Seamless Visions, Seamful Realities: Anticipating Rural Infrastructural Fragility in Early Design of Digital Agriculture

Gloire Rubambiza
Cornell University
Department of Computer Science
Ithaca, New York, USA
gloire@cs.cornell.edu

Phoebe Sengers
Cornell University
Departments of Information Science and Science & Technology Studies
Ithaca, New York, USA
sengers@infosci.cornell.edu

Hakim Weatherspoon
Cornell University
Department of Computer Science
Ithaca, New York, USA
hweather@cs.cornell.edu

ABSTRACT

Rural infrastructure is known to be more prone to breakdown than urban infrastructure. This paper explores how the fragility of rural infrastructure is reproduced through the process of engineering design. Building on values in design, we examine how eventual use is anticipated by engineering researchers building on emerging infrastructure for digital agriculture (DA). Our approach combines critically reflective technical systems-building with interviews with other practitioners to understand and address moments early in the design process where the eventual effects of DA systems may be being built-in. Our findings contrast researchers' visions of seamless farming technologies with the seamful realities of their work to produce them. We trace how, when anticipating future use, the seams that researchers themselves experience disappear, other seams are hidden from view by institutional support, and seams end users may face are too distant to be in sight. We develop suggestions for the design of these technologies grounded in a more artful management of seamfulness and seamlessness during the process of design and development.

CCS CONCEPTS

• **Social and professional topics** → **Socio-technical systems**; • **Human-centered computing** → *Field studies.*

KEYWORDS

values in design, digital agriculture, computer networking, critical technical practice, seamlessness, infrastructure

ACM Reference Format:
Gloire Rubambiza, Phoebe Sengers, and Hakim Weatherspoon. 2022. Seamless Visions, Seamful Realities: Anticipating Rural Infrastructural Fragility in Early Design of Digital Agriculture. In *CHI Conference on Human Factors in Computing Systems (CHI '22), April 29-May 5, 2022, New Orleans, LA, USA.* ACM, New York, NY, USA, 15 pages. https://doi.org/10.1145/3491102.3517579

1 INTRODUCTION

This paper addresses issues that arise in infrastructure development for rural contexts. Compared to urban infrastructure, infrastructure in rural contexts tends to be simultaneously less robust and at a lower priority for repair [15, 39]. This occurs because infrastructures are often designed and governed from more urban centers in ways poorly suited to rural specificities [58, 107]. Here, we examine how these issues are anticipated in the early process of building new infrastructure for rural regions. Our goal, following from work on values in design, is to identify and address moments early in the design process where these eventual effects of new infrastructure may be being unintentionally built in.

Specifically, we look at the early development of new infrastructure to support digital agriculture [65, 96]. These infrastructures are understood as on the cusp of enabling a major transformation in the agriculture industry [8]. We present a study of researchers and practitioners, collectively referred to as lead developers, who are building on emerging infrastructure to adopt and adapt new digital farming technologies before they are ready for open-market consumption. The question we address in this paper is how these lead developers are imagining and orienting towards how their technologies will be eventually used on rural farms, and what consequences that orientation will have for the fragility of rural infrastructure.

Our study has two components. First, drawing on critical technical practice [2, 3] and informed by autobiographical design methods [72], we spent 24 months deploying experimental DA technologies in lab settings and on research farms in the Northeastern US, while documenting our own everyday experiences with getting the technology to work. Second, building on our experiences, we conducted an interview study with six colleagues who are involved in related early-stage efforts to deploy and build applications overlaying similar technologies.

The core argument we will make in this paper is that even when, as in our case, engineering researchers have the direct aim to design robust technologies that address the known challenges of rural networking, institutional and disciplinary barriers make it difficult to effectively anticipate and address challenges that will arise in the eventual use context. These barriers produce faith in an eventual seamlessness of the technology for end users, even in the face of the many material challenges that engineers themselves encounter in the development of experimental systems. Specifically, we find that many of the infrastructural seams experienced by engineers disappear in the pivot to creating research results, other seams are hidden by institutional support, and yet other seams that will exist in rural contexts are structurally invisible to researchers during the process of developing these early systems.

This work is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike International 4.0 License.

CHI '22, April 29-May 5, 2022, New Orleans, LA, USA
© 2022 Copyright held by the owner/author(s).
ACM ISBN 978-1-4503-9157-3/22/04.
https://doi.org/10.1145/3491102.3517579

This analysis demonstrates one way in which the fragility of rural infrastructure is reproduced through the very process of engineering design: by creating an illusion of eventual seamlessness. Unanticipated seams matter because, if not caught and addressed, they render the expected competitive benefits of digital agriculture structurally uneven. Competitive advantage will accrue more significantly to large farms which maintain their own infrastructure and to outside firms who are able to gain control over data and/or the technology used to generate it, than to smaller farmers and other stakeholders who might seek to harness this technology in a more decentralized fashion. We suggest specific changes to the processes of developing DA that can address the seamful challenges identified in this research.

2 MOTIVATION AND RELATED WORK

Social scientists have found that rural infrastructure tends to be less built out, more prone to breakdown, and less likely to be repaired than urban infrastructure [15, 51, 52]. Technologies, standards and regulations that shape infrastructure are often developed by urban centers and map poorly to rural specificities [4, 107]. For example, because of scale issues, infrastructures are often designed for urban centers, with rural customers an afterthought [58]. Because of this lack of attention, rural electricity, telephone, and roads were often established in the US by farmers themselves and their cooperatives, rather than provided as end goods by companies or engineers [58].

The decentering of rural communities in networked infrastructures matters because it produces a structural marginalization of rural communities. Burrell, for example, describes how the connectivity expectations built into Internet applications break down in rural regions, leading to rural users being sidelined in both technology design and shared social conventions of use that rest on expectations of urban connectivity [15]. Vigil and Duarte et al. find similar issues of network-based exclusion affecting rural Native American reservations [23, 103]. As Melvin and Bunt express it, from the point of view of remote and rural participants, networked technology is "designed for work, but not from here," [70] rendering rural employment precarious. Similarly, Hardy argues that the reliance of social technologies' design on growth and scale renders them inoperative in rural communities. In the process, he argues, these technologies divert resources and attention away from designing goods and services that address the needs of remote, rural populations [36]. Johnson et al. find comparable dynamics affect rural peer production [55].

These observations suggest two conclusions: first, that infrastructural challenges for rural communities are not simply usability problems, but existential threats to their flourishing; second, that rural infrastructure's fragility can be understood as a designed brokenness, a byproduct of a structurally "metronormative" [106] (i.e., city-centered) orientation to technology innovation. In this paper, we investigate how such brokenness may emerge from the disciplinary and institutional formation of technology innovation in the early stages of design.

Here, we build on the insight of researchers in the area of values in design (VID) [19, 26, 27, 59, 73, 74, 89, 91], who argue that the values and impacts of technology are often unintentionally built-in in the early stages of design. Examining the impact of technologies after they have already emerged is too late. VID develops means for technology designers to productively identify and engage with issues related to societal impact in the early stages of technical design, rather than waiting until later stages of design and production when impact issues may already have been 'baked in.'

We specifically examine these issues within the design of emerging digital infrastructure for agriculture, often referred to as 'smart farming' or digital or data-driven agriculture (DA). Building on what is framed as the prior three revolutions in agriculture - i.e., mechanization of farm equipment, the 'green revolution' of manufactured agrichemicals such as fertilizer, and genetic manipulation of plants and animals - many journalists, policymakers, and researchers are now speaking of an oncoming 'digital revolution' which is said to be optimizing the productivity and eco-efficiency of farming [8]. Anxiously anticipated by farmers [63] and dubbed "Agriculture 4.0" [85], this digital revolution is believed to be poised to transform agricultural practice through research, development, and proliferation of digital tools.

With this work, we build on interest in HCI in rural computing [38, 98], including calls for design to address rural issues, experiences, and values [10, 23, 37, 99]. This work also connects with calls in social science for engaged work within technology development for DA in order to improve the societal impact of technology currently being developed largely for industrial agriculture [5, 85]. HCI is well-positioned to address this call, but technological development for large-scale industrial agriculture is until now largely flying under the radar in HCI. While there has been work in HCI to address food production [66, 76, 81], with few exceptions [65, 96], work on North American farming focuses on small-scale [30, 56, 75, 96, 97] and urban food production [6, 11, 21, 41–44, 67, 68, 77], rather than on the mid-size and large farms that produce more than 3/4 of the food in the US [69].

We recognize that the inattention to industrial agriculture in HCI likely arises from the very real concerns that HCI researchers have about the negative impacts of industrial agriculture, concerns that are shared by many sociologists of agriculture. But, as those sociologists recognize, given the enormous investment in the development of DA from powerful stakeholders including farm service providers [33], universities [1, 12, 24, 28, 82], governmental agencies [8, 83], major technology corporations [16, 32, 62] and startups [48, 63], infrastructure for digital agriculture will come into being, and, in so doing, produce winners and losers in ways that carry huge economic implications for rural communities. As Bronson has shown, such consequences are already immanent in the early stages of design [13]. In line with Steup et al.'s call for engagement with the designers and producers of DA technology [96], the choice we make is to engage and improve. Precisely because of the scale of industrial agriculture in North America, the case of industrial technological development is an important test for understanding how and to what degree the fragility of rural infrastructure may be built-in in the early stages of design, and to develop recommendations for how new infrastructure can be better designed to "work from here."

3 APPROACH

In this work, we build on the VID approach to examine how technical researchers envision the eventual functioning of DA technology in their everyday practices during early design. Our methodology is based in critical technical practice as developed by Agre [2, 3]. While VID typically supports reflection on values issues by engaging social and technical researchers dialogically in the early stages of design, Agre integrates critical and technical work into a single unified practice, weaving critical reflection into the everyday practice of building systems. Within HCI, critical technical practice has been occasionally used as part of critically reflective approaches to system design and implementation [29, 57, 88]. Our approach in this paper is to analyze how the fragility of rural infrastructure may be produced or addressed in DA by building technological infrastructure for DA. We engage reflectively with our own practice, and through an interview study with colleagues working with similar technology.

3.1 Case Study: The Software-Defined Farm (SDF)

Our work is oriented around a case study of the Software-Defined Farm (SDF), an emerging DA architecture under development by our research group at our university's research farms. The SDF (Figure 1) is intended to support data-driven agriculture by providing a flexible architecture that connects disparate software and hardware to collect and process farm data, while addressing the challenges of limited Internet connectivity and routine weather-related outages that typically contribute to network fragility in rural, remote areas. To address the paucity of high-speed Internet in many rural locations, the SDF leverages bandwidth in existing networks, such as 4G LTE, as well as new networking strategies such as unlicensed TV White Spaces (TVWS) [7, 84]. To address weather-related outages, we store data locally on farm premises (also known as the "edge cloud") and support opportunistic syncing with the cloud.

In addition to network fragility, our architecture is also intended to provide an alternative to vendor lock-in, i.e. product development tactics that bind users of DA soft- and hardware to a single company. In DA this occurs through tactics like selling farm sensors whose data can only be accessed through a particular cloud vendor. Vendor lock-in would be addressed in our architecture by supporting local access to and storage of data, as well as by supporting syncing of that data with any private or public cloud provider.

The core software engineering idea behind the SDF is to sense, transmit (in byte-addressable format), and analyze farm data to produce actionable insights for farm operators. The acts of sensing, transmitting, analyzing, and actuating farm data map to the four distinct steps labeled in the architecture shown in Figure 1. Our vision is that, upon logging into SDF user interfaces, farmers would be able to visualize aggregate data from normally incompatible sensing systems. In addition, they could run analytics on their data to make future farm decisions based on timely plant and/or animal health indices. It would also be possible for SDF applications to automate farm work such as triggering irrigation when sensors indicate water-stressed plants.

3.2 Methodology

Our work investigates issues that come up in the early development of such DA infrastructure that may ameliorate or exacerbate the known fragility of rural infrastructure. This focus on early design is inspired by values in design (VID). Yet infrastructural design is a particular challenge for VID, because, as Shilton details, infrastructure's effects are broader and more indirect than specific user-facing technologies. Often, infrastructure will be framed as ideally 'neutral' to the applications which will use it. This apparent application-neutrality can make it difficult for designers of infrastructure to anticipate or appreciate the potential effects on end users of early design decisions, since ideally the infrastructure could be used for anything [90]. In this work, we address this issue by focusing on ourselves and our colleagues: developers at universities and on commercial farms who are advancing computing systems and networking layers for DA, building on shared experimental code which provides some DA infrastructure functionality. As technical researchers, we are in a sense lead users [104] of emerging infrastructure, and simultaneously lead developers of new applications this infrastructure is understood to enable. Our positionality at the cusp of an infrastructure's imagined eventual uses, then, may better place us to anticipate what an infrastructure may bring about, lending more traction to VID analysis of networking research and development than Shilton found in her work on Internet protocol development.

Our specific focus at these early stages of design is on how researchers are practically oriented towards particular visions for our technologies. This orientation builds on work in Science & Technology Studies (STS) which has described how expectations [14, 60], visions [9, 25, 64], and imaginaries [31, 46, 47, 53, 54] about future sociotechnical worlds are constructed and utilized within and around technoscientific practice [61]. In this work, we examine in particular the visions held by lead developers for how our research projects and the emerging infrastructure we are building on are intended to work. We examine how ideas of how the infrastructure *should* work are shaping the manner and degree to which resulting infrastructure may eventually *be workable* in rural contexts. We see researchers' efforts as a form of what Steinhardt and Jackson term "anticipation work" - "practices that cultivate and channel expectations of the future, design pathways into those imaginations, and maintain those visions in the face of a dynamic world" [95, p. 443]. Here, we analyze how developers practically orient to these visions through their everyday experiences of knitting together various, often incompatible, hardware and research code to establish the potential of this infrastructure in their research test beds.

Our study is grounded in critical technical practice as a method, involving extended hands-on technical development interleaved with critical reflection. Recognizing possible limitations to this work when taking a first-person perspective, we drew on methodological suggestions to limit designer bias developed for autobiographical design [72]. Specifically, we incorporated systematic data collection about our experiences as we went along, rather than relying on memory or opinions after the fact. We included outsider perspectives by incorporating feedback from an ethnographic observation team into our work. Because it is difficult to generalize from a single person's experiences, we added an interview study component

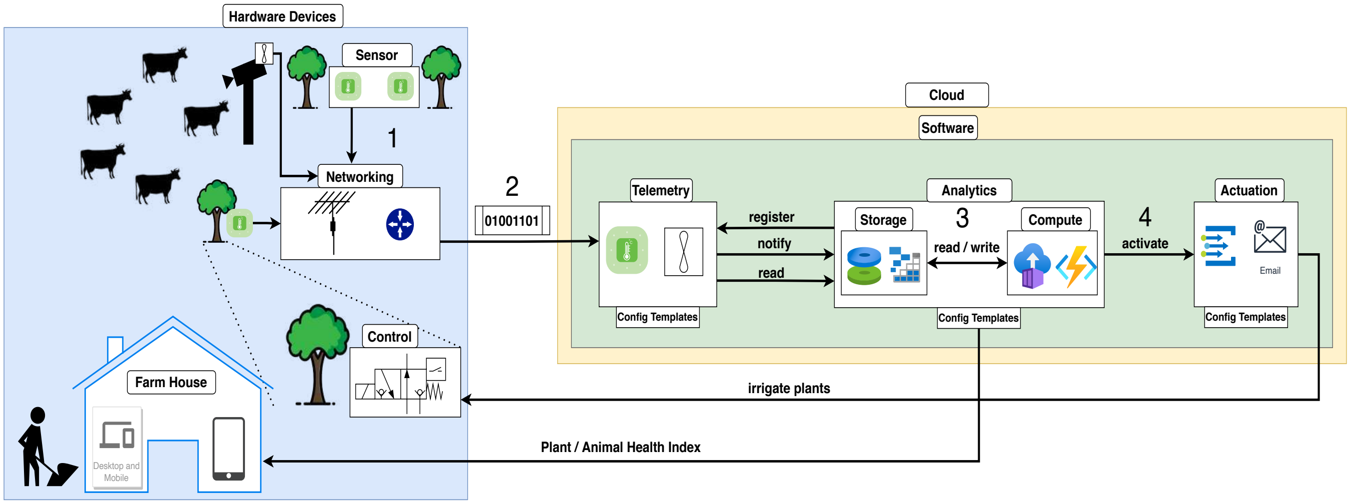

Figure 1: The SDF is intended as a general architecture to sense, transmit, analyze, and actuate on data from networked plants and animals on rural farms.

to compare and contrast our experience with those of other lead developers building related systems.

Our study, then, consisted of two major elements: our own technical work with multiple DA systems, and an interview study with other lead developers leveraging the same underlying research code. The first part of the study involved deployment of various wired and wireless state-of-the-art networking research technologies at our university's test farms. The first and third authors are networking researchers. Over the course of 24 months, we worked with plant scientists, animal scientists, and chemical and biomolecular engineers at our university, as well as collaborators at Microsoft. Together, we anticipated building three DA applications: 1) measuring tree trunk water potential with microelectromechanical sensors (MEMS) to study water consumption in apple orchards, 2) high-throughput plant breeding with light sensors to understand light intensity influence on physiological traits, and 3) measuring solar-induced chlorophyll fluorescence with drones to reveal plant physiological responses to climate change. In the course of system building, these applications changed significantly in response to development challenges.

During development, the first author recorded bi-weekly diary logs in GitHub [49] over 12 months, reflecting on technical successes and frustrations, and the influence of various material barriers on our research visions. Each diary entry consisted of summary, deployment, and development sections. The summary gave a high-level overview of our progress to date in building the research applications. The deployment and development sections delved into technical details regarding our hardware deployments and software development progress, respectively. As we worked to get a functional prototype, we began complementing the summary section with image updates of the evolving SDF architecture (e.g. Figure 1) approximately six months into the diary logs. On occasions when diary logs were not readily accessible (e.g. hardware troubleshooting sessions), we recorded audio clips that were later transcribed for analysis. In a period of eight months overlapping the diary logs, a team of four social scientists, including the second author, engaged in ethnographic participant-observation of SDF research meetings and reported back on the results. The goal of this study was to develop a deeper understanding of the technical work involved in deploying networked DA technologies, and to critically reflect on how and in what aspects future societal implications of the technology might be already immanent in the everyday practices of networking research.

The second part of the study is a semi-structured interview study exploring the experiences of similarly situated lead developers. Our interview study drew on contacts we developed while taking part in monthly workshops organized by Microsoft, where developers showcased their deployment experiences and Microsoft unveiled advances in related hardware and software services for DA. The workshop attendees included university and government researchers, industry partners, and Microsoft researchers, software engineers, and university partnership coordinators. These community meetings formed a shared backdrop for our conversations with our partners. As part of our system development, both we and our partners drew on experimental research code made available by Microsoft. The shared context of our technical work with this code allowed us to raise technical questions directly or indirectly related to potential societal impact. Example interview questions are listed below:

- Can you describe the context in which you were using the shared research code?
- Have you had to modify any of the research software or proprietary hardware to make it work for you? Why or why not? If so, how did it work out for you?
- Imagine everyone is using applications built atop the experimental code, what major changes do you see in the agriculture industry?
- What worries you about projects layered over the research software and hardware?

The interviews were conducted by the first author. The interviews ranged from 50-90 minutes. They were recorded and transcribed. Of the six participants, five were researchers and one was a farmer with significant technical expertise. The researchers represented various engineering disciplines, with electrical engineering and computer science (EECS) being the most represented. Their experiences working with the common research code ranged from 2 - 24 months. The interviews were coded iteratively using standard grounded analysis methods. We interleaved rounds of coding and analyzing the interviews with critical reflection on our own ongoing experiences building DA technologies, comparing themes with those that emerged from re-reading diary entries and using these comparisons to drive further coding and analysis.

Our initial expectation was that our analysis would focus on how positive and negative societal impacts were anticipated by researchers in the process of development. Our own experiences highlighted the enormous amount of mundane but challenging technical work involved in knitting together a set of technologies that, in principle, were intended to be seamless. As we worked with the interview data, we found similar struggles with material resistances were common among other lead developers and often became the focus of attention in their work. Our analysis therefore came to focus on the interactions between these material struggles and visions of seamlessly functioning technology on farms, and how the nature of this interaction might influence the eventual fragility of infrastructure in rural contexts.

4 RESULTS

Next, we describe the visions that researchers had for how the systems we were layering over the leading edge networking infrastructure should work for end users. Then, we describe two major challenges researchers faced in working towards these visions: technical challenges and challenges related to organizational labor and support. Finally, we describe how researchers anticipated future farm use of their systems: who we expect end users to be, how we imagine the systems would meet their needs, and anticipated benefits and risks participants associated with the technology.

4.1 Visions of Seamless Interoperability

As the image in Figure 1 suggests, the SDF architecture is grounded in a vision of seamless, plug-and-play interoperability between computational components being used on the farm, such as sensors, networking routers, cameras, data processing in the cloud, and actuators such as watering systems. Our goal is to create networking abstractions that form an intermediary software layer within farm networking infrastructure. These abstractions are intended to generalize from and layer over lower-level networking and sensing systems to support a wide range of agricultural applications. These abstractions serve two purposes: (1) creating a custom interface whereby agricultural software applications can access, transmit, and process agricultural data without dealing with technical details of the underlying soft- and hardware; and (2) setting a general framework that makes it possible to swap in different low-level networking technologies without altering software applications that layer over the SDF's abstractions. In other words, SDF is intended as a platform that will shield applications and the soft- and hardware components they use from each other's technical details. SDF builds on and is intended to extend prior systems' capacity and promises to support seamless plug-and-play.

This capacity for seamless plug-and-play was supported in part by experimental research code provided by Microsoft, which provided functionality to collect data from farm-based sensors and transmit to a cloud. The code supported collecting data from sensors and sending it to a farm computer, leveraging networking advances in already-available bandwidth such as Long Range Radio (LoRa) and unlicensed TV White Spaces (TVWS) [7, 84]. It also supported summarizing and packetizing data for transmission from the farm computer to the cloud via the Internet. The driving factor behind our choice to build on this research code was that it would allow any stage of the data pipeline from sensor to cloud to be modified to support new networking hardware, communication protocols, software abstractions, or overlaying applications. Thus, we would be able to modify what is effectively an emerging infrastructure for digital agriculture research.

Similar considerations influenced our colleagues' choices to adopt this code, as well as other hardware and software components available through open source or commercially. In imagining and creating agricultural futures, our colleagues see existing DA systems as ideally LEGO-like tools that can be seamlessly integrated, applying sensors, telecommunication, the cloud, and artificial intelligence (AI) toward a streamlined experience of data collection, processing, and use for farms. For example, P2 described a complex pipeline of intermediary networking infrastructure which powers their computer vision application, transforming sensed data into immediate insights on plant and soil health. In other words, our colleague is leveraging disparate networking systems and software components to stitch together a complex data pipeline that is accessible and usable by end users. Another colleague put the vision of seamlessness expected from an exemplary system simply: "[It's] one of the first products that actually delivers on the idea that you install it, you put batteries in [the sensor], you go home and see the data" (P5).

4.2 Grunt Work

While researchers envision seamlessly operating integrations, in reality, developing these imagined integrations creates numerous day-to-day challenges. For instance, in July 2020 we envisioned a two-phased networking deployment to support our study of water consumption in an apple orchard. The first phase would encompass integrating, on a single Raspberry Pi 3 [79], environmental data from an experimental hardware platform with in-plant MEMS sensing data streamed to our collaborators' storage account on a different platform. The second phase would reuse the experimental hardware for environmental sensing beyond the spring and summer growing seasons to test its durability over the fall and winter seasons.

However, this technical vision quickly became engulfed in low-level frustrations. The first phase was hampered by both hardware and software peculiarities. For example, the familiar 'righty tighty lefty loosey' aphorism did not apply to screwing sensors into our hardware's Printed Circuit Boards (PCB). We exasperatedly discarded PCBs once they no longer held sensor wires in place. In software, the Raspberry Pi 3 lacked critical libraries for the Software Development Kits (SDKs) required to connect to our cloud data processing infrastructure. The only solution was to upgrade to the Raspberry Pi 4B [80]. The second phase was mired in troubleshooting often cryptic error messages on the cloud gateway device. Whenever the cloud path was ruled out as the source of errors, we spent hours on random tricks such as switching antenna modules between USB ports on the gateway until we observed the much-anticipated green light signaling packet transmission.

Similarly, our colleagues relate that, compared to the ideal of plug-and-play systems, implementation poses significant hardships. In reality, before any data can be seen on cloud user portals, one must spend numerous hours, days, or months "with a camping chair in the field" (P4) jury-rigging hardware compartments, pondering the feasibility of telecommunication with radios in metal sheds, updating firmware, dealing with short-lived D-batteries due to extreme temperature cycles, and so on. With regards to the documentation for one of their experimental systems, one colleague recounted:

> [T]he documentation was decent... but it needs revisions as the documentation that I received was for the sensor box version two, but the sensor box[es] that I received were version three. So there were inconsistencies of what they were saying [at] the different locations... for the first week ...I was pulling out my hair, like, why I'm not able to read anything when I send to find out the version command. (P1)

One specific set of challenges that researchers routinely faced arose from the blackboxing of commercial hardware and software. For example, as reflected in a diary entry from February 2021 during the plant breeding experiments, troubleshooting problems arising in experimental deployments was difficult because we lacked direct access to the internal functioning of closed soft- and hardware:

> The initial deployment of [sensing hub AA33] to the greenhouse did not work because the sensor hub was unable to reach the [cloud] gateway at the orchard. However, once I got it working, it is unclear whether the [initial] failure was because the [LoRa] communication was impossible or because the hotspot had died due to the cold weather (we found it at 4% battery level)

While such troubles in setting up early systems were pervasive for researchers, they were not understood as problems that would really affect eventual end users working with a commercial version of this kind of technology. As two of the researchers put it:

> You know, some of the things that I've experienced most other users won't experience, because I'm kind of doing – helping along with the research and development. (P4)

> I think they are probably things that every user would probably go through. It was a matter of time... I don't view these as fundamental problems at all, they were just ... some minor logistics. (P3)

Because they were working with experimental code and using blackboxed commercial hardware in new contexts, researchers did not expect such technology would be easy for them to use. They expected that such issues would be sorted out later in the development pipeline, before such technologies are released in eventual commercial systems.

Precisely because these everyday challenges that swallow up researchers' time and attention are considered irrelevant to eventual end users, it was difficult for them to connect their experiences in the early stages of building to the eventual use and impacts of the technology they were developing. Upon asking fellow researchers for any questions on their part before starting the interview, respondents frequently pointed to their lack of having already built a functioning system, apparently as a reason to discount their ability to contribute to the anticipated discussions of societal impact:

> [J]ust a heads-up I would like to give you is that we are still trying to set up the system and have it working without any issues. Due to Covid-19, like, we were planning to get everything set up by end of May, but due to some logistical issues, we didn't get all the components, the sensors, the boxes themselves, and everything... I have only set up one sensor box over here, and still trying to get the [cloud gateway] device on the university network. (P1)

> We are working to deploy the system, but right now we don't have the system ready... [I]f your expectation is that we have a process right now with results, we don't have it. (P2)

The sense that these discussions conveyed was that eventual societal impact of the resulting systems seems fundamentally divorced from their ongoing work in these early stages, rendering them incapable of discussing it in an informed way before the system they are building is fully functional.

4.3 Organizational Labor and Support

The previous section described challenges to producing smoothly running systems that were created by technical issues such as incompatible software or hardware or out-of-date documentation. But the everyday resistances to creating a functional system go far beyond the scope of the purely technical. For example, in February 2021 we began working on another sensor network deployment to support plant breeding experiments in a university greenhouse. Because the experiments rely on light intensity as a control variable, they required light sensors, which we had previously used in the still-running orchard deployment. When we arrived at the orchard to retrieve the sensors, we found the 50-square foot plot covered with two feet of hardened snow. After 20 minutes of fruitless digging, we had to delay a few days to find snow shovels. In placing PCB and sensor orders two years earlier, we had not anticipated the need for snow shovels to make the system work. Then, our plant science collaborator found out from the growing manager that her experimental greenhouse did not have functional electric plugs to power our cloud gateway device, which then delayed our deployment by another few weeks.

In another instance, miscommunications around import shipping delayed our networking upgrade from phone hotspots to TV White Space (TVWS) antennas by nearly three months. The third author, the Principal Investigator on the SDF project, was unaware that duty taxes had to be paid to United Parcel Service (UPS) for the TVWS equipment upon arrival in the US. Thus, following a long wait at a UPS distribution center and multiple failed delivery notices posted on their office door while they worked from home during the pandemic, the equipment was sent back to our vendors in Toronto, Canada.

Indeed, even when our systems worked, they did so not only because of our technical work; they also depended crucially on our ability to navigate regulations and bureaucracies, and on material and labor support from our university. The university engineering buildings provided working electric plugs for equipment testing; the university IT staff provided Visual Studio [71] licenses for inspecting research code written in C#; university-employed carpenters and electricians mounted our TV antennas, and so on. Our efforts to build these systems thus required interfacing with other units and organizations. Interactions with building support staff and outside companies interleaved with the technical work needed, as in this project status update from a diary entry on April 9, 2021:

> Gary is waiting on confirmation from the carpenter that would mount the antennas at the orchard. Other requirements include getting GPS signals to query the Red Spectrum database in addition to setting up a $20 month[ly] subscription to the database.

These experiences point to the ways in which early DA research prototypes are built, deployed, and maintained within organizational structures which not only provide the structure for them to function, but also condition how they are used. Similar reflections arose in our colleagues' responses to a question about what could deter the adoption of digital agriculture technology in general, and the software and hardware on which they were building in particular. Their answers often focused on the organizational relationships between universities and technology companies producing these products and those imagined in the future between such companies and end adopters. In the short term, our colleagues imagined the necessity of a continuous back-and-forth between companies producing cutting-edge DA technology and lead developers to move the technology toward seamless deployments in research farms. One researcher described how future lead developers might resolve challenges they had had in getting data from a sensor into the cloud this way:

> [M]aybe this partner need[s] to adjust things in the hardware part... or they need, they, I mean [the company providing the cloud platform], needs to adjust something in their web platform to talk with a specific sensor that they don't have in the list. (P2)

Obviously, such personalized interactions between organizations would not be realistic for eventual large-scale, commercial farm deployments. In the long term, our colleagues described seeing the need for support such as self-setup kits for eventual consumer-facing products. The most pessimistic outlooks for adoption were motivated by the myriad material barriers that the technology currently poses, barriers which were seen as requiring more intensive organizational support to overcome. The majority of researchers described a need to transfer the grunt work of getting systems up and running from the end user to an installation support service. The challenge, as one researcher working closely with farmers in a Midwestern state pointed out, is that these services do not yet exist:

> I think that it's the installation part that's the problem. You know when you buy a carpet from Home Depot, the carpet installation guys... you don't know who they are, but Home Depot gets them to show up and do it for you. We don't have a good market in the Ag world right now for that, where you can go to [a company that produces a technical product] and say, 'I want to buy [your product]', and [the company] also sends an installer to get it working, you know? I think that's maybe what's missing. (P5)

4.4 Envisioning future farm use

As these colleagues' comments suggest, researchers are already clearly anticipating future usage of our systems by reflecting on what future farm experiences might be like and developing theories of the needs of end users, generally described as 'farmers', and how they could be met by cutting edge DA infrastructure and the applications we are building over it. In our own work on SDF, we speculated on the needs of farmers in making design choices. For example, a bi-weekly reflection in October 2020 reflects our anticipation of needs a farmer might have to swap in and out different components:

> [I]t's not necessary that a TVWS-enabled or 4G/LTE-enabled farm system be the only options for the farmer. Depending on the farm size and desired data rates, it may be the case that Bluetooth nodes [are] good enough for some applications. Thus, the goal is to build something that does the network design and decides the best architecture for a given farm and available physical media (WiFi, TV White Space channels, etc).

These thoughts resulted in us developing a prototype web application taking user input describing farm characteristics (imagined to be entered by the farmer) and producing a graphic representation of the lowest-cost way to connect sensors to gateways on that farm.

Like us, our colleagues viewed their tasks not merely as producing computer science advances, but as bridging computer science with agricultural science and practice. Therefore, their speculations coupled the limited integrations that were enabled by the disparate components they were using with a willingness to step into the farmer's shoes to imagine a system's effects. In the process, researchers implicitly created a future farming persona. They did so by anticipating farmers' backgrounds, skills, wants, and needs and forecasting how their experimental DA infrastructure and overlaying future applications would meet those needs. For example, the envisioned interoperability researchers were working towards was seen as advantageous given farmers' expected lack of significant computational background:

> Maybe the farmer doesn't have the skills nor understand how is [the system] working... I mean AI, computer vision, hardware, software, all of those things integrated in a transparent system. You don't need to know anything about machine learning (ML), but you

> can obtain the data running in your computer or in your phone using ML in your field. (P2)

As they imagined future use, researchers identified specific problems that might arise. For example, three of our colleagues noted that interference between blackboxed devices relying internally on similar radio bandwidth, a common problem in urban deployments, could be unintentionally exported to rural farms through DA. As P5 put it,

> I could see... in the future we have this spectrum problem with phones and Wi-Fi and things like that now, so now it's going to be in the Ag[ricultural] space... "Well, you installed your new fancy whatever and it broke my older fancy thing, because you're too close to me."

P5 saw these issues of radio interference as outside the scope of technical design, "more of a social problem than a real problem."

Colleagues anticipated a variety of benefits of a networked and automated farm for farmers and the broader society, including more family time for the farmer, human labor cost reduction, environmental sustainability, and management of worldwide crop price (in)stability. A major potential downside of smart farming approaches was seen to be its economic cost. Our colleagues shared our belief that technical value must be matched with economic value if this technology were to be widely adopted. As remarked by one participant:

> Farmers often operate under very challenging financial constraints, with pretty low or very, very low margins. And they don't have the luxury of... working with moonshots. (P3)

These concerns were echoed by P4, a broadacre crop (e.g. corn, soybeans) farmer with a technical background and extensive software consulting experience. Agreeing that farmers shop for economic value out of DA platforms, they recalled:

> I looked into some alternatives... but to be honest... they were just way too expensive. 'Cause I guess I am a little price-sensitive, or maybe decently price-sensitive – but for broadacre crops you don't have as much profit per acre as these high-value crops like vegetables or orchards, vineyards. So I get priced out of a lot of these things really quickly. You know, they would want thousands of dollars for a weather station. I'm, like, 'Well, how could I put ten of those around my farm? You know, that's getting up to the price of, you know, a used tractor.' (P4)

Compared to ourselves and our other colleagues, this experienced farmer's visions of future farming are much better grounded in contemporary farming realities. Still, their experiences are not representative of all farms. Considering their neighbors' opinions of this farmer's own high-tech farming practices, they reflected:

> Some think I'm wasting my time. Some are intrigued. A lot don't believe that I'm either saving as much time or as much money as I'm saying. You know, you're never going to convince everyone. To be honest, some of my neighbors still farm like it's 1950. They work their field 500 times, they have terrible erosion, they spray the same chemicals on the whole field no matter what, and that's just the way they farm. (P4)

This insight identifies an important distinction between researchers' imagined farming futures and current farming realities. That is, we are developing technologies which we anticipate may have a 30-year horizon, while some farms rely on techniques which we might consider 70 years out of date. This perceived temporal gap of a century between the anticipated site of adoption and current site of consumption is a sign of a potentially significant conflict between how researchers imagine farming and the reality of real-world farms - an issue we will return to in the discussion section.

5 DISCUSSION

In this section, we reflect on what these findings can tell us about how researchers are envisioning the futures they are creating for farms, how those visions relate to their everyday practices, and how these modes of anticipation may be shaping the eventual fragility of these technologies.

5.1 Seamless visions

The fundamental vision that we share with our colleagues is of eventual plug-and-play systems that would allow for seamless connection between disparate, off-the-shelf technologies. Such systems would allow eventual end users to be able to reap the benefits of data collection and processing without having to undergo the tedious work of configuring technology. We dream of seamless integration of hardware and software toward a simple, usable digital farming experience: one should be able to install sensor network software, put batteries in the sensors, and go home, while the system takes care of the processing.

This is a similar orientation to seamlessness that animates much interface design work, with the goal of hiding technical details under the surface, enabling users of those systems to focus only on the tasks they are engaged in [50]. Seamlessness, as Inman and Ribes point out, emphasizes technology as "invisible or backgrounded to the user" [50, p. 4]. This ideal of invisibility and backgroundedness is also a general goal of infrastructural development. As Star and Ruhleder describe it, for most users, infrastructure tends to be transparent, becoming visible only upon breakdown [93].

The goal of seamlessness matters particularly for DA infrastructure because the seamlessness we are proposing to create starkly contrasts with the realities of rural infrastructure, which, as we noted previously, is less well-developed, more liable to break, and slower to be repaired than urban infrastructure. Such infrastructural challenges are, in fact, exactly what technology like the SDF is intended to solve. Research into rural networking is often explicitly oriented towards solving challenges arising from the lack of reliable infrastructure [18, 39, 84, 100, 101]. Our and our colleagues' goal is to develop an infrastructure for cutting-edge data processing capabilities on farms that is resilient to issues such as power outages and poor network connectivity, as well as end users' likely lack of familiarity with computer science. If infrastructural breakdown is the problem, then seamlessness, we hope, could be the solution.

5.2 Material resistances

What's striking in DA research is how deeply this vision of seamlessness contrasts with the everyday reality of material resistances to that vision. These material resistances continuously produce new seams and discontinuities that researchers struggle to bridge. We observe ourselves and other researchers spending weeks and months fighting material resistances to create a simulacrum of seamless futures. The struggles take many shapes, including clerical work (perusing inconsistent documentation and setting up virtual troubleshooting calls), computer engineering (updating firmware and debugging hardware components in the field), logistical negotiations (powering a base station in a metal shed), responding to weather and seasonality (digging sensor boxes out of hardened snow), etc. These material resistances produce an odd phenomenological contradiction: while researchers have a vision of eventual seamless functioning, their everyday lived experience is of continual, painful grappling with material resistance to that seamlessness.

Clearly, material resistances and the seams they induce are continually produced by numerous factors. One additional factor, ironically, is the very goal of seamlessness itself, and how that is oriented towards differently by companies that produce technological products versus the researchers who utilize them. As organizations, these companies' imperative in creating eventual seamlessness is to produce technologies which are black-boxed, often with tightly coupled hardware and software components that can stand on their own as easy-to-use products in the marketplace. In so doing, design and implementation choices in these systems necessarily constrain the ways that they can be integrated with other systems, even in cases where the code is openly shared with researchers. But researchers' goals are to tinker with these technologies, to open the black box, to innovate and use them in unexpected ways, and to tie them into other existing systems. In doing so, they often run into roadblocks in the way the technologies have been packaged. Thus, companies developing DA technologies aim to produce seamlessness by preconfiguring technology, but researchers want to produce their own new seamless futures by reconfiguring that technology. The tension between these two approaches produces more resistances, which may need to be negotiated across the organizational seam that lies between those companies and the university research and commercial farms using them.

In any case, the weight of all these material resistances is extensive, and grappling with them forms the primary everyday work of research in this area. The contrast between the larger goals of easy-to-use agricultural technologies and the mundane, messy realities of trying to get a technology to work in practice produces a chasm between the lifeworlds that researchers imagine they are producing for farmers, and the lifeworlds they themselves inhabit. The farmer enjoying family time while an automated system senses and waters their plants couldn't be further removed from the researcher immersed in the configuration and maintenance grunt work to make such a system possible.

5.3 Anticipating seamlessness

A core question that emerges in the face of this dichotomy between seamless visions of farming futures and researchers' own seamful realities is the following: *how do researchers maintain faith in the eventual seamlessness of their systems on farms in the face of our own seamful experience?*

One way in which this faith is maintained is through practical reasoning: by positing means later in the research-to-product pipeline to resolve the material challenges that we face. Researchers recognize that there is a gulf separating the world we are working in from that which end users, imagined as farmers, can be expected to inhabit. Researchers attempt to bridge this gulf by identifying places where we believe our experiences are likely different from end users, and anticipating how those differences could be addressed when the technology is eventually publicly released. In imagining eventual farm use, some of the challenges we ourselves face are seen to be, in principle, solvable through improvements in the technology design itself, such as through cleaner API's, more flexible configurations of sensor hubs, the work of later interface designers, or the technological innovations the researchers themselves are working on. Other challenges are seen as likely not addressable by the technology, requiring non-technical solutions, such as retraining of end users, support from the companies producing the technology, and/or organizational innovations, such as the development of a new class of service providers to install DA technologies. Such innovations, it is hoped, can transform technologies that are seamful for researchers into ones that are seamless for end users.

But even while researchers identify means to address seams that they experience, we also find that many potential seams are rendered invisible to researchers by the disciplinary and organizational structure of technology innovation. In the next sections, we will describe three key ways in which faith in eventual seamlessness rests on structural invisibility of seams that could be experienced by end users. The first renders observed seams as incidental or unimportant, leading to *disappearing seams*; the second obscures seams relevant to research experiences from view, leading to *hidden seams*; and the third places seams systematically beyond researcher experience, leading to *distant seams*.

5.3.1 Disappearing seams. The first form of invisibility is grounded in the very nature of the work that researchers are primarily engaged in. Much of the work of producing a functioning prototype is 'invisible work,' which Daniels defines as work "that disappears from our observations and reckonings" [20]. In technical context, this includes work that has to be done for a computational system to function, but will likely not be referenced in a researcher's own presentations or papers, because it is not part of their formal knowledge claims [78, 87]. In our case, this includes things like tracking down parts which have gotten lost in shipping, meeting with building managers to convince them to allow the installation of network components, or figuring out where to get updated documentation for a sensor. Following Star and Strauss's formulation, such work is the hidden "back stage" work that makes the visible "front stage" work of demos, publications, and research talks possible [94].

Largely unreported, this work can feel incidental to the system actually functioning, experienced as just technical or logistical details that are a hassle to deal with, but don't really matter for the big picture. Built into the vision of seamlessness is the hope that end users will not, in fact, bear the weight of this type of labor – the hope is that it will be eliminated. But precisely because this work is invisible, often unaccounted for, and felt to be incidental, the full scope and form of this work can be quickly forgotten, left out of the imagination of how these systems would practically work in the primarily rural end contexts.

5.3.2 Hidden seams. The second form of invisibility is produced by the role of organizations themselves in mitigating seams, by providing structures and resources that eliminate barriers and challenges that researchers would otherwise have to navigate. For one thing, at universities and technical research centers, researchers are afforded the time and financial flexibility to tinker with new technologies. This organizational support allows us to deemphasize financial decision-making in our everyday practice. However, such resources are likely not available in the contexts that researchers imagine as the final setting for the technologies they are developing. For example, commercial farmers operate under stringent time and financial constraints. As our colleague with farming experience highlighted, current DA platforms tend to be designed for farms with access to economies of scale and profits such as vineyards, whose resources better match that available to technical researchers.

In addition to financial resources, the universities most researchers belong to also supply technological infrastructure (such as always-on electricity and robust networking capacity) and human capital (including students, IT staff, carpenters, and electricians) to support the research enterprise. These resources are likely not available in the contexts that researchers imagine as the final setting for the technologies they are developing. For example, inexpensive express shipping of urgently needed repair parts is much more available in college towns than on remote farms. Additionally, in less-dense rural contexts, repair services may be far away, difficult to access and slow. While larger industrial farms may have a dedicated workforce supplying onsite support and technical expertise, this is not the case for medium-size and small farms.

Indeed, as described earlier, the lack of such resources and infrastructures is what motivates the vision of seamlessness for these technologies in the first place: these technologies are intended to supply their own functioning infrastructure to replace the patchiness of what is available remotely, and to do so without requiring tinkering or extensive technical knowledge. But because we are used to relying on a rich organizational context, we may not realize which things that are seamless for us will be far from seamless for an end user.

5.3.3 Distant Seams. The third form of invisibility is produced by the fact that certain seams arise from details of the use context that are beyond researchers' direct or indirect experience. As described previously, bridging the gulf between seamful building and anticipated seamless use requires a capacity for researchers to imaginatively identify how such seams would appear and could be mitigated in the end use context. One significant challenge to this capacity is that, by and large, we often lack a detailed familiarity with the intended use situation we are designing for, making it difficult to anticipate how systems might be adopted and used in practice. While one of our colleagues was a practicing farmer, most of us are technical specialists with a detailed understanding of the technologies we are working with, but little knowledge of the pressures, structure, and practices in the contemporary agricultural sector. For example, researchers often spoke of designing "for farmers," without recognizing the substantial differences in design contexts for farm managers, farm workers, off-farm service providers, or the larger agricultural corporations such as equipment or agrichemical suppliers which are likely to reap the data collected through DA technologies on farms.

While access to user studies about agricultural contexts could help mitigate this issue, it would not completely solve it. This is because, as our participants reported, the distance between their experiences of developing systems and the imagined world of use leads to a lack of felt capacity to address issues around the eventual effects of their systems. Mired in the details of getting the system working, researchers report not being in a position to consider the consequences for how it will eventually be used at all. Their sense is that they just aren't there yet – they don't have enough working that they can even start thinking about what might happen when systems like those they are building would be released into the broader world. Even with more information about the world of use, then, these seams may remain phenomenologically distant from research practice.

5.4 Towards an artful engagement with seams

We began our work with the question of whether and how the fragility of rural infrastructure may be built in during the early stages of its design. Our work revealed a core conundrum, in which visions of seamlessness are maintained in the context of pervasive experiences of seamfulness. We and our colleagues try to puzzle out how the obstacles we know about would eventually be overcome to create the seamless experience we hope for. Still, the impact of our own seamful experiences on how we imagine and produce farming futures is limited, for 3 reasons: (1) because of *disappearing seams*, arising when the work of overcoming those seams is invisible and discounted; (2) because of *hidden seams*, arising when our organizations smooth over seams which will emerge when these technologies are used in a broader world; and (3) because of *distant seams*, arising when disciplinary structures inhibit researchers' ability to notice eventual seams that will emerge for users, while the challenge of material resistances inhibit their ability to orient towards them.

Our work documents how seams are rendered structurally invisible in the early design of new rural infrastructure. However, this structural invisibility does not necessarily mean that these seams will be experienced by end users. Certainly, it is possible that the seams which engineering researchers do not address will be resolved later in the research-to-product pipeline by those closer to and more familiar with the context of use.

But our results suggest 3 key problems with researchers relying on later actors in the product pipeline to clear away seams rendered invisible in the early stages of design. First, it wastes researchers' expertise, since early-stage researchers have concrete knowledge about existing seams which is lost in the pivot to research results. Second, while researchers have the goal of producing eventually seamless technologies, it is difficult for us to be confident we are actually doing so when we lack capacity to address seams that are hidden or distant. Finally, postponing fixes to seams until later in the pipeline cedes those fixes to entities acting under different constraints, in ways that may undermine the values which motivate university researchers. For example, we often envision seamlessness as being produced through open, interoperable systems, while for commercial vendors it may make more sense to produce seamlessness by locking users in to a single brand system.

So how should researchers address the prevalence of invisible seams in the design of rural infrastructure? From a design perspective, the largest consequence is that taking seamlessness as an inviolate goal for new digital agriculture infrastructure may not be the most useful way to approach this work. As Inman and Ribes argue, neither seamfulness nor seamlessness "can be approached as a simple virtue or vice; rather... we .... must ultimately resolve [which to use] in design practice" [50, p. 1].

Given rural communities' struggles with current seamful infrastructures, seamlessness matters and has clear benefits. Nevertheless, our analysis suggests that seamlessness and its production through blackboxing also has significant downsides for rural use. Blackboxing trades off ease of use against end users' knowledge of and control over how the technology works. In rural contexts, this can make it hard to adapt technology to specific farms. It can also lead to repair issues which the distance to repair service and parts render more difficult to resolve than in urban environments. Blackboxing creates new dependencies on off-farm providers of technology services and repair. As it does so, it provides opportunities for more powerful stakeholders, including service providers and the companies who reap and process data, to capture the possible benefits of DA at the cost of the farms that produce it. The very ideal of seamlessness as a solution to rural infrastructural fragility may mask the ways in which these technologies embody the interests of other stakeholders.

To the degree that seamlessness is nevertheless desirable, it is important to recognize the limits of its achievability. Technology can never be truly seamless, particularly in situations such as arise in DA, where the world of use is both highly differentiated and distant from the world of design. Jackson and Singh point out that such discontinuities between design and use manifest as infrastructural seams that demand invisible work of users to manage [92, p. 4784]. More positively, as Vertesi establishes, seams don't always need to be eliminated, because end users are already artfully managing not only seams within, but also seams between infrastructures [102].

In order to support such artful management and avoid inflicting more invisible work than necessary, it will be important for researchers to explicitly identify seams that already exist, and that are likely to come to exist as the technology is adopted. Identifying such seams can then inspire means to better manage them during adoption. In the next section, we provide guidance for how to do so.

6 IMPLICATIONS FOR DESIGN

In this section, we build on these insights to provide three concrete suggestions to support the artful management of seams in digital agriculture: by supporting the right to tinker, by documenting invisible work and its effects, and by bridging the gulf between research and commercial farms.

6.1 Support the right to tinker

We have observed that researchers spend significant amounts of time tinkering with equipment in order to produce functioning deployments. We similarly observe that farmers routinely tinker with their equipment to fit their farm's particular geographic constraints [45]. Thus, while researchers understand seamlessness as a necessary goal because of end users' lack of technical expertise, tinkering is actually a core value driving innovation and appropriation for *both* the engineering *and* the farming communities. This ethos of tinkering is, however, threatened for both by the encapsulation of commercial software and hardware. Just as commercial technologies place limitations on how components can be integrated with them, commercial farm service providers rely on copyright law and end user license agreements that void warranties if farmers modify equipment in unintended ways [17, 35]. This practice discourages innovation, tinkering, and self-repair.

Given what we know about the comparative fragility of rural infrastructure and challenges of accessing third-party rural repair, and recognizing that seams and challenges are likely inherent to its design, digital agriculture platform design should embed access for tinkering by researchers and farmers. Going hand-in-hand with the right to repair movement in electronic and automotive industries is *the right to tinker* [34, 40, 105]. Embedding such a right to tinker is particularly crucial for DA because every farm presents its own peculiarities, embedded in local geographies and micro-climates, which resist the capacity of generalized systems to meet their needs [65]. Tinkering would allow DA systems that are designed for the farms technology developers see as 'average' – likely larger-scale, industrial farms – to still be useful and usable for smaller-scale and less industrialized farms. Supporting such appropriation will require not only openness in architecture, but also structures and organizations that facilitate community sharing of knowledge about tweaking.

6.2 Document invisible work and its effects

Our results highlight the invisible work of configuration and logistics that is required to create functioning prototypes. This invisible work is experienced but discounted by researchers as relevant to end users, or is hidden from their view because of the support provided by research organizations.

Given known logistical and infrastructural challenges in rural communities, confidence that these seams will simply disappear seems unwarranted. Some of these challenges will indeed be resolved by technology companies developing them, in part through feedback from lead developers, including but not limited to university researchers themselves. In such cases, designers and developers may not fully appreciate how their own navigation of material resistance in the early stages is influencing the shape of final products and how that navigation will shape how the products impact end users. Other challenges will remain and need to be addressed before the technology becomes a product in the marketplace.

Thus, we suggest that farm technology developers explicitly document these implementation road bumps and discuss them within the developer community. This documentation should be used to reflect on the types of challenges they face, how they might compare to eventual farm challenges, and understand the gradual yet important effects of their experiences on system and product design decisions. It should also be used to identify issues that will need to be addressed in other ways when the technology is released to a broader audience.

6.3 Bridge the gulf to farms

Our discussion highlighted the wide gulf between the farm deployment context imagined by researchers and the daily realities of farming. An obvious conclusion is a need for user studies in HCI covering industrial agriculture and other medium- and large-scaled farms, to complement and extend the work on small-scale farming in North America which is relatively common in HCI [21, 41, 43, 44, 67, 68, 77, 97], and the use of such studies to inform technical research work in areas such as networking. But our analysis of the role of material resistance in obscuring considerations of impact, the obfuscation of seams through invisible labor, and the masking of seams by organizational support suggest that simply knowing more about farms, while helpful, is not enough.

A more significant shift in aligning the worlds of design and use of these technologies could be produced by rethinking the unidirectional, black-boxing assumptions about technology transfer underlying these technologies. We currently produce our technologies at research labs and universities with ample organizational support, with the idea behind our seamless visions that they will be encapsulated as easy-to-use technologies when they eventually go to market. But recognizing the historical role of farmers as producers of infrastructure and contemporary role as tinkerers and adapters suggests that this model could be rethought as a two-way street which better aligns research production with farm expertise and innovation.

Our first suggestion is to develop opportunities to more effectively bring farming experience into research and development. Technically trained farmers such as P4 are not as rare as might be imagined. They provide important reality checks for emerging technology. Other farmers can be engaged, for example, through co-design workshops between researchers and farmers where the gap between research visions and farming realities could be recognized and addressed [86]; for one example, see [22]. Another option would be to deliberately recruit rural youth as research assistants on technical research projects, and valuing their knowledge of rural experiences, values, and practices as an important form of expertise informing the project. We note that agricultural extension agents have historically provided an important link in translating between cutting-edge research and on-farm practice and can provide a valuable reality check for technical research.

Our second suggestion is to develop approaches to technology transfer that create more room for the fine-tuning of technology by appropriators at the site of consumption. The prior adoption of similar systems in rural regions makes clear that technology typically undergoes evolution and appropriation to fit the social-technical norms of its deployment location and community [4, 51]. While farmers are already tinkerers, educational training will be crucial to adopt these more complex technologies. By educational training, we do not imply needing a computer science degree. Rather, in acknowledging the seams masked by the sites of production (i.e. university or industrial research), the farmer may benefit from "cheat sheets" that explain how to do the invisible labor of bridging seams that will be required to take advantage of nominally seamless technologies. To facilitate acquaintance with these new technologies, we recommend organizing workshops where participants could be trained on the benefits and, importantly, limitations of new hardware/software products for DA.

7 CONCLUSION

This paper explores how the fragility of rural infrastructure is anticipated and can be addressed in the early design of new infrastructure for digital agriculture. To do so, we explore how the future of farming is being envisioned and realized by researchers who are developing new applications over emerging DA infrastructure. We find that the visions of seamless interoperability motivating DA infrastructure research coexist with researchers' seamful realities of colliding into a host of material resistances. We discuss how and why faith in the vision of seamlessness is nevertheless upheld in the face of these experiences: some seams are discounted by researchers and disappear, others are hidden away by organizational and logistical support, and yet others are distant and unknown. We develop recommendations to support a more artful management of seams for end users, enabling this infrastructure to be better adapted to and appropriated in the farming context.

Our approach to do so used critical technical practice as a methodology to accomplish the goals of VID: to explore and alter how potential consequences of the technology are built in at early stages of design. Our choice to work with lead developers using and building applications on an emerging infrastructure addressed the challenge in VID of bringing eventual effects of an infrastructure closer to the experience of the technical researchers building it. Indeed, unlike Shilton's work with Internet protocol developers [90], our colleagues had no difficulty in enumerating societal issues that could potentially be impacted by their experimental DA systems, discussing issues such as time savings, productivity, or price stability, all of which could provide starting points for VID engagement. Yet our analysis ended up focusing, not on the specific issues that researchers anticipated, but on aspects of researcher practice that unintentionally shaped impact on rural communities by producing a potential fragility of the infrastructure. Our analysis demonstrates one way in which the fragility of rural infrastructure can be produced through the process of engineering design: by creating a faith in seamlessness through the structural invisibility of relevant seams. This work suggests a path forward for infrastructural VID that is less reliant on technology developers being able to identify eventual societal impact within early design: by reflecting on the downstream consequences of developers' everyday experiences.

For ourselves and our colleagues, visions of seamlessness seemed key to sparking the 'digital revolution' many of us hope this technology might produce. But our analysis suggests that this technology may be more seamful than we realize or hope, and that seamlessness, when achieved, may carry unexpected negative consequences. If we focus exclusively on producing seamlessness, then, we could be exacerbating the very challenges of rural infrastructure that we had intended our work to resolve. Instead, while enabling some forms of seamlessness, we must also leave room to recognize and document seams, and provide opportunities for end users to grapple productively with them.

ACKNOWLEDGMENTS

This work is supported by the US National Science Foundation (NSF) under grants #1955125 and #1908327, NSF STC under grant #2019674, a Microsoft Investigator Fellowship, and the Cornell Institute for Digital Agriculture (CIDA). Gloire Rubambiza is supported by an NSF NRT Digital Plant Science Fellowship under grant #1922551 and a Microsoft Cornell Summer Research Fellowship. The authors would like to thank Ranveer Chandra, Jen Liu, Samir Passi, and the anonymous reviewers for their constructive feedback and insightful discussions during the manuscript's preparation. The various SDF projects benefited from expertise and logistical support from our collaborators in Animal Science (Julio Giordano and Martin Perez), Electrical and Computer Engineering (José Martínez, Mueed Rehman), Systems Engineering (Shiang-Wan Chin), Plant Pathology (Fernando Romero Galvan and Katie Gold), and Plant Science (Savanah Dale and Mike Gore). The networking infrastructure for this project would not have been possible without the help of numerous Information Technology professionals, building managers (especially Scott Albrecht), orchard managers, and carpenters at Cornell University. The authors appreciate the support from Microsoft partners, including Tusher Chakraborty, Elizabeth Bruce, and Stacey Wood. Lastly, the authors are grateful to the anonymous participants whose contributions to the comparative analysis were instrumental to the paper. All opinions expressed are those of the researchers, not the NSF, Microsoft, or CIDA.

REFERENCES

[1] Vikram Adve. 2020. *Center for Digital Agriculture at Illinois receives $20M to develop new AIFARMS institute.* Retrieved December 01, 2021 from https://aces.illinois.edu/news/center-digital-agriculture-illinois-receives-20m-develop-new-aifarms-institute

[2] Philip E. Agre. 1997. *Computation and Human Experience.* Cambridge University Press, USA.

[3] Philip E. Agre. 1997. Toward a Critical Technical Practice: Lessons Learned in Trying to Reform AI. In *Social Science, Technical Systems, and Cooperative Work: Beyond the Great Divide.* Erlbaum, Mahwah, NJ, 131–157.

[4] Madeleine Akrich. 1992. The De-Scription of Technical Objects. Shaping Technology/Building Society: Studies in Sociotechnical Change. In *Shaping Technology, Building Society: Studies in Sociotechnical Change*, Wiebe Bijker and John Law (Eds.). MIT Press, Cambridge, MA, 205–224.

[5] Miguel Altieri, Clara Nicholls, and Rene Montalba. 2017. Technological Approaches to Sustainable Agriculture at a Crossroads: An Agroecological Perspective. *Sustainability* 9, 3 (2017), 349.

[6] Danny Ardianto. 2014. Understanding Social Media-Enabled Participation and Resilience in Urban Farming Communities. In *Proceedings of the 26th Australian Computer-Human Interaction Conference on Designing Futures: The Future of Design (OzCHI '14).* ACM, New York, NY, USA, 111–114. https://doi.org/10.1145/2686612.2686627

[7] Paramvir Bahl, Ranveer Chandra, Thomas Moscibroda, Rohan Murty, and Matt Welsh. 2009. White Space Networking with Wi-Fi like Connectivity. *SIGCOMM Comput. Commun. Rev.* 39, 4 (Aug. 2009), 27–38. https://doi.org/10.1145/1594977.1592573

[8] Hannah Barrett and David Christian Rose. 2020. Perceptions of the Fourth Agricultural Revolution: What's In, What's Out, and What Consequences are Anticipated? *Sociologia Ruralis* n/a, n/a (2020). https://doi.org/10.1111/soru.12324 arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/soru.12324

[9] Frans Berkhout. 2006. Normative Expectations in Systems Innovation. *Technology Analysis & Strategic Management* 18, 3-4 (2006), 299–311.

[10] Nicola J. Bidwell. 2009. Anchoring Design in Rural Customs of Doing and Saying. In *Proceedings of the 12th IFIP TC 13 International Conference on Human-Computer Interaction: Part I (INTERACT '09).* Springer-Verlag, Berlin, Heidelberg, 686–699. https://doi.org/10.1007/978-3-642-03655-2_75

[11] Susanne Bødker, Henrik Korsgaard, and Joanna Saad-Sulonen. 2016. 'A Farmer, a Place and at Least 20 Members': The Development of Artifact Ecologies in Volunteer-based Communities. In *Proceedings of the 19th ACM Conference on Computer-Supported Cooperative Work & Social Computing (CSCW '16).* Association for Computing Machinery, New York, NY, USA, 1142–1156. https://doi.org/10.1145/2818048.2820029

[12] Rosemary Brandt. 2021. *Researchers Develop Tools to Listen, Talk to Plants with $25M from NSF.* Retrieved December 01, 2021 from https://news.arizona.edu/story/researchers-develop-tools-listen-talk-plants-25m-nsfs

[13] Kelly Bronson. 2019. Looking through a Responsible Innovation Lens at Uneven Engagements with Digital Farming. *NJAS-Wageningen Journal of Life Sciences* 90-91, December (2019), 1–6.

[14] Nik Brown and Mike Michael. 2003. A Sociology of Expectations: Retrospecting Prospects and Prospecting Retrospects. *Technology Analysis & strategic management* 15, 1 (2003), 3–18.

[15] Jenna Burrell. 2018. Thinking Relationally about Digital Inequality in Rural Regions of the US. *First Monday* 23, 6 (2018).

[16] Teresa Carlson. 2020. *Mission: Technology-enabled, sustainable agriculture.* Retrieved September 06, 2021 from https://aws.amazon.com/blogs/publicsector/mission-technology-enabled-sustainable-agriculture/

[17] Michael Carolan. 2018. 'Smart' Farming Techniques as Political Ontology: Access, Sovereignty and the Performance of Neoliberal and Not-so-Neoliberal Worlds. *Sociologia Ruralis* 58, 4 (2018), 745–764.

[18] Ranveer Chandra and Stewart Collis. 2021. Digital Agriculture for Small-Scale Producers: Challenges and Opportunities. *Commun. ACM* 64, 12 (Dec. 2021), 75–84.

[19] EunJeong Cheon and Norman Makoto Su. 2018. Futuristic Autobiographies: Weaving Participant Narratives to Elicit Values around Robots. In *Proceedings of the 2018 ACM/IEEE International Conference on Human-Robot Interaction (HRI '18).* ACM, New York, NY, USA, 388–397. https://doi.org/10.1145/3171221.3171244

[20] Arlene Kaplan Daniels. 1987. Invisible Work. *Social Problems* 34, 5 (Dec. 1987), 403–415. https://doi.org/10.2307/800538

[21] Carl DiSalvo and Tom Jenkins. 2017. Fruit Are Heavy: A Prototype Public IoT System to Support Urban Foraging. In *Proceedings of the 2017 Conference on Designing Interactive Systems (DIS '17).* ACM, New York, NY, USA, 541–553. https://doi.org/10.1145/3064663.3064748

[22] Carl DiSalvo, Jonathan Lukens, Thomas Lodato, Tom Jenkins, and Tanyoung Kim. 2014. Making Public Things: How HCI Design Can Express Matters of Concern. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14).* Association for Computing Machinery, Toronto, Ontario, Canada, 2397–2406. https://doi.org/10.1145/2556288.2557359

[23] Marisa Elena Duarte, Morgan Vigil-Hayes, Ellen Zegura, Elizabeth Belding, Ivone Masara, and Jennifer Case Nevarez. 2021. As a Squash Plant Grows: Social Textures of Sparse Internet Connectivity in Rural and Tribal Communities. *ACM Transactions on Computer-Human Interaction* 28, 3 (July 2021), 16:1–16:16. https://doi.org/10.1145/3453862

[24] Grace Dusseau. 2021. *University of Virginia Biocomplexity Institute to Contribute High-Tech Expertise in National Research Institute Developing Artificial Intelligence for Agriculture.* Retrieved December 01, 2021 from https://biocomplexity.virginia.edu/news/university-virginia-biocomplexity-institute-contribute-high-tech-expertise-national-research

[25] Malcolm Eames, William Mcdowall, Mike Hodson, and Simon Marvin. 2006. Negotiating Contested Visions and Place-Specific Expectations of the Hydrogen Economy. *Technology Analysis & Strategic Management* 18, 3-4 (2006), 361–374.

[26] Casey Fiesler, Shannon Morrison, and Amy S. Bruckman. 2016. An Archive of Their Own: A Case Study of Feminist HCI and Values in Design. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16).* ACM, New York, NY, USA, 2574–2585. https://doi.org/10.1145/2858036.2858409

[27] Mary Flanagan, Daniel C. Howe, and Helen Nissenbaum. 2005. Values at Play: Design Tradeoffs in Socially-Oriented Game Design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '05).* ACM, New York, NY, USA, 751–760. https://doi.org/10.1145/1054972.1055076

[28] Center for Advanced Innovation in Agriculture. n.d.. *Welcome To CAIA.* Retrieved December 01, 2021 from https://caia.cals.vt.edu

[29] Nick Foster, Luke Compston, and Daniel Barkho. 2006. MAIL: A Framework for Critical Technical Practice. In *Proceedings of the 18th Australia Conference on Computer-Human Interaction: Design: Activities, Artefacts and Environments* (Sydney, Australia) *(OZCHI '06).* Association for Computing Machinery, New York, NY, USA, 205–212. https://doi.org/10.1145/1228175.1228212

[30] Jessica Katherine Frawley and Laurel Evelyn Dyson. 2014. Animal Personas: Acknowledging Non-Human Stakeholders in Designing for Sustainable Food Systems. In *Proceedings of the 26th Australian Computer-Human Interaction Conference on Designing Futures: The Future of Design (OzCHI '14).* ACM, New York, NY, USA, 21–30. https://doi.org/10.1145/2686612.2686617

[31] Joan H. Fujimura. 2003. Future Imaginaries: Genome Scientists as Socio-Cultural Entrepreneurs. *Genetic Nature/Culture: Anthropology and Science Beyond the Two Culture Divide* (2003), 176–199.

[32] Elliott Grant. 2020. *Mineral: Bringing the era of computational agriculture to life.* Retrieved December 01, 2021 from https://blog.x.company/mineral-bringing-the-era-of-computational-agriculture-to-life-427bca6bd56a
[33] Matthew J. Grassi. 2016. *Opinion: Climate Corp. is the Jewel in Bayer's Monsanto Deal Crown.* Retrieved Dec 26, 2020 from https://www.precisionag.com/digital-farming/opinion-climate-corp-is-the-jewel-in-bayers-monsanto-deal-crown/
[34] Leah Chan Grinvald and Ofer Tur-Sinai. 2019. Intellectual Property Law and the Right to Repair. *Fordham Law Review* 88 (2019), 63.
[35] Daniel A. Hanley, Claire Kelloway, and Vaheesan Sandeep. 2020. *Fixing America: Breaking Manufacturers' Aftermarket Monopoly and Restoring Consumers' Right to Repair.* Technical Report. Washington, D.C., District of Columbia, USA.
[36] Jean Hardy. 2019. How the Design of Social Technology Fails Rural America. In *Companion Publication of the 2019 on Designing Interactive Systems Conference 2019 Companion (DIS '19 Companion)*. ACM, New York, NY, USA, 189–193. https://doi.org/10.1145/3301019.3323906
[37] Jean Hardy, Chanda Phelan, Morgan Vigil-Hayes, Norman Makoto Su, Susan Wyche, and Phoebe Sengers. 2019. Designing from the Rural. *Interactions* 26, 4 (June 2019), 37–41. https://doi.org/10.1145/3328487
[38] Jean Hardy, Susan Wyche, and Tiffany Veinot. 2019. Rural HCI Research: Definitions, Distinctions, Methods, and Opportunities. *Proc. ACM Hum.-Comput. Interact.* 3, CSCW, Article 196 (nov 2019), 33 pages. https://doi.org/10.1145/3359298
[39] Shaddi Hasan, Mary Claire Barela, Matthew Johnson, Eric Brewer, and Kurtis Heimerl. 2019. Scaling Community Cellular Networks with CommunityCellularManager. In *16th USENIX Symposium on Networked Systems Design and Implementation (NSDI 19)*.
[40] Masayuki Hatta. 2020. The Right to Repair, the Right to Tinker, and the Right to Innovate. *Annals of Business Administrative Science* 19 (08 2020). https://doi.org/10.7880/abas.0200604a
[41] Sara Heitlinger, Nick Bryan-Kinns, and Rob Comber. 2018. Connected Seeds and Sensors: Co-Designing Internet of Things for Sustainable Smart Cities with Urban Food-Growing Communities. In *Proceedings of the 15th Participatory Design Conference: Short Papers, Situated Actions, Workshops and Tutorial - Volume 2 (PDC '18)*. ACM, New York, NY, USA, Article 18, 18:1–18:5 pages. https://doi.org/10.1145/3210604.3210620
[42] Sara Heitlinger, Nick Bryan-Kinns, and Rob Comber. 2019. The Right to the Sustainable Smart City. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. ACM, New York, NY, USA, Article 287, 287:1–287:13 pages. https://doi.org/10.1145/3290605.3300517
[43] Sara Heitlinger, Nick Bryan-Kinns, and Janis Jefferies. 2013. Sustainable HCI for Grassroots Urban Food-Growing Communities. In *Proceedings of the 25th Australian Computer-Human Interaction Conference: Augmentation, Application, Innovation, Collaboration (OzCHI '13)*. ACM, New York, NY, USA, 255–264. https://doi.org/10.1145/2541016.2541023
[44] Sara Heitlinger, Nick Bryan-Kinns, and Janis Jefferies. 2014. The Talking Plants: An Interactive System for Grassroots Urban Food-Growing Communities. In *CHI '14 Extended Abstracts on Human Factors in Computing Systems (CHI EA '14)*. ACM, New York, NY, USA, 459–462. https://doi.org/10.1145/2559206.2574792
[45] Vaughan Higgins, Melanie Bryant, Andrea Howell, and Jane Battersby. 2017. Ordering Adoption: Materiality, Knowledge and Farmer Engagement with Precision Agriculture Technologies. *Journal of Rural Studies* 55 (Oct. 2017), 193–202. https://doi.org/10.1016/j.jrurstud.2017.08.011
[46] Stephen Hilgartner. 2015. Capturing the Imaginary: Vanguards, Visions and the Synthetic Biology Revolution. In *Science and Democracy*, Clark Miller and Rob Hagendijk (Eds.). Routledge, 51–73.
[47] Michael Hockenhull and Marisa Leavitt Cohn. 2021. Hot Air and Corporate Sociotechnical Imaginaries: Performing and Translating Digital Futures in the Danish Tech Scene. *New Media & Society* 23, 2 (Feb. 2021), 302–321. https://doi.org/10.1177/1461444820929319
[48] Michael Hytha. 2021. *'Biofacturing' Firm Zymergen Raises $500 Million in Expanded IPO.* Retrieved December 01, 2021 from https://www.bloomberg.com/news/articles/2021-04-22/-biofacturing-firm-zymergen-raises-500-million-in-expanded-ipo
[49] GitHub Inc. n.d.. *GitHub: Where the world builds software.* Retrieved September 09, 2021 from https://github.com/
[50] Sarah Inman and David Ribes. 2019. "Beautiful Seams": Strategic Revelations and Concealments. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–14.
[51] Esther Jang, Mary Claire Barela, Matt Johnson, Philip Martinez, Cedric Festin, Margaret Lynn, Josephine Dionisio, and Kurtis Heimerl. 2018. Crowdsourcing Rural Network Maintenance and Repair via Network Messaging. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, Article 67, 67:1–67:12 pages. https://doi.org/10.1145/3173574.3173641
[52] Esther Han Beol Jang, Philip Garrison, Ronel Vincent Vistal, Maria Theresa D. Cunanan, Maria Theresa Perez, Philip Martinez, Matthew William Johnson, John Andrew Evangelista, Syed Ishtiaque Ahmed, Josephine Dionisio, Mary Claire Aguilar Barela, and Kurtis Heimerl. 2019. Trust and Technology Repair Infrastructures in the Remote Rural Philippines: Navigating Urban-Rural Seams. *Proceedings of the ACM on Human-Computer Interaction* 3, CSCW (Nov. 2019), 99:1–99:25. https://doi.org/10.1145/3359201
[53] Sheila Jasanoff and Sang-Hyun Kim. 2009. Containing the Atom: Sociotechnical Imaginaries and Nuclear Power in the United States and South Korea. *Minerva* 47, 2 (June 2009), 119. https://doi.org/10.1007/s11024-009-9124-4
[54] Sheila Jasanoff and Sang-Hyun Kim. 2015. *Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power.* University of Chicago Press.
[55] Isaac L. Johnson, Yilun Lin, Toby Jia-Jun Li, Andrew Hall, Aaron Halfaker, Johannes Schöning, and Brent Hecht. 2016. Not at Home on the Range: Peer Production and the Urban/Rural Divide. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 13–25. https://doi.org/10.1145/2858036.2858123
[56] Zoe Kahn and Jenna Burrell. 2021. A Sociocultural Explanation of Internet-Enabled Work in Rural Regions. *ACM Transactions on Computer-Human Interaction* 28, 3 (July 2021), 17:1–17:22. https://doi.org/10.1145/3443705
[57] Vera Khovanskaya, Maria Bezaitis, and Phoebe Sengers. 2016. The Case of the Strangerationist: Re-interpreting Critical Technical Practice. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems (DIS '16)*. Association for Computing Machinery, Brisbane, QLD, Australia, 134–145. https://doi.org/10.1145/2901790.2901860
[58] Ronald R Kline. 2000. *Consumers in the Country: Technology and Social Change in Rural America.* JHU Press.
[59] Cory Knobel and Geoffrey C. Bowker. 2011. Values in Design. *Commun. ACM* 54, 7 (July 2011), 26–28. https://doi.org/10.1145/1965724.1965735
[60] Kornelia Konrad. 2006. The Social Dynamics of Expectations: The Interaction of Collective and Actor-Specific Expectations on Electronic Commerce and Interactive Television. *Technology Analysis & Strategic Management* 18, 3-4 (2006), 429–444.
[61] Kornelia Konrad, Harro Van Lente, Christopher Groves, and Cynthia Selin. 2016. Performing and Governing the Future in Science and Technology. In *The Handbook of Science and Technology Studies*, Ulrike Felt, Rayvon Fouché, Clark A. Miller, and Laurel Smith-Doerr (Eds.). MIT Press, 465–493.
[62] Frederic Lardinois. 2019. *Microsoft Azure gets into ag tech with the preview of FarmBeats.* Retrieved September 06, 2021 from https://techcrunch.com/2019/11/04/microsoft-azure-gets-into-agtech-with-the-preview-of-farmbeats/
[63] Katharine Legun and Karly Burch. 2021. Robot-ready: How apple producers are assembling in anticipation of new AI robotics. *Journal of Rural Studies* 82 (2021), 380–390. https://doi.org/10.1016/j.jrurstud.2021.01.032
[64] Kenneth Lipartito. 2003. Picturephone and the Information Age: The Social Meaning of Failure. *Technology and Culture* 44, 1 (2003), 50–81.
[65] Jen Liu and Phoebe Sengers. 2021. Legibility and the Legacy of Racialized Dispossession in Digital Agriculture. *Proc. ACM Hum.-Comput. Interact.* 5, CSCW2, Article 480 (Oct 2021), 21 pages. https://doi.org/10.1145/3479867
[66] Szu-Yu (Cyn) Liu, Shaowen Bardzell, and Jeffrey Bardzell. 2019. Symbiotic Encounters: HCI and Sustainable Agriculture. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. ACM, New York, NY, USA, Article 317, 317:1–317:13 pages. https://doi.org/10.1145/3290605.3300547
[67] Peter Lyle, Jaz Hee-jeong Choi, and Marcus Foth. 2014. Designing for Grassroots Food Production: An Event-Based Urban Agriculture Community. In *Proceedings of the 26th Australian Computer-Human Interaction Conference on Designing Futures: The Future of Design (OzCHI '14)*. ACM, New York, NY, USA, 362–365. https://doi.org/10.1145/2686612.2686666
[68] Peter Lyle, Jaz Hee-jeong Choi, and Marcus Foth. 2015. Growing Food in the City: Design Ideations for Urban Residential Gardeners. In *Proceedings of the 7th International Conference on Communities and Technologies (C&T '15)*. ACM, New York, NY, USA, 89–97. https://doi.org/10.1145/2768545.2768549
[69] James M. McDonald and Robert A. Hoppe. 2017. Large Family Farms Continue To Dominate U.S. Agricultural Production. *Amber Waves* (March 2017).
[70] Roberta M. Melvin and Andrea Bunt. 2012. Designed for Work, but Not from Here: Rural and Remote Perspectives on Networked Technology. In *Proceedings of the Designing Interactive Systems Conference (DIS '12)*. ACM, New York, NY, USA, 176–185. https://doi.org/10.1145/2317956.2317984
[71] Microsoft. 2021. *Visual Studio 2019 version 16.11 Release Notes.* Retrieved December 11, 2021 from https://docs.microsoft.com/en-us/visualstudio/releases/2019/release-notes
[72] Carman Neustaedter and Phoebe Sengers. 2012. Autobiographical Design in HCI Research: Designing and Learning through Use-It-Yourself. In *Proceedings of the Designing Interactive Systems Conference* (Newcastle Upon Tyne, United Kingdom) *(DIS '12)*. Association for Computing Machinery, New York, NY, USA, 514–523. https://doi.org/10.1145/2317956.2318034
[73] Helen Nissenbaum. 1998. The Cutting Edge: Values in the Design of Computer Systems. *SIGCAS Comput. Soc.* 28, 1 (March 1998), 38–39. https://doi.org/10.1145/277351.277359
[74] Helen Nissenbaum. 2001. How Computer Systems Embody Values. *Computer* 34, 3 (2001), 120–119.

[75] Juliet Norton, Birgit Penzenstadler, and Bill Tomlinson. 2019. Implications of Grassroots Sustainable Agriculture Community Values on the Design of Information Systems. *Proceedings of the ACM on Human-Computer Interaction* 3, CSCW (Nov. 2019), 34:1–34:22. https://doi.org/10.1145/3359136

[76] Juliet Norton, Ankita Raturi, Bonnie Nardi, Sebastian Prost, Samantha McDonald, Daniel Pargman, Oliver Bates, Maria Normark, Bill Tomlinson, Nico Herbig, and Lynn Dombrowski. 2017. A Grand Challenge for HCI: Food + Sustainability. *Interactions* 24, 6 (Oct. 2017), 50–55. https://doi.org/10.1145/3137095

[77] William Odom. 2010. "Mate, We Don't Need a Chip to Tell Us the Soil's Dry": Opportunities for Designing Interactive Systems to Support Urban Food Production. In *Proceedings of the 8th ACM Conference on Designing Interactive Systems (DIS '10)*. ACM, New York, NY, USA, 232–235. https://doi.org/10.1145/1858171.1858211

[78] Samir Passi. 2021. *Making Data Work*. PhD Thesis. Cornell University, Ithaca, NY.

[79] Raspberry Pi. 2021. *Raspberry Pi 3 Model B*. Retrieved December 10, 2021 from https://www.raspberrypi.com/products/raspberry-pi-3-model-b/

[80] Raspberry Pi. 2021. *Raspberry Pi 4 Model B*. Retrieved December 10, 2021 from https://www.raspberrypi.com/products/raspberry-pi-4-model-b/

[81] Barath Raghavan, Bonnie Nardi, Sarah T. Lovell, Juliet Norton, Bill Tomlinson, and Donald J. Patterson. 2016. Computational Agroecology: Sustainable Food Ecosystem Design. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '16)*. ACM, New York, NY, USA, 423–435. https://doi.org/10.1145/2851581.2892577

[82] Krishna Ramanujan. 2021. *$25M center will use digital tools to 'communicate' with plants*. Retrieved December 01, 2021 from https://news.cornell.edu/stories/2021/09/25m-center-will-use-digital-tools-communicate-plants

[83] Mollie Rappe. 2019. *$10M Grant to NC State, USDA-ARS to Advance Cover Crops, Transform Agriculture*. Retrieved December 01, 2021 from https://cals.ncsu.edu/news/10m-grant-to-nc-state-usda-ars-to-advance-cover-crops-transform-agriculture/

[84] S. Roberts, P. Garnett, and R. Chandra. 2015. Connecting africa using the TV white spaces: from research to real world deployments. In *The 21st IEEE International Workshop on Local and Metropolitan Area Networks*. IEEE, 1–6. https://doi.org/10.1109/LANMAN.2015.7114729

[85] David Christian Rose and Jason Chilvers. 2018. Agriculture 4.0: Broadening Responsible Innovation in an Era of Smart Farming. *Frontiers in Sustainable Food Systems* 2 (2018), 87. https://doi.org/10.3389/fsufs.2018.00087

[86] Elizabeth B.-N. Sanders and Pieter Jan Stappers. 2008. Co-creation and the new landscapes of design. *CoDesign* 4, 1 (2008), 5–18. https://doi.org/10.1080/15710880701875068 arXiv:https://doi.org/10.1080/15710880701875068

[87] Michael J Scroggins and Irene V Pasquetto. 2020. Labor out of Place: On the Varieties and Valences of (in) Visible Labor in Data-Intensive Science. *Engaging Science, Technology, and Society* 6 (2020), 111–132.

[88] Phoebe Sengers, Kirsten Boehner, Shay David, and Joseph 'Jofish' Kaye. 2005. Reflective Design. In *Proceedings of the 4th Decennial Conference on Critical Computing: Between Sense and Sensibility (CC '05)*. Association for Computing Machinery, Aarhus, Denmark, 49–58. https://doi.org/10.1145/1094562.1094569

[89] Katie Shilton. 2010. Technology Development with an Agenda: Interventions to Emphasize Values in Design. In *Proceedings of the 73rd ASIS&T Annual Meeting on Navigating Streams in an Information Ecosystem - Volume 47 (ASIS&T '10)*. American Society for Information Science, Silver Springs, MD, USA, Article 4, 4:1–4:10 pages.

[90] Katie Shilton. 2018. Engaging Values despite Neutrality: Challenges and Approaches to Values Reflection during the Design of Internet Infrastructure. *Science, Technology, & Human Values* 43, 2 (2018), 247–269.

[91] Katie Shilton, Jes A. Koepfler, and Kenneth R. Fleischmann. 2014. How to See Values in Social Computing: Methods for Studying Values Dimensions. In *Proceedings of the 17th ACM Conference on Computer Supported Cooperative Work & Social Computing (CSCW '14)*. ACM, New York, NY, USA, 426–435. https://doi.org/10.1145/2531602.2531625

[92] Ranjit Singh and Steven J. Jackson. 2017. From Margins to Seams: Imbrication, Inclusion, and Torque in the Aadhaar Identification Project. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 4776–4824. https://doi.org/10.1145/3025453.3025910

[93] Susan Leigh Star and Karen Ruhleder. 1996. Steps toward an Ecology of Infrastructure: Design and Access for Large Information Spaces. *Information systems research* 7, 1 (1996), 111–134.

[94] Susan Leigh Star and Anselm Strauss. 1999. Layers of Silence, Arenas of Voice: The Ecology of Visible and Invisible Work. *Computer Supported Cooperative Work (CSCW)* 8, 1 (March 1999), 9–30. https://doi.org/10.1023/A:1008651105359

[95] Stephanie B. Steinhardt and Steven J. Jackson. 2015. Anticipation Work: Cultivating Vision in Collective Practice. In *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing (CSCW '15)*. Association for Computing Machinery, New York, NY, USA, 443–453. https://doi.org/10.1145/2675133.2675298

[96] Rosemary Steup, Lynn Dombrowski, and Norman Makoto Su. 2019. Feeding the World with Data: Visions of Data-Driven Farming. In *Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19)*. ACM, New York, NY, USA, 1503–1515. https://doi.org/10.1145/3322276.3322382

[97] Rosemary Steup, Arvind Santhanam, Marisa Logan, Lynn Dombrowski, and Norman Makoto Su. 2018. Growing Tiny Publics: Small Farmers' Social Movement Strategies. *Proc. ACM Hum.-Comput. Interact.* 2, CSCW, Article 165 (Nov. 2018), 165:1–165:24 pages. https://doi.org/10.1145/3274434

[98] Norman Makoto Su, Jean Hardy, Morgan Vigil-Hayes, Tiffany Veinot, and Rob Comber. 2021. Introduction: Performing Rurality with Computing. *ACM Transactions on Computer-Human Interaction* 28, 3 (July 2021), 16e:1–16e:13. https://doi.org/10.1145/3461832

[99] Sharifa Sultana, François Guimbretière, Phoebe Sengers, and Nicola Dell. 2018. Design Within a Patriarchal Society: Opportunities and Challenges in Designing for Rural Women in Bangladesh. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–13.

[100] Mohit Taneja, Nikita Jalodia, John Byabazaire, Alan Davy, and Cristian Olariu. 2019. SmartHerd management: A microservices-based fog computing–assisted IoT platform towards data-driven smart dairy farming. *Software: Practice and Experience* 49, 7 (2019), 1055–1078. https://doi.org/10.1002/spe.2704 arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1002/spe.2704

[101] Deepak Vasisht, Zerina Kapetanovic, Jongho Won, Xinxin Jin, Ranveer Chandra, Sudipta Sinha, Ashish Kapoor, Madhusudhan Sudarshan, and Sean Stratman. 2017. FarmBeats: An IoT Platform for Data-Driven Agriculture. In *14th USENIX Symposium on Networked Systems Design and Implementation (NSDI 17)*. USENIX Association, Boston, MA, 515–529. https://www.usenix.org/conference/nsdi17/technical-sessions/presentation/vasisht

[102] Janet Vertesi. 2014. Seamful Spaces: Heterogeneous Infrastructures in Interaction. *Science, Technology, & Human Values* 39, 2 (March 2014), 264–284. https://doi.org/10.1177/0162243913516012

[103] Morgan Vigil, Matthew Rantanen, and Elizabeth Belding. 2015. A First Look at Tribal Web Traffic. In *Proceedings of the 24th International Conference on World Wide Web (WWW '15)*. International World Wide Web Conferences Steering Committee, Republic and Canton of Geneva, Switzerland, 1155–1165. https://doi.org/10.1145/2736277.2741645

[104] Eric Von Hippel. 1986. Lead Users: A Source of Novel Product Concepts. *Management science* 32, 7 (1986), 791–805.

[105] Kit Walsh. 2017. *Supreme Court Victory for the Right to Tinker in Printer Cartridge Case*. Retrieved September 07, 2021 from https://www.eff.org/deeplinks/2017/05/supreme-court-victory-right-tinker-printer-cartridge-case

[106] Xiaowei Wang. 2020. *Blockchain Chicken Farm: And Other Stories of Tech in China's Countryside*. FSG Originals.

[107] Laura Watts. 2018. *Energy at the End of the World: An Orkney Islands Saga*. MIT Press.