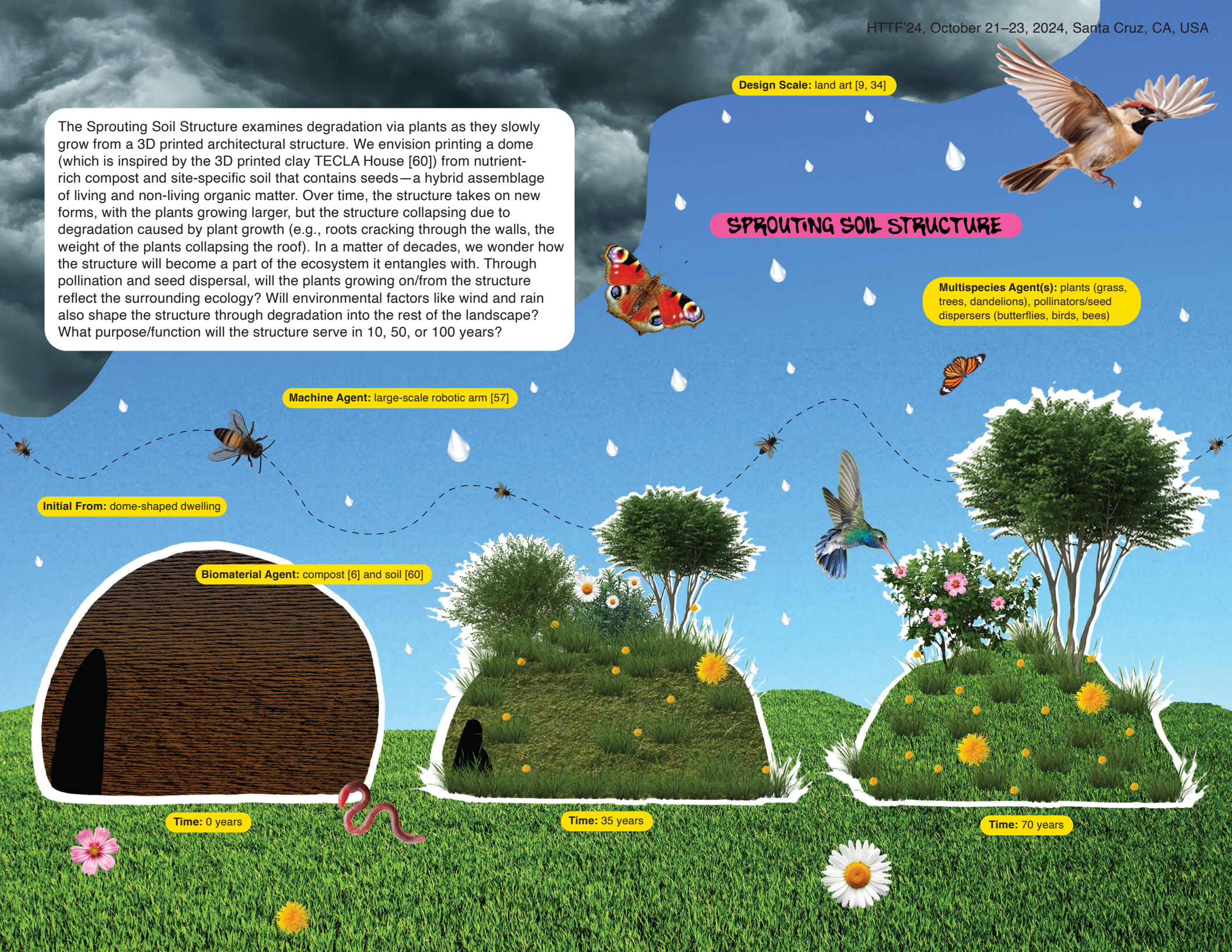
During the development of a biomaterial consisting of corn and wheat flour (dyed blue with food colorant) [10], we found a collapsed test print that was eaten by ants. While the external structure of the print was mostly intact, internal portions were eaten away, revealing unexpected patterns.



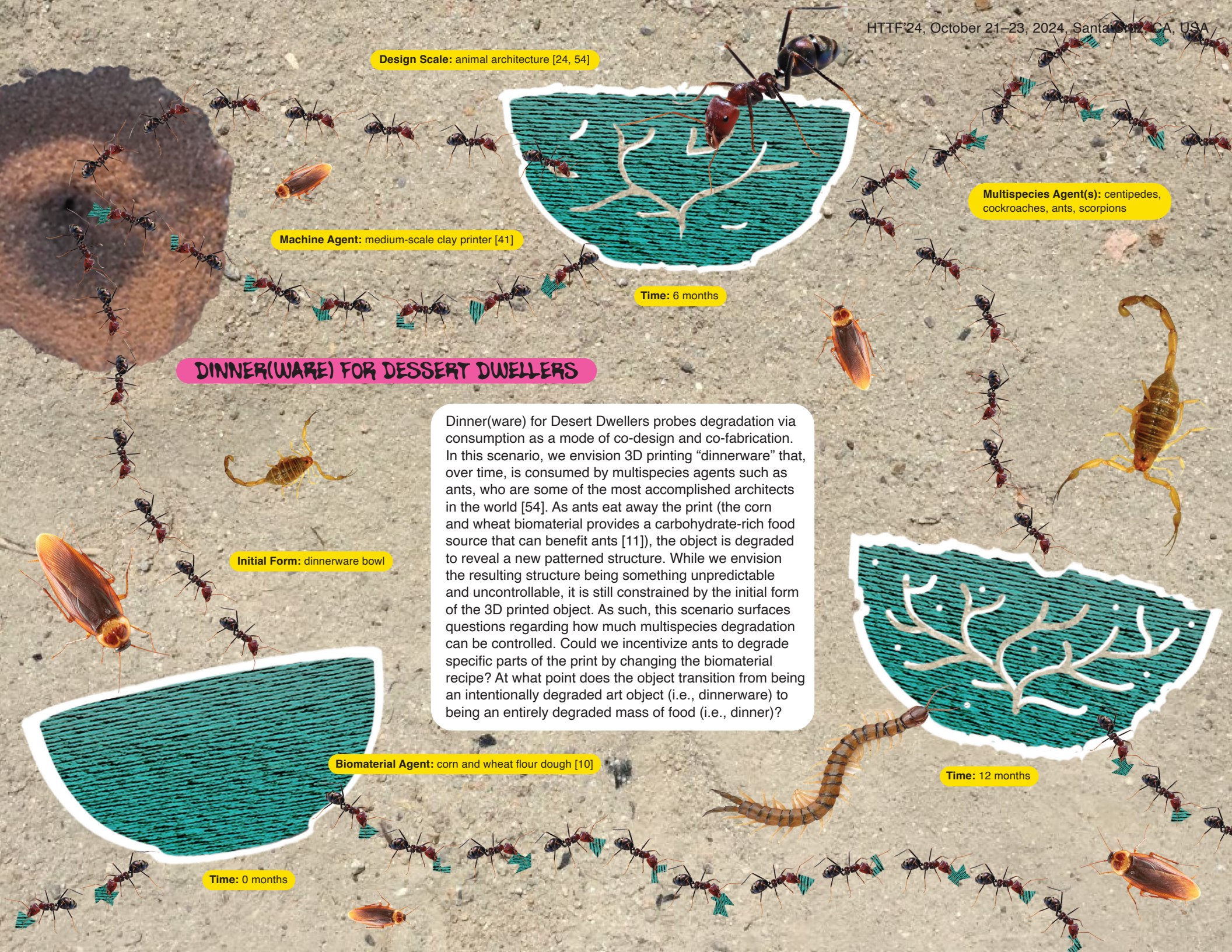
When drying a biomaterial made from orange peels, we found distinct differences between drying prints in a dehydrator (130°F/55°C) versus on a desk in our lab (70°F/21°C). The orange peel prints dried "normally" in a dehydrator, however, when they were dried on a desk, the prints started to mold. The mold continues to propagate on these prints even now, half a year after they were printed.

FUTURE ENGAGEMENTS

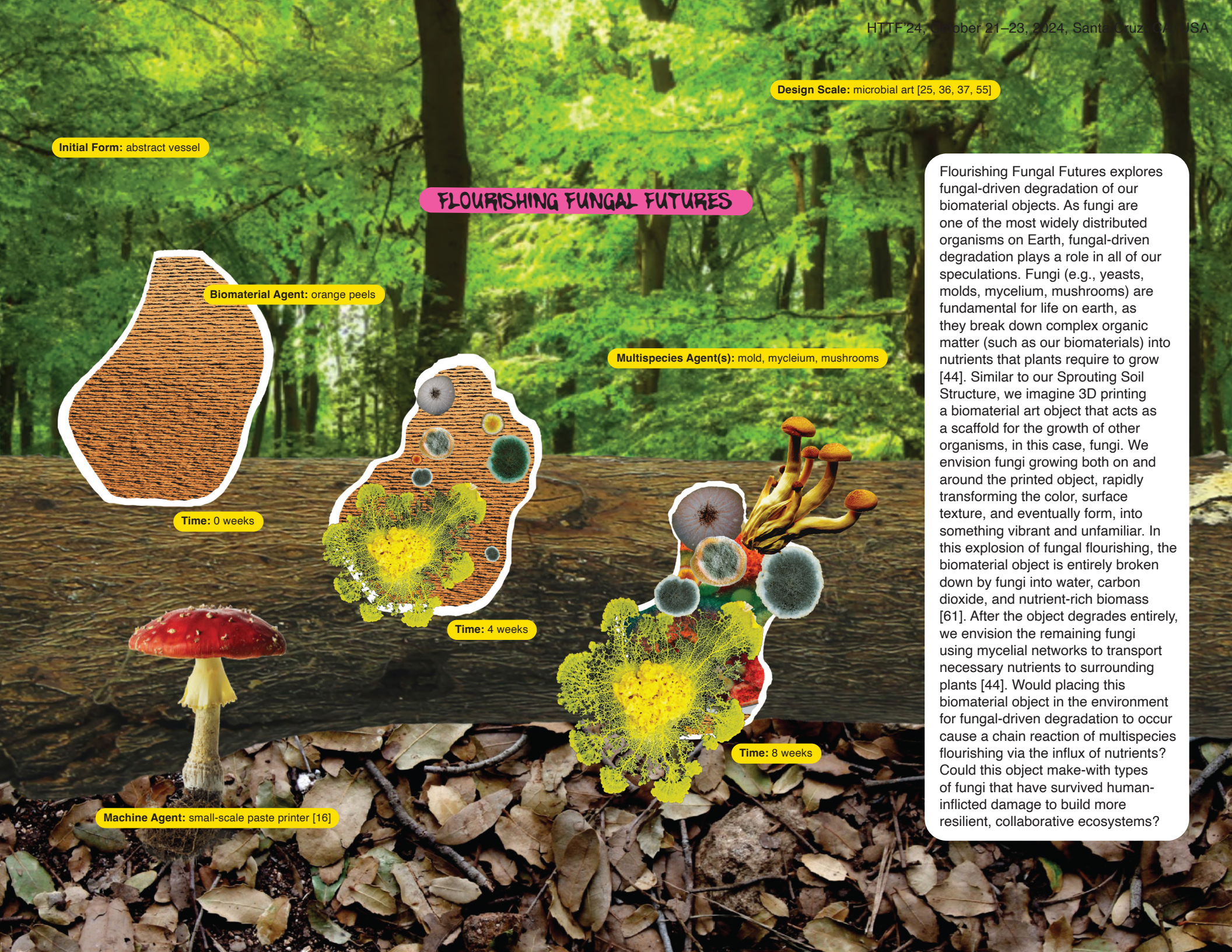
Informed by our past encounters, we speculate on near-future engagements that plants, insects, and fungi might have with our 3D printed biomaterials, where initially printed objects are transformed into something new through degradation. Collages made up of photos of our previous biomaterial samples and free stock images present scenarios that we imagine as directions for future research. We include specific design dimensions (design scale, biomaterial agent, machine agent, multispecies agent(s), initial form, and time) to help guide and distinguish each scenario. To build out these scenarios and objects, we took inspiration from speculative design [14] and design fabulations [28, 50, 53]. Due to our focus on the relationship between biomaterial and multispecies agents (and lack of focus on human agents entangled in these scenarios), we acknowledge that our speculations come across as quite utopian. By leaving out other human-made objects and materials such as plastics, we intentionally amplify how human-made biomaterials that are already showing benefits to our planet [7] can lead to even more environmentally harmonious futures.



The Sprouting Soil Structure examines degradation via plants as they slowly grow from a 3D printed architectural structure. We envision printing a dome (which is inspired by the 3D printed clay TECLA House [60]) from nutrient-rich compost and site-specific soil that contains seeds—a hybrid assemblage of living and non-living organic matter. Over time, the structure takes on new forms, with the plants growing larger, but the structure collapsing due to degradation caused by plant growth (e.g., roots cracking through the walls, the weight of the plants collapsing the roof). In a matter of decades, we wonder how the structure will become a part of the ecosystem it entangles with. Through pollination and seed dispersal, will the plants growing on/from the structure reflect the surrounding ecology? Will environmental factors like wind and rain also shape the structure through degradation into the rest of the landscape? What purpose/function will the structure serve in 10, 50, or 100 years?



Dinner(ware) for Desert Dwellers probes degradation via consumption as a mode of co-design and co-fabrication. In this scenario, we envision 3D printing "dinnerware" that, over time, is consumed by multispecies agents such as ants, who are some of the most accomplished architects in the world [54]. As ants eat away the print (the corn and wheat biomaterial provides a carbohydrate-rich food source that can benefit ants [11]), the object is degraded to reveal a new patterned structure. While we envision the resulting structure being something unpredictable and uncontrollable, it is still constrained by the initial form of the 3D printed object. As such, this scenario surfaces questions regarding how much multispecies degradation can be controlled. Could we incentivize ants to degrade specific parts of the print by changing the biomaterial recipe? At what point does the object transition from being an intentionally degraded art object (i.e., dinnerware) to being an entirely degraded mass of food (i.e., dinner)?



Flourishing Fungal Futures explores fungal-driven degradation of our biomaterial objects. As fungi are one of the most widely distributed organisms on Earth, fungal-driven degradation plays a role in all of our speculations. Fungi (e.g., yeasts, molds, mycelium, mushrooms) are fundamental for life on earth, as they break down complex organic matter (such as our biomaterials) into nutrients that plants require to grow [44]. Similar to our Sprouting Soil Structure, we imagine 3D printing a biomaterial art object that acts as a scaffold for the growth of other organisms, in this case, fungi. We envision fungi growing both on and around the printed object, rapidly transforming the color, surface texture, and eventually form, into something vibrant and unfamiliar. In this explosion of fungal flourishing, the biomaterial object is entirely broken down by fungi into water, carbon dioxide, and nutrient-rich biomass [61]. After the object degrades entirely, we envision the remaining fungi using mycelial networks to transport necessary nutrients to surrounding plants [44]. Would placing this biomaterial object in the environment for fungal-driven degradation to occur cause a chain reaction of multispecies flourishing via the influx of nutrients? Could this object make-with types of fungi that have survived human-inflicted damage to build more resilient, collaborative ecosystems?

DISCUSSION

Through our speculative scenarios and objects, we pose multispecies agents (plants, insects, fungi) as active co-designers that are physically engaged in *making-with* [27] our 3D printed objects. Through modes of degradation (and interconnected growth), multispecies agents both subtractively and additively contribute to the aesthetic design of each object through texture, color, and form. While the speculations showcase outwardly utopian futures, we bring attention to several tensions that arise.

This work actively troubles the boundary between *making* versus *unmaking* [35, 47, 48]. Our speculations showcase recognizable versions of our initially printed objects as multispecies agents degrade them, however, there reaches a point in time where the objects are broken down entirely, no longer resembling a form (or function) that is recognizable to us as humans—leading us to ask, how does degradation blur the boundaries between (un)making these objects?

This boundary brings into question the aesthetics of (un)making. While degradation is understood as an aesthetic, it is typically associated with unfavorable connotations of dirtiness, decay, and destruction. Consequently, this negatively impacts how we as humans perceive the more-than-human world that plays a role in degradation, for example, the abject revulsion felt when finding a cockroach scurry across a bathroom floor or unintentionally grabbing a moldy piece of bread [8]. In this light, the degradation of our 3D printed objects might be seen as something to be averse towards, something that is disgusting and even ugly. However, by posing degradation as an active mode of making objects that are potentially beneficial for the environment, we (re)consider what aesthetic qualities and values might be deemed "beautiful". Our speculative objects then exemplify degradation as an opportunity for embracing more-than-human aesthetics that challenge the dichotomy of beautiful versus gross. We in turn question: what new aesthetic qualities and values might arise?

Along these lines, we also probe tensions between digital and biological making and the resulting aesthetics these methods convey. Digitally made objects are often associated with perfection and predictability. One of the greatest benefits of digital fabrication, and specifically 3D printing, is the precision and repeatability of making, which can allow humans to manufacture precise parts for biomedical or aerospace applications [1] or create precise replicas of mathematical equations in 3D space [20]. In contrast, making with biomaterials and living organisms is often imperfect and unpredictable [3, 29]. By combining these contrasting methods of making, we (re)incorporate elements of imperfection, unpredictability, and ephemerality [15, 52] into digital making—*elements that humans share with all other living organisms*. Could embracing imperfection and unpredictability in such objects encourage human humbleness and empathy towards our more-than-human others?

We find that the duality between digital and biological also highlights a key difference in how much control we have in the making of objects. While 3D printing allows us to *impose control*, degradation via multispecies engagements encourages us to *relinquish control* over the (un)making of objects. However, as with many of these dichotomies, the boundary between (lack-of-) control is fuzzy. While 3D printing can result in "perfect", "controlled" prints, material inconsistencies, code blips, and machine hiccups can impart unique traces in objects, exemplifying other more-than-human agencies present in the process [5, 12, 13, 20]. Similarly, multispecies engagements of degradation are often "unpredictable" and "messy", however, we as humans can potentially control these engagements by, for instance, pruning plants and spraying pesticides. As such, we find that these speculative bio-digital objects encourage us to recognize the nuances of (un)controlled making and ask which agent(s) hold power in the making process?

Our speculative work does not provide many direct answers, but instead provokes questions that ask us to think critically about future next steps for our research. Accordingly, our speculations probe the boundaries between making/unmaking, beautiful/gross, digital/biological, controlled/uncontrolled. By exploring these dualities and looking towards futures in which they are merged, we make room for more nuanced, more-than-human perspectives and agencies—ultimately challenging predominantly human-centered notions of design that have led to the dangerous degradation of our more-than-human world.

CONCLUSION

How do we not only design *for*, but also *with* multispecies agents? Interest in rapidly degradable biomaterials has surged over the past few years due to their sustainability. While this consideration of degradation for sustainability purposes (i.e., degradation *for* multispecies growth) is a commendable goal to have when designing new materials and objects—especially given how much non-degradable waste we are currently producing—we position degradation as a starting point to think about how we might make-*with* multispecies agents as co-designers and co-fabricators. Our speculations in turn examine how multispecies agents such as plants, insects, and fungi might transform 3D printed objects into entirely new designs that have different aesthetics, functionalities, and perspectives. However, we recognize that these speculations distinctly lack human agents; thus, we conclude by questioning: How might we as humans then interact with these newly designed more-than-human objects? How do continued interactions with these objects sensitize us to our role, as humans, in a greater entangled ecosystem and in the process of degradation and eventual (re)growth? How can these situated, human-centered interactions support or prevent planetary flourishing?

ACKNOWLEDGEMENTS

We would like to recognize the multispecies agents who engaged and continue to engage with our research, as well as the other living beings that inspired us to consider what future entanglements might look like, including, but not limited to: the cockroach that lives in our lab's bathroom, our (un)official lab dog Star, and the jar of microbial cellulose that sits in the corner of our lab. We further acknowledge that this work took place at the University of New Mexico, which sits on the traditional homelands of the Pueblo of Sandia. We honor the land itself and those who remain stewards of this land throughout the generations and also acknowledge our committed relationship to Indigenous peoples. We sincerely thank all the members of the Hand and Machine Lab for their feedback, as well as Mirela Alistar and Netta Ofer from the Living Matter Lab for providing foundational support on ReClaym. This work was funded by the National Science Foundation (NSF) IIS Future of Work Grant at the Human-Technology Frontier Program (Award: 2026218).

REFERENCES

[1] Mohsen Attaran. 2017. The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. Business Horizons 60, 5 (Sept. 2017), 677–688. https://doi.org/10.1016/j.bushor.2017.05.011

[2] Fiona Bell, Latifa Al Naimi, Ella McQuaid, and Mirela Alistar. 2022. Designing with Alganyl. In Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction. ACM, Daejeon Republic of Korea, 1–14. https://doi.org/10.1145/3490149.3501308

[3] Fiona Bell, Derrek Chow, Hyelin Choi, and Mirela Alistar. 2023. SCOBY BREASTPLATE: SLOWLY GROWING A MICROBIAL INTERFACE. In Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction. ACM, Warsaw Poland, 1–15. https://doi.org/10.1145/3569009.3572805

[4] Fiona Bell, Camila Friedman-Gerlicz, Jamie Gould, Erin McClure, Deanna Gelosi, Alyshia Bustos, Monica Silva Lavato, Jeff Suina, and Leah Buechley.2024. Demonstrating New Materials, Software, and Hardware from the Hand and Machine Lab. In CHI Conference on Human Factors in Computing Systems Extended Abstracts. ACM, Honolulu HI USA, 1–5. https://doi.org/10.1145/3613905.3648647

[5] Fiona Bell, Erin Mcclure, Camila Friedman-Gerlicz, Ruby Ta, and Leah Buechley. 2024. Shape-Changing Clay-Dough: Taking a Material-Oriented Approach to 3D Printing Ceramic Forms. In Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24). Association for Computing Machinery, New York, NY, USA, 1–19. https://doi.org/10.1145/3613904.3642246

[6] Fiona Bell, Netta Ofer, and Mirela Alistar. 2022. ReClaym our Compost: Biodegradable Clay for Intimate Making. In CHI Conference on Human Factors in Computing Systems. ACM, New Orleans LA USA, 1–15. https://doi.org/10.1145/3491102.3517711

[7] Fiona Bell, Shanel Wu, Nadia Campo Woytuk, Eldy S. Lazaro Vasquez, Mirela Alistar, and Leah Buechley. 2024. Making Biomaterials for Sustainable Tangible Interfaces. In Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction. ACM, Cork Ireland, 1–5. https://doi.org/10.1145/3623509.3634740

[8] Heidi R. Biggs, Jeffrey Bardzell, and Shaowen Bardzell. 2021. Watching Myself Watching Birds: Abjection, Ecological Thinking, and Posthuman Design. In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21). Association for Computing Machinery, New York, NY, USA, 1–16. https://doi.org/10.1145/3411764.3445329

[9] Emily Brady. 2007. Aesthetic Regard for Nature in Environmental and Land Art. Ethics, Place & Environment 10, 3 (Oct. 2007), 287–300. https://doi.org/10.1080/13668790701578538

[10] Leah Buechley and Ruby Ta. 2023. 3D Printable Play-Dough: New Biodegradable Materials and Creative Possibilities for Digital Fabrication. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23). ACM, Hamburg, Germany, 15 pages. https://doi.org/10.1145/3544548.3580813

[11] C. R. Carroll and D. H. Janzen. 1973. Ecology of Foraging by Ants. Annual Review of Ecology and Systematics 4 (1973), 231–257. https://www.jstor.org/stable/2096812 Publisher: Annual Reviews.

[12] Audrey Desjardins and Timea Tihanyi. 2019. ListeningCups: A Case of Data Tactility and Data Stories. In Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19). Association for Computing Machinery, New York, NY, USA, 147–160. https://doi.org/10.1145/3322276.3323694

[13] Laura Devendorf, Abigail De Kosnik, Kate Mattingly, and Kimiko Ryokai. 2016. Probing the Potential of Post-Anthropocentric 3D Printing. In Proceedings of the 2016 ACM Conference on Designing Interactive Systems (DIS '16). Association for Computing Machinery, New York, NY, USA,170–181. https://doi.org/10.1145/2901790.2901879

[14] Anthony Dunne and Fiona Raby. 2024. Speculative Everything, With a new preface by the authors: Design, Fiction, and Social Dreaming. MIT Press. Google-Books-ID: RKzIEAAAQBAJ.

[15] Tanja Döring, Axel Sylvester, and Albrecht Schmidt. 2013. A design space for ephemeral user interfaces. In Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction (TEI '13). Association for Computing Machinery, New York, NY, USA, 75–82. https://doi.org/10.1145/2460625.2460637

[16] Eazao. 2022. Eazao Zero - Eazao. https://www.eazao.com/product/eazao-zero/

[17] Jeremy Faludi, Corrie M. Van Sice, Yuan Shi, Justin Bower, and Owen M. K. Brooks. 2019. Novel materials can radically improve whole-system environmental impacts of additive manufacturing. Journal of Cleaner Production 212 (March 2019), 1580–1590. https://doi.org/10.1016/j.jclepro.2018.12.017

[18] Laura Forlano. 2017. Posthumanism and Design.

She Ji: The Journal of Design, Economics, and Innovation 3, 1 (March 2017), 16–29. https://doi.org/10.1016/j.sheji.2017.08.001

[19] Christopher Frauenberger. 2019. Entanglement HCI The Next Wave? ACM Transactions on Computer-Human Interaction 27, 1 (Nov. 2019), 2:1–2:27. https://doi.org/10.1145/3364998

[20] Camila Friedman-Gerlicz, Deanna Gelosi, Fiona Bell, and Leah Buechley. 2024. WeaveSlicer: Expanding the Range of Printable Geometries in Clay. In Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24). Association for Computing Machinery, New York, NY, USA, Article 352, 1–16. https://doi.org/10.1145/3613904.3642622

[21] Çağlar Genç, Emilia Launne, and Jonna Häkkilä. 2022. Interactive Mycelium Composites: Material Exploration on Combining Mushroom with Off-the-shelf Electronic Components. In Nordic Human-Computer Interaction Conference. ACM, Aarhus Denmark, 1–12. https://doi.org/10.1145/3546155.3546689

[22] Elisa Giaccardi, Nazli Cila, Chris Speed, and Melissa Caldwell. 2016. Thing Ethnography: Doing Design Research with Non-Humans. In Proceedings of the 2016 ACM Conference on Designing Interactive Systems (DIS '16). Association for Computing Machinery, New York, NY, USA, 377–387. https://doi.org/10.1145/2901790.2901905

[23] Phillip Gough, Praneeth Bimsara Perera, Michael A. Kertesz, and Anusha Withana. 2023. Design, Mould, Grow!: A Fabrication Pipeline for Growing 3D Designs Using Myco-Materials. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems. ACM, Hamburg Germany, 1–15. https://doi.org/10.1145/3544548.3580958

[24] James L. Gould and Carol Grant Gould. 2012. Animal Architects: Building and the Evolution of Intelligence. Basic Books.

[25] Ryan Gregory, Simon Park, and Niall Hamilton. 2024. Microbial Art. http://www.microbialart.com/

[26] Michael Haldrup, Kristine Samson, and Thomas Laurien. 2022. Designing for Multispecies Commons: Ecologies and Collaborations in Participatory Design. In Proceedings of the Participatory Design Conference 2022 - Volume 2 (PDC '22, Vol. 2). Association for Computing Machinery, New York, NY, USA, 14–19. https://doi.org/10.1145/3537797.3537801

[27] Donna J. Haraway. 2016. Staying with the Trouble: Making Kin in the Chthulucene. Duke University Press. https://doi.org/10.1515/9780822373780

[28] Karey Helms, Marie Louise Juul Søndergaard, and Nadia Campo Woytuk. 2021. Scaling Bodily Fluids For Utopian Fabulations. https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-298043

[29] Elvin Karana, Bahareh Barati, and Elisa Giaccardi. 2020. Living artefacts: Conceptualizing livingness as a material quality in everyday artefacts. International Journal of Design 14, 3 (2020), 37–53. http://www.scopus.com/inward/record.url?scp=85098942474&partnerID=8YFLogxK

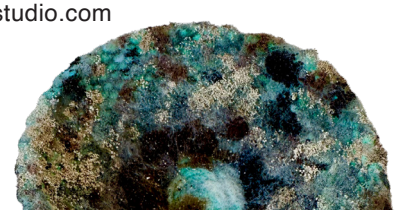
[30] Cayla Key, Cally Gatehouse, and Nick Taylor. 2022. Feminist Care in the Anthropocene: Packing and Unpacking Tensions in Posthumanist HCI. In Proceedings of the 2022 ACM Designing Interactive Systems Conference (DIS '22). Association for Computing Machinery, New York, NY, USA, 677–692. https://doi.org/10.1145/3532106.3533540

[31] Marion Koelle, Madalina Nicolae, Aditya Shekhar Nittala, Marc Teyssier, and Jürgen Steimle. 2022. Prototyping Soft Devices with Interactive Bioplastics. In Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology. ACM, Bend OR USA, 1–16. https://doi.org/10.1145/3526113.3545623

[32] Jeffrey J. Kolstad, Erwin T. H. Vink, Bruno De Wilde, and Lies Debeer. 2012. Assessment of anaerobic degradation of Ingeo™ polylactides under accelerated landfill conditions. Polymer Degradation and Stability 97, 7 (July 2012), 1131–1141. https://doi.org/10.1016/j.polymdegradstab.2012.04.003

[33] Myer Kutz. 2018. Handbook of Environmental Degradation of Materials. William Andrew.

[34] Maya Lin. 2024. Maya Lin Studio. https://www.mayalinstudio.com



[35] Kristina Lindström and Åsa Ståhl. 2020. Un/Making in the Aftermath of Design. In Proceedings of the 16th Participatory Design Conference 2020 - Participation(s) Otherwise - Volume 1 (PDC '20). Association for Computing Machinery, New York, NY, USA, 12–21. https://doi.org/10.1145/3385010.3385012

[36] Robert E. Mitchell. 2015. Bioart and the Vitality of Media. University of Washington Press.

[37] Audrey Ng. 2017. Grown microbial 3D fiber art, Ava: fusion of traditional art with technology. In Proceedings of the 2017 ACM International Symposium on Wearable Computers. ACM, Maui Hawaii, 209–214. https://doi.org/10.1145/3123021.3123069

[38] Madalina Nicolae, Vivien Roussel, Marion Koelle, Samuel Huron, Jürgen Steimle, and Marc Teyssier. 2023. Biohybrid Devices: Prototyping Interactive Devices with Growable Materials | Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology. In Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology (UIST '23). Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3586183.3606774

[39] Netta Ofer and Mirela Alistar. 2023. Felt Experiences with Kombucha Scoby: Exploring First-person Perspectives with Living Matter. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23). Association for Computing Machinery, New York, NY, USA, 1–18. https://doi.org/10.1145/3544548.3581276

[40] Doenja Oogjes and Ron Wakkary. 2022. Weaving Stories: Toward Repertoires for Designing Things. In Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI '22). Association for Computing Machinery, New York, NY, USA, 1–21. https://doi.org/10.1145/3491102.3501901

[41] 3D Potter. 2024. 3D PotterBot 10 PRO | 3D Potter. https://3dpotter.com/product/3d-potterbot-10-pro/

[42] Michael L. Rivera, S. Sandra Bae, and Scott E. Hudson. 2023. Designing a Sustainable Material for 3D Printing with Spent Coffee Grounds. In Proceedings

of the 2023 ACM Designing Interactive Systems Conference (DIS '23). Association for Computing Machinery, New York, NY, USA, 294–311. https://doi.org/10.1145/3563657.3595983

[43] Mariet Sauerwein and Zjenja Doubrovski. 2018. Local and recyclable materials for additive manufacturing: 3D printing with mussel shells. Materials Today Communications 15 (2018), 214–217. https://doi.org/10.1016/j.mtcomm.2018.02.028

[44] Merlin Sheldrake. 2021. Entangled Life: How Fungi Make Our Worlds, Change Our Minds & Shape Our Futures. Random House Publishing Group. Google-Books-ID: EJ4jEAAAQBAJ.

[45] Nancy Smith, Shaowen Bardzell, and Jeffrey Bardzell. 2017. Designing for Cohabitation: Naturecultures, Hybrids, and Decentering the Human in Design. In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17). Association for Computing Machinery, New York, NY, USA, 1714–1725. https://doi.org/10.1145/3025453.3025948

[46] Eugene Soh, Zhi Yong Chew, Nazanin Saeidi, Alireza Javadian, Dirk Hebel, and Hortense Le Ferrand. 2020. Development of an extrudable paste to build mycelium-bound composites. Materials & Design 195 (Oct. 2020), 109058. https://doi.org/10.1016/j.matdes.2020.109058

[47] Katherine W Song, Fiona Bell, Himani Deshpande, Ilan Mandel, Tiffany Wun, Mirela Alistar, Leah Buechley, Wendy Ju, Jeeeun Kim, Eric Paulos, Samar Sabie, and Ron Wakkary. 2024. Sustainable Unmaking: Designing for Biodegradation, Decay, and Disassembly. In Extended Abstracts of the 2024 CHI Conference on Human Factors in Computing Systems (CHI EA '24). Association for Computing Machinery, New York, NY, USA, 1–7. https://doi.org/10.1145/3613905.3636300

[48] Katherine W Song and Eric Paulos. 2021. Unmaking: Enabling and Celebrating the Creative Material of Failure, Destruction, Decay, and Deformation. In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems. ACM, Yokohama Japan, 1–12. https://doi.org/10.1145/3411764.3445529

[49] Marie Louise Juul Søndergaard and Nadia Campo Woytuk. 2023. Feminist Posthumanist Design of Menstrual Care for More-than-Human Bodies. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems. ACM, Hamburg Germany, 1–18. https://doi.org/10.1145/3544548.3581083

[50] Marie Louise Juul Søndergaard, Nadia Campo Woytuk, Noura Howell, Vasiliki Tsaknaki, Karey Helms, Tom Jenkins, and Pedro Sanches. 2023. Fabulation as an Approach for Design Futuring. In Proceedings of the 2023 ACM Designing Interactive Systems Conference (DIS '23). Association for Computing Machinery, New York, NY, USA, 1693–1709. https://doi.org/10.1145/3563657.3596097

[51] Oscar Tomico, Anton Poikolainen Rosén, Svenja Keune, Ferran Altarriba Bertran, Danielle Wilde, Daniel Fernández Galeote, Tau Ulv Lenskjold, Ruut Tikkanen, Oğuz 'Oz Buruk, and Velvet Spors. 2024. Seeding a Repository of Methods-To-Be for Nature-Entangled Design Research. In Proceedings of the 2024 ACM Designing Interactive Systems Conference (DIS '24). Association for Computing Machinery, New York, NY, USA, 1101–1115. https://doi.org/10.1145/3643834.3660745

[52] Vasiliki Tsaknaki and Ylva Fernaeus. 2016. Expanding on Wabi-Sabi as a Design Resource in HCI. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16). Association for Computing Machinery, New York, NY, USA, 5970–5983. https://doi.org/10.1145/2858036.2858459

[53] Vasiliki Tsaknaki, Pedro Sanches, Tom Jenkins, Noura Howell, Laurens Boer, and Afroditi Bitzouni. 2022. Fabulating Biodata Futures for Living and Knowing Together. In Proceedings of the 2022 ACM Designing Interactive Systems Conference (DIS '22). Association for Computing Machinery, New York, NY, USA, 1878–1892. https://doi.org/10.1145/3532106.3533477

[54] Walter R. Tschinkel. 2021. Ant Architecture: The Wonder, Beauty, and Science of Underground Nests. Princeton University Press.

[55] Eldy S. Lazaro Vasquez and Katia Vega. 2019. Myco-accessories: sustainable wearables with biodegradable materials. In Proceedings of the 23rd International Symposium on Wearable Computers. ACM, London United Kingdom, 306–311. https://doi.org/10.1145/3341163.3346938

[56] Ron Wakkary. 2021. Things We Could Design: For More Than Human-Centered Worlds. MIT Press.

[57] WASP. 2024. 3d Printer House | Crane WASP. https://www.3dwasp.com/en/

[58] Jennifer Weiler, Piyum Fernando, Nipuni Siyambalapitiya, and Stacey Kuznetsov. 2019. Mycelium Artifacts: Exploring Shapeable and Accessible Biofabrication. In Companion Publication of the 2019 on Designing Interactive Systems Conference 2019 Companion. ACM, San Diego CA USA, 69–72. https://doi.org/10.1145/3301019.3325156

[59] Daisy Yoo, Tilde Bekker, Peter Dalsgaard, Eva Eriksson, Simon Skov Fougt, Christopher Frauenberger, Batya Friedman, Elisa Giaccardi, Anne-Marie Hansen, Ann Light, Elisabet Nilsson, Ron Wakkary, and Mikael Wiberg. 2023. More-Than-Human Perspectives and Values in Human-Computer Interaction. In Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems. ACM, 1–3. https://doi.org/doi.org/10.1145/

3544549.3583174 Archive Location: world.

[60] Maged Youssef and Lena Abbas. 2023. APPLYING 3D PRINTING TECHNOLOGY IN CONSTRUCTING SUSTAINABLE HOUSES. Architecture and Planning Journal (APJ) 29, 1 (March 2023). https://doi.org/10.54729/2789-8547.1190

[61] Michael Thomas Zumstein, Arno Schintlmeister, Taylor Frederick Nelson, Rebekka Baumgartner, Dagmar Woebken, Michael Wagner, Hans-Peter E. Kohler, Kristopher McNeill, and Michael Sander. 2018. Biodegradation of synthetic polymers in soils: Tracking carbon into CO2 and microbial biomass. Science Advances 4, 7 (July 2018), eaas9024. https://doi.org/10.1126/sciadv.aas9024