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Rethinking 'responsibility' in precision agriculture innovation: lessons from an interdisciplinary research team

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ABSTRACT
We examine the interactions, decisions, and evaluations of an interdisciplinary team of researchers tasked with developing an artificial intelligence-based agricultural decision support system that can provide farmers site-specific information about managing nutrients on their land. We answer the following research questions: (1) How does a relational perspective help an interdisciplinary team conceptualize 'responsibility' in a project that develops precision agriculture (PA)? and (2) What are some lessons for a research team embarking on a similar interdisciplinary technology development project? We show that how RI is materialized in practice within an interdisciplinary research team can produce different understandings of responsibility, notions of measurement of 'matter,' and metrics of success. Future interdisciplinary projects should (1) create mechanisms for project members to see how power and privilege are exercised in the design of new technology and (2) harness social sciences as a bridge between natural sciences and engineering for organic and equitable collaborations.

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Introduction

Changes in the Anthropocene are unanticipated and disruptive with serious distributional implications for humans and non-human nature within food and agricultural systems. Precision agriculture (PA) addresses challenges of climate change, food production, and water security under these new conditions. Development of artificial intelligence (AI), internet of things, and robotics in agriculture provides an opportunity to

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reduce uncertainty in on- and off-farm decision making by providing temporally and spatially specific agronomic and supply chain recommendations to the farmer. These technologies address many of the economic and environmental challenges in agriculture by applying principles of 'management with measurement' and 'farming by the foot' approaches to planting, fertilizing, spraying, and harvesting. These technologies rely on large data-sets, machine learning algorithms, and AI decision-support systems (DSS) that make location and time-specific farming recommendations. By generating targeted recommendations about using nutrients and pesticides, PA can reduce the need for blanket application of inputs, thus reducing pollution from excess or untimely nutrient applications and harmful pesticides. These are some ways in which PA is envisioned and often discussed in the contours of innovation and policy circles as a driver of environmental and economic sustainability (Rose and Chilvers 2018).

Though technology is often at the forefront in these discourses, various social and environmental considerations warrant unpacking if PA is to fulfill its promise. On the social side, researchers must be mindful of an array of *human* actors (namely, companies, farmers, policymakers, researchers, regulators, and technology developers); on the environmental side, researchers must be mindful of an array of *nonhuman* actors (namely, algorithms, analog technologies, data, environmental systems, living organisms, sensors, and software). Rijswijk et al. (2021) formalize these elements within their terming of PA as a 'social-cyber-environmental system.'

Innovation for sustainability is presently undergoing two radical shifts that resonate with this terming. First, recent technology development relies on agency and expertise to be distributed. The notion of an isolated genius or the ability of a single academic discipline to produce novel solutions to solve complex world problems is naïve. This idea of distributed agency is becoming the new normal in innovation. It implies that technology results from complex decisions made by people and organizations in heterogeneous networks (Escobar 2018). In agriculture specifically, Comi (2020) has begun to address distributed agencies in agricultural technology (AgTech) within a Midwestern context specifically. The other shift, perhaps a corollary of the first, is the understanding that responsible innovation (RI) can guide research and development toward bringing envisioned benefits to society (Frahm et al. 2022). But one particular challenge in extending RI's application lies in its Eurocentric development, reflected in the greater majority of RI projects coming out of the European Union (EU). While RI shows promise for its aims and current traction, one must be aware of its adoption of Western precepts of what is democratic and just (Prasad 2020) in its aims of anticipation, inclusion, reflexivity, and responsiveness (AIRR) (Stilgoe, Owen, and Macnaghten 2013).

There is a desire among researchers and designers to move beyond dualist perspectives on nature and culture, real and representation, and instead move toward attitudes that are more interested in relations, interconnectedness, and democracy (Escobar 2018). Recent research has examined PA as a social-cyber-environmental system, which consists of a network of human actors and institutions (e.g. knowledge, user practices, cultural values, markets, policies) and non-human objects, including other living entities (e.g. crops, livestock), and non-living objects (e.g. machine learning, AI, the internet-of-things, and robotics) (Geels 2005; Pigford, Hickey, and Klerkx 2018). This approach to systems thinking implies that social, cyber, and physical-environmental systems cannot be considered in isolation of one another but must be understood as related, coupled systems. However, when dealing with sustainability research from a relational perspective, particularly research relevant to emergent agricultural technologies, the notion of responsibility is often not clear. Who is responsible? Are we responsible to human actors only? What about non-human actors? How do we become more sensitive to other entities beyond humans – to include AI, weather conditions, animals, landscape/nature, infrastructure for the internet, and other technological infrastructures? While most researchers acknowledge innovation should become less concerned *only* with meeting consumer desires and instrumental needs and more 'participatory, socially oriented, situated, and open ended in ways that challenge the business as usual model of being, producing, and consuming' (Escobar 2018, 27), it is challenging to collectively define and operationalize RI.

Our objective is to survey the interactions, decisions, and evaluations of an interdisciplinary team of researchers who are tasked with developing an AI-DSS that can provide farmers site-specific information about managing nutrients. By doing so, we answer the following research questions: (1) How does a relational perspective help an interdisciplinary team conceptualize 'responsibility' in a project that develops PA? and (2) What are some lessons for a research team embarking on a similar interdisciplinary technology development project? We look to the project team as a source of inquiry and questions what RI means to them and, what that means for a project that strives to achieve responsibility in PA. We show that *how* RI is materialized in practice within an interdisciplinary team of researchers can produce different understandings of responsibility, different notions of measurement of 'matter,' and different outcomes or metrics of success, working from what 'matter' is to what 'matters' for a project. This paper imagines responsibility in PA as emerging in a world that is always in flux and becoming (Deleuze and Guattari 1987). Data and algorithms central to the development of PA are neither amoral nor apolitical (Bronson 2019). They are deeply connected to ideology, techniques, and sociopolitical forces. They are immanent in political and economic interests (Dixon-Roman 2016). Data are produced from the multiplicity of forces that are both material and discursive apparatuses, e.g. project goals, organizational responsibilities, rules and institutions, and even the broader influence of political economic circumstances (Dixon-Roman 2017). This paper shows how taking a relational turn in interdisciplinary research necessitates a purposive ontological and epistemological shift in how interdisciplinary research is conducted for societal benefit.

Literature

RI as a bedrock of innovation governance

RI presents a promising frontier for innovation governance. It builds on lessons from key failures of previous scientific and innovation endeavors (Von Schomberg 2013). RI provides constructive approaches to develop rather than inhibit innovation. It rests upon an AIRR framework (Stilgoe, Owen, and Macnaghten 2013) that differentiates itself from other traditional approaches of innovation governance. Traditional governance, such as regulation, is primarily reactive and can restrict pathways to the development of new technology (Owen, Macnaghten, and Stilgoe 2012). On the contrary, RI is fundamentally proactive and inspires social actors in the innovation system to work upstream or in the early stages of innovation to drive innovation for societal good (Voegtlin and Scherer 2017). RI is longer-sighted; it encourages a comprehensive understanding of the unintended consequences of innovation and uses that knowledge as a guiding or starting point for building capacity and achieving effective and equitable governance. Equitable governance relies on going beyond scientific expertise and incorporating pluralist understandings of knowledge and risks in order to co-create solutions that are well-adapted to local realities, scientifically sound, and socially robust (Tschersich and Kok 2022).

Still there is a debate as to what RI is and how it is conceptualized in a real-world interdisciplinary context. There are difficulties translating RI's ambitions into practice in large-scale interdisciplinary research teams, particularly those enrolling multiple university campuses (Hartley et al. 2019). Disagreements that can emerge involve definition of goals, outcomes, and methods (Balmer et al. 2016). Collaborators may ascribe different meanings to not just particular technologies and technological approaches (Hartley et al. 2019), but also to more abstract terms like responsibility (Pansera et al. 2020) and reflexivity (Balmer et al. 2016). These disagreements and nuanced distinctions can, in turn, pit social scientists in awkward positions wherein their expertise may be misconstrued as putting conversations on responsibility solely onto their plate (Hartley et al. 2019).

RI scholars have several recommendations for how to instead support collective imagination. One is an early and exhaustive phase of anticipation and foresight among project members. Hartley et al. (2019) find that this can collectively shape the means and directives of a given study. Another is to create spaces of dialogue via public and artistic deliverables. Creative project outlets like staged performances and festivals can enroll the public into dialogue with the research at hand not only to foster a fuller sense of inclusion, but to invite researchers to articulate their perspectives through means less fixed by disciplinary vocabularies (Pansera et al. 2020). These challenges are not exclusive to RI projects. Participatory studies have long faced such questions of collective imagination, interdisciplinary articulation, and quantification of impact of action research (Pansera et al. 2020).

When applied to research and innovation on the digitalization of food and agricultural systems, the RI lens has been used to examine the production of collective responsibility (Burch and Legun 2021; Burch et al. 2022; Bronson 2019; Eastwood et al. 2017; Rose and Chilvers 2018; Klerkx, Jakku, and Labarthe 2019; Gardezi and Stock 2021; Stock and Gardezi 2021). Some studies have emphasized the need for innovation governance that enables multiple actors to responsibly co-produce sociotechnical transitions in agriculture (Rose et al. 2021). For instance, Eastwood et al. (2017) extend the AIRR framework (Stilgoe, Owen, and Macnaghten 2013) to investigate how innovations in the smart dairy farming sector might become more responsive to societal and environmental demands. They proposed that more open and inclusive conversations with a wide range of agricultural stakeholders could identify areas of contestation and consensus on these technologies and help steer the direction of innovation (Eastwood et al. 2017). The RI lens urges social actors and organizations to not only deliberate on the products of science and innovation (what is it?) and their purpose (why do it?), but also what they may reap: their unintended and undesired implications for society and the environment (Owen, Macnaghten, and Stilgoe 2012, 28; Gardezi et al. 2022). Through understanding of responsibility and interdisciplinarity is growing within RI literature at large

(Glerup, Davies, and Horst 2017; Regan 2021), when applied to PA specifically, limited knowledge exists on how an interdisciplinary team understands responsibility when it comes to innovations in PA (see Burch and Legun 2021). This paper highlights opportunities based on our applied project experiences to extend these intriguing lines of inquiry.

Three views of responsibility

There are several ways to think about responsibility (see Table 1). For instance, responsibility can be proactive and hence described as 'care' and framed in terms of stewardship over the future. But responsibility can also be retroactive and focus on taking accountability *now* for future consequences. The proactive understanding of responsibility acknowledges that innovation processes have a duty to the wider public and future generations to create and innovate in ethical ways (Van der Burg, Bogaardt, and Wolfert 2019). This is especially true of any democratic governance of technology carried out to effectively steward the future for human and non-human nature. The retroactive version of governance suggests innovation processes should also be able to react to the potential negative consequences of action, and relevant stakeholders should work to address them during the innovation process. This process of analyzing potential consequences and acting to respond is understood to be a continuous and recurring process, and significantly central to RI.

From a new materialism perspective, however, 'responsibility' can be understood somewhat differently. Barad (2012) tackles responsibility as 'response-ability,' which pays attention to all the possible and different ways of responding in situated settings. Barad argues that the producers of scientific knowledge are always response-able within their situated relations and are thus responsible and accountable. They may not be aware of their situatedness and may not acknowledge their responsibility to other humans and non-human actors. The dominant epistemologies and ontologies that cloud their worldviews may prevent them from being able to take actions that are ethical and morally correct, but that does not mean that they are not in relation and not causing harm. It only implies that they are unable to acknowledge their responsibility and the lack of potentially doing things differently if needed. Barad's (2007) insights on response-ability encourage researchers to locate themselves and their actions within the dynamic processes of innovation and highlights that their decisions and actions are not only technically but deeply political. This is what brings us to the second important concept that we borrow from Barad (2007): 'mattering.'

Barad uses the term mattering as a verb. Mattering includes actions and practices that hold together living beings, material things, projects goals, or other phenomena (Burch

Table 1. A typology of definitions and ambitions for responsibility in RI-based applications.

Vision of responsibility	What characterizes responsibility	Implications of vision
Proactive	Empathy and caretaking for human and non-human nature	Setting ethical innovation pathways from the start
Reactive	Accountability, monitoring, and responding to risks	Correcting innovation pathways as they progress
New materialist	Emergence and distribution	Creating reflexive spaces for transdisciplinarity

and Legun 2021). Barad's work on mattering is about rendering 'how matter comes to matter.' In other words, for Barad, it is through the relational and networked characteristics of relevant actors and objects that agency comes about. According to Draude (2020), 'Agency then is not an intrinsic quality of an independent entity encountering another independent entity but something that is realized through relational settings (25).' Another way to interpret this is to think that we constantly take part in world-making; we describe the world and then act. Barad calls this 'ethico-onto-epistemology,' which is the co-constitution of knowing, being, thinking, and mattering.

Similar to our conception of responsibility as a form of collective experimentation, Barad introduces posthumanist performativity as a direct challenge to representationalism:

> the 'knower' does not stand in relation of absolute externality to the natural world being investigated – there is no such exterior observational point … 'We' are not outside observers of the world. Nor are we simply located at particular places in the world; rather, we are part of the world in its ongoing intra-activity. (Barad 2003)

Performativity provides a way to understand the world as being constituted and reconstituted in material-discursive practices. For example, the performativity of financial models has been found to produce the market conditions they describe. The very popular Black–Scholes options pricing model initially described the world of options pricing, and over time, produced that world by materially enacting trading skills, computer algorithms, and financial institutions (MacKenzie 2006). From a performative-relational perspective, 'the relations between entities are more important than the entities themselves. No entity preexists the relation that constitutes it' (Walsh, Böhme, and Wamsler 2021, 76).

According to Barad, and as explained by Burch and Legun (2021) in their interdisciplinary research project on co-designing digital agriculture tools with farm workers, interdisciplinary collaborations present an opportunity to broaden our understanding of response-abilities. But these collaborations have to be carefully orchestrated, and processes need to have critical sensibilities built into it. Human actors are always responding in relations to humans and more-than-humans and are therefore collectively answerable, but their epistemologies and ontologies (dominant ways of believing and methods of finding truth) can make it difficult for them to be aware of their relations with more-than-humans. Barad reminds us that we are always in relation, and decisions about whether we decide to include or exclude human and more-than-humans are political as much as technical decisions (Burch and Legun 2021). These decisions are situated and have material consequences. This paper expands the scope of 'responsibility' through engaging it with new materialism, where responsibility also means 'accounting for how practices matter' for both human and non-human nature (Barad 2007, 88). New materialism invokes questions of politics of innovation, such as how we innovate, who frames or defines the problem, and how research is conducted.

Method

In this paper, commensurate with the AIRR framework, we hold a mirror to our own deliberations and actions as a project team, one in the early stages of our imagining and intervening in PA as a system continually made and remade by the interests of various actors in a distributed system. Below, we describe (a) the nature and guiding purpose of this transdisciplinary project, (b) description of the evaluation data, and (c) the analytical approach.

Study setting

Our project is a multi-organizational collaboration involving scholars from four universities: [Names hidden for peer review]. Scholars hail from a range of disciplines and cover a broad set of disciplinary training, including agronomy, engineering, environmental science, the social sciences, and computer science. Co-principal investigators (Co-PIs), senior personnel, and graduate students on the project converge around several different themes: (1) AI-Decision Support System (AI-DSS) development, (2) Payment for Ecosystem Services (PES) experimentation, and (3) drawing policy relevant insight for RI. See Table 2 for a breakdown of the team by role and theme. Authors on this paper span across these different roles and themes.

The project has an advisory board comprised of technology developers from the industry and research universities, farmers and farm workers from South Dakota and Vermont, civil society organizations, and other actors concerned about the environment. The team consulted with these board members on an annual basis during the period of data collection. These conversations have helped shape our approach to our research as well as our operationalization of RI. We offer examples of these insights later in the article.

The project team aims to develop a DSS that can recommend to farmers more 'accurate' and 'precise' Nitrogen (N) and Phosphorus (P) use. These materials if overapplied on the land can have serious impact on the environment, and if underapplied can be deleterious for farm yield. The project focuses on RI in PA to steer existing farming practices toward sustainable agriculture. PA tries to find the 'right' balance so that farmers can reduce the use of these valuable and expensive inputs, maintain desired yields, and in the process also protect the environment. Perhaps the best rephrasing of the project goals in prototyping AI-DSS and a PES mechanism comes from the following quote from one of our team members: 'Is it data and information or incentives or both that change farmers' behavior?'

The focus on climate solutions, in turn, within the project specifically builds off prior research in the Lake Champlain Basin, Vermont that helped simulate local climate change effects. It equally helped build relationships across disciplines and with local stakeholder communities seminal to the project. Many researchers are new to such collaborations and applications of their expertise. During an evaluation session, one project member commented that '[m]any of us are new to the idea of working to find

Table 2. A chart of 32 team members on the project organized by team member role and theme.

Role	AI-DSS development	PES experimentation	Policy relevant insights for RI	Total
Co-PI	3	1	1	5
Graduate students	4	2	3	9
Post-docs	2	-	1	3
Senior personnel	10	3	2	15

Table 3. Data gathered for evaluation during the first two years of the five-year project.

Data Source	Description
Project Evaluation with PIs	Year one evaluation (September 2021)
Advisory Committee	Survey results from advisory committee members (2020–2021)
Notes from team meetings	Team-wide discussions (September 2021–April 2022)
Project Team Evaluation	Mid-term evaluation with whole team (March 2022)
Informal team-wide focus groups	Exercises on defining responsibility (April 2022)

effective ways to engage farmers in technology design,' while another identified a key challenge in 'setting up unique partnerships that differ in each state' considering the project's two case studies (South Dakota and Vermont).

Our project seeks to make a lasting intervention in sustainable agriculture through its pedagogical component. One of the project objectives is to develop training for the agricultural labor force that enhances understanding and ultimately adoption of sustainable farming solutions. Our focus on training toward sustainable agricultural practices will provide a deeply entrenched intervention into agri-food systems within a living labs framework (Leminen and Westerlund 2019; Ballon, Pierson, and Delaere 2005; Eriksson, Niitamo, and Kulkki 2005; Niitamo et al. 2006; Bergvall-Kåreborn and Ståhlbröst 2009; Almirall and Wareham 2008; Leminen, Westerlund, and Nyström 2012; Dell'Era and Landoni 2014). The living labs framework will implement RI as a means of including farmers as stakeholders.

Our project is based out of the US. In contrast with EU projects, ours was not required to adopt RI. This warrants being reflexive about extending a framework coming from a European context as previously discussed. Even when not required by a funding agency, however, we believe in adopting RI principles in the context of AgTech development. Rather than instrumentalizing farmers for the sole purposes of user testing, farmers will actively shape our research agenda not just in terms of what variables they would be interested in having measured, but also of what products they envision as helpful and changes they would like to realize to achieve an ethical and accountable implementation of sustainable PA. Because of the living lab framework, there is a great deal of flexibility needed among researchers as the project progresses, and that is exactly why this paper carves out space to consider how to work in transdisciplinary collaborations where so much agency is always in motion.

Data

Data for this paper were collected using developmental evaluation when both work and organizational relationships and technology development processes are nascent and undetermined (Patton 2011). Designed to evaluate work that is emergent and systems focused, this approach engages team members and leaders in periodic evaluative sessions to capture the learning along the way. This process, largely led by those on the project trained in the social sciences, involves exploring questions team leaders want to answer during the evaluation activities and engaging them quarterly in a discussion of what team members are learning and how the team can harvest additional learning.

We designed our learning from our work sessions using Appreciative Inquiry to discover what is working well and why in applying RI, working as a team, and integrating our expertise to produce transdisciplinary results. Appreciative Inquiry thus serves as a participatory method that establishes infrastructure for continued dialog through a 4-D (Discovery, Dream, Design, and Destiny) process (Stavros, Godwin, and Cooperrider 2015). In these conversations, the team identified what was emergent, relational, and generative (thus engaging with response-ability) and how we could more clearly and effectively make change in our work and our fields. We conducted much of this during regularly scheduled Zoom meetings where all team members are present to provide updates on objective work, case studies, and research opportunities.

Analytical approach

We reflect on experiences of a large interdisciplinary project on PA that uses RI as the bedrock for decisions on innovation and innovation governance. We focus on how social elements, including symbols, interactions, and elements of culture, intersect with material elements (settings, objects, and technologies). Our analysis focuses on relations of these elements to understand how heterogeneous social-material 'things' assemble and reassemble to produce 'responsibility' in a large-scale research project. We do this by describing project evaluations, stories, and conversations among the project team to understand *how* 'responsibility' originates. From a relational way of exploring aspects of the material world, we aim to avoid making a priori assumptions. Instead, our focus is on exploring the sustained interaction between, and relation among, social and material things.

Here, the reflexive exercise the team is engaging in by way of writing this paper collaboratively on our own authority and expertise in the design process is imperative. Following the Stilgoe, Owen, and Macnaghten (2013) AIRR framework toward responsibility, in applying reflexivity as an integral part of responsibility, foresight exercises (*anticipation*) had already been conducted as part of the planning grant activities. *Inclusion*, by the very nature of the living labs framework, sets into motion the ambition for a deliberative mode of governance that extends care across relevant stakeholders to care for nonhuman entities, such as soil and water. The end result of the project is to achieve the aims of *responsiveness* and what we hope will prove a long-lasting social and policy infrastructure to carry on beyond the grant timeline. *Reflexivity* remains the hanging question: how might we best, as a large transdisciplinary project, hold up a mirror to our own actions, assumptions, definitions, and disciplinary perspectives as our interventions take shape? This paper examines how a relational perspective has helped our interdisciplinary team conceptualize 'responsibility' in a project that develops PA. We reflect on the challenges and opportunities of interdisciplinary RI projects to generate lessons that may help other researchers to embark on their technology development projects.

Results

Responsible approaches to data are open and vague

Our project considers a need for N and P measurements specifically in the design of our AI-DSS. When applying insights from 'response-ability,' one challenge lies in the emergent agencies constituted between researchers, stakeholders, and data capturing techniques and technologies. A team member made this connection in an early evaluation session in

> working with farmers through the living lab and using new equipment to collect new kinds of data that we really don't know how to process. These data include hundreds of variables. It is a challenge to know which are more important than others.

From a new materialist perspective, this challenge highlights how data is produced by researchers in situated settings and then becomes a non-human actor that farmers and researchers relate with and are thus accountable for. This raises a number of important questions about whether or not a researcher or farmer is actually able to respond or be response-able with PA. Still, instead of proving prohibitive for responsible innovation, these are guiding challenges for our collective inquiry to follow the interactions that make responsibility contested. In the broader project's early conversations on RI in PA, one project lead working most closely with the eventual AI-DSS design remarked during a weekly meeting, 'This is the whole reason I got into engineering.' Indeed, work on such complex problems is galvanizing and allows for project-based collaborative learning that undercuts preconceived divides between design, social sciences, and technical work (Snow 1959).

Drone capture is particularly noteworthy in this conversation. Drone imaging can aggregate a range of variables, including soil moisture, micro-topography metrics, plant height, growth, vegetation index, general health productivity, and nutrient data at the field scale. Drones with hyperspectral capacity can also determine plant yields and plant quality (protein, energy, fiber, etc.), which is extremely valuable information for many farmers (Oliveira et al. 2020). In our team comprising partners from multiple universities, one group had procured a hyperspectral drone at the beginning of year two while multispectral imaging had already occurred on roughly 20 fields in another state. What had galvanized some members of the team around collecting hyperspectral data was the unique research opportunity of training a prototype AI-DSS that can then make predictions using satellite data in terms of the aforementioned soil and plant-related variables. Hyperspectral sensors, however, are more costly than multispectral sensors. This exacerbates the issue of affordability and access for farmers who may not be able to capture a comparable level of imaging on their own after the project ends. These considerations have precedent from the start of the project, with one project lead asking in an early evaluation, 'How do we develop tools that farmers can easily use and address profitability?' Questions of access and capacity that arise as galvanizing elements from a disciplinary perspective for some on the team can serve as a barrier to responsibility in the broader project.

Another challenge is that for graduate students currently being trained in the use of particular tools, there can be a sizable gap between understanding what counts as responsible research in the abstract on one hand and how to think about use of a tool in a grounded approach in terms of responsibility on the other hand. It is equally worth following how 'politics of collaboration' enter the fray. By use of this term, we as authors refer to possibilities that collaboration presents to both reinforce and contest structures of power (Elwood 2002) and to work with adversaries as much as it does allies (Baguley, Kerby, and MacDonald 2021; Fortun and Cherkasky 1998). Likewise, Baguley et al.

(2021) assert that it is ‘unwise for any academic to assume that a shared destination negates all other points of difference.’ In our reference to the politics of collaboration, we see politics of identity, different standings of researchers from graduate students to early career researchers and tenured faculty, and different disciplines at work on the team as some of these ‘points of difference.’ To expand on the latter, those trained in different disciplines see their work and the different worlds that said work intervenes in differently. These visions are also ones that scholars are trained to defend to justify a given discipline’s legitimacy. In reflecting on experiences early on in the project, one senior personnel expressed that ‘you learn a lot about humility and that collaboration and cooperation is the bigger factor for everyone’s success than having your ego and being our own boss.’ Contestations thus emerge over how the broader team enacts a living labs framework and how to forge this imagined system in a responsible manner.

There is also a need to consider data processing labor from a research perspective, particularly for graduate students, who often conduct the bulk of this labor. In encouraging students to think about processing challenges, the project co-PIs brought up this topic and the associated time requirements as early challenges when working with hyperspectral data. Some graduate students had been processing and analyzing hyperspectral data for months – a time consuming activity. Another challenge of working with hyperspectral data lies in how it serves as an emergent horizon for the application of different sets of expertise. It makes possible novel means for expressing, translating, and combining disparate sets of disciplinary knowledge. Two quotes coming out of our evaluative data are worth noting here. The first recognizes some of the iterative work necessary in launching weekly meetings in the second year of the project as it relates to the diversity of disciplinary training: ‘[t]here has to be some starting over as we are not aware of all that is going on, and this is a new field with brand new tools.’ The second deals explicitly with the act of translation: ‘We have a huge amount of data collected by the hyperspectral scanner. How do we combine gene expression leading to innovation?’ What the team considers as data and what variables are to be measured in our living lab collaboration with farmers has faced various tensions which project evaluation activities have helped to identify and negotiate.

Graduate students have also shared the discomfort they feel in providing their feedback and perspective, an essential ingredient in the transdisciplinary scope of this project. In the project’s Year One Evaluation Report, the project leaders clearly demonstrated a desire and commitment to mentor postdoctoral researchers and students involved in the project as to how their expertise and skillsets can meaningfully contribute to problem-centered, transdisciplinary research designs. As one project member put it, transdisciplinarity can pose ‘a challenge for students and postdocs who come with more discipline specific experiences. We can empower them by giving them ownership of the dialog. Communication is critical.’ The ambitions of the team have always been to integrate graduate students fully within its transdisciplinary agenda. In our evaluation data, one team leader noted, ‘We have to make sure they don’t work in isolation with a conscious effort to do team building.’ Suggestions have included establishing a graduate student advisory committee, reading groups, and annual retreat planning, much of which faced hardships or delays in part due to the COVID-19 pandemic, but also as a result of the necessary remote collaboration when the nature of work is distributed across four different university campuses. We find these considerations particularly important given the prevalence of graduate student and senior personnel (see Table 2) in the labor involved in the project. It is this labor that most often deals in the more granular work (data collection and aggregation, field sites, extension services, and so on) enrolling the more-than-human agencies that are often devalued but that response-ability seeks to follow. Collaboration to help share the insights coming out of this labor towards a more response-able approach has come in more informal ways as graduate students self-organize around conference and special issue proposals, but the team's collaboration in authoring this article is part of an attempt toward response-ability to establish more concerted connections.

Participatory PA research is challenging

Our 'Year One Evaluation Report' highlighted both enthusiasm and trepidation at the prospect of collaborating with diverse stakeholders. For some project members, collaborating with stakeholders in real-life settings and co-developing a research agenda with them lay outside of their typical disciplinary training. Other project members were excited by the prospect of working with stakeholders that have been historically excluded from exercising full agency in shaping a research design. A consensus arose out of both our advisory committee meetings and our evaluative data from PIs that more defined goals, outcomes, and roles would be crucial given these possibilities. Two admissions from PIs stand out in this regard. The first is that 'I want to pull my weight in the project but still not sure of what weight is needed.' The second is that '[h]ow people view expectations [about the project] is unknown, and I am concerned when I have little to report.' While the advisory committee expected such definitions would become clearer over time, this emerged as more of a priority in their feedback, recognizing the malleable process involved in this type of interdisciplinary research. One advisory committee member arguably summed this dynamic up best in relaying, '[s]ometimes it's easy to get caught in the day-to-day and lose sight of the endgame – I think that's where the advisory committee can help the most.'

Two other key matters of definition come into play in assessing this particular set of tensions. One is the matter of who these stakeholders are and how they should be best included in a project in which one is following emergent patterns in data and the social relationships they cue as a means of responsibly including actors into the research itself. This includes how to resolve conflict between research team and stakeholders when end goals diverge. In a project that seeks to broach PA through RI, reflexivity is a key component of research where the broader team has made strides but equally recognizes that work remains. The team recognizes that the different sets of disciplinary training condition what we see as data itself.

The second is the matter of agency for the stakeholders involved, including ourselves as researchers. Who makes decisions, and by what set of conditions or processes? As part of a living labs approach, researchers must see not just the typical actors (themselves, companies, and policymakers) as stakeholders, but also communities of impact (in our case, farmers) and environments of use (land, soil, and water) (Rijswijk et al. 2021). Scholarship often traces this expansion from the triple helix model of innovation to a quadruple or quintuple model (Etzkowitz and Leydesdorff 1995; Habibipour et al. 2022). For some collaborators enrolled in the project, this is second nature; for others, it is a less clearly defined terrain. Actors outside of 'the usual suspects' having agency to shape the research process is a more radical shift in the practices associated with their discipline. In sum, given the range of disciplines involved in PA research, challenges in setting up a participatory framework include a lack of methodological training in working alongside research subjects as driving stakeholders along with a lack of shared vision for how to follow data in ways that help signal who to include as stakeholders and how.

Discussion

Lessons for transdisciplinary RI research

Lesson 1: create mechanisms for team members to see how power and privilege are exercised in the design and development of PA

A new materialist turn in RI provides an important starting point for a project team to conceptualize interdisciplinary work more critically. For instance, the types and amount of data collected from farms and farmers, as well as how to define and measure the success of the AI algorithm were common themes during our project team meetings. We encourage interdisciplinary teams to engaging in conversation explicitly on responsibility with the whole team as part of their evaluation process. This process can open several dynamic lines of inquiry. One front of this shared responsibility lies in what we – as the project team – owe stakeholders and what we must hold ourselves accountable to internally as we work in a team with stakeholder data. Another lies in how we define and represent data – that is, how we distinguish data from information, how might farmers define data, under what conditions do farmers accept data as fact, and what counts as responsibility in how we represent data back to the farmer (be it by a particular mode of visualization or platform choice).

Our project team deliberated on how farmers turn data into information. We found that this in itself is a labor-intensive process. One of the things at stake in enacting a responsible approach to research is how do we provide a sustainable system that assists farmers in constructing epistemic resources to define data and perform that labor (Ottinger 2022). Is it more responsible on the project's team part, say, to design a fully functioning system, or to experiment and help farmers speculate which presentations of data may better steward this labor? Of equal concern among team members were the representations and lifespan of data, particularly in relation to drone capture. If farmers are not currently using drones, will they have reservations about drones for multispectral and hyperspectral imaging? It was unclear whether smaller scale operations in Vermont might adopt these tools. And what if any implications do access to expensive technologies (such as drones) have in exaggerating existing disparities between small scale and mid-sized farms and farmers. The politics of representation on such a project are thus not separate from conversations on responsibility (Frahm et al. 2022), especially when it comes to public perceptions on invasive over-the-ground drones, satellite imagery, and on-the-ground sensor capture. Within the consideration of researchers, responsible approaches must scrutinize whose labor it becomes to translate data in these emergent ways and not just who or what it serves.

Power is also exercised by gatekeepers of disciplinary knowledge and in discussion spaces, such as in team meetings. Working across disciplinary boundaries shifts perspectives, encourages reflexivity, emphasizes the connection between process and achieving goals, and inspires new ways of thinking and creating new science. However, this process takes time and patience. Learning to listen, to develop common vocabulary, and pushing ourselves from different corners of the academy creates emergent conditions ripe with the potential for innovation that require 'disciplines sitting at the table because you don't know what dots to connect if they all are not at the table.' As one student put it, 'We are bringing quasi-experimental methods to areas where they have not been applied before.' Working together, the team sees the opportunity for their work to 'move the needle' on matters of global environmental change. One of the way that this team was able to maintain equity in the decision making process was by ensuring student and Post-doc voices were included, we were able to avoid concerns that 'Because people are experts in their field, they can be hesitant to cede authority to the team.' or 'Egos that view one's own discipline as more important and then by extension others' perspectives immaterial and unnecessary.' For those trained in disciplines where the hierarchy of knowledge and the dominant epistemological paradigm are seldom questioned, learning to intentionally focus on team and relationship building is also a door to understanding the need for a foundation built on epistemological inclusivity. It can directly service response-able interactions in the creation of new science that emerges from outside the disciplinary silos. As one senior personnel excited to be part of the experiment of how to do interdisciplinary research as well as to create new and meaningful technology put it, with the 'science of team science you learn a lot about humility and that collaboration and cooperation is the bigger factor for everyone's success than having your ego and being our own boss.' A relational turn in interdisciplinary RI research can necessitates a purposive ontological and epistemological shift in how interdisciplinarity research is conducted for societal benefit.

Lesson 2: harness social sciences as a bridge between natural sciences and engineering for organic and equitable collaborations

Our project inquired what 'responsibility' meant and how it was embodied within social practices of a large interdisciplinary research group. Various needs are evident in facilitating these broad conversations on responsibility. One is to build a common vocabulary as a team on which to base said discussions. Another is to generate a collective sense of background for the project based on our individual researchers' existing research projects and interests. A third is to establish criteria for project success that builds off of those distinct areas of expertise. Last but not least, there has been a clear emphasis on building an infrastructure for student engagement and support. In light of these needs, the team established regular weekly meetings at the start of Year Two of the project involving all members of the research team from PIs, senior personnel, postdocs, and graduate students.

Through the regular team meetings, our project team members came to understand that how we work together is critical to what we can achieve by working together. Often senior faculty enthused with their work and the creative energy connected with science at the edge of new knowledge, can overlook how they come across in working with less experienced and knowledgeable scientists in training. A comment from senior personnel in the project team speak to the need to manage not only tasks but relationships and the communication that connects the two, 'you … can't do it [project activities] in a cookie cutter fashion; it comes down to communication, relationships, and trust. Giving space for people to talk is very important.' In response to this comment, we shifted our weekly project meeting format to include more breakout sessions and opportunities for check in and discussion.

Yet, an interdisciplinary project often warrants that decisions be made fairly quickly after capturing insights from the team. Some decisions, of course, emerge as a matter of practicality. Deliberation, being a slow process, warrants recognition that different decisions and actions will not be made as swiftly as team members may at times expect or want based on other collaboration experiences. This has arguably been most pronounced in discussions of field site selection and farmer recruitment. PIs have underscored that site selection and farmer recruitment needs a defined process and sound reasoning in order to account for high spatial and temporal variability present in agronomic and climate data. The latter is being piloted from the ground up working with local groups to recruit interested farmers, who we interview and plan to involve in co-designing an AI-DSS prototype. Yet many decisions, such as site selection and farmer recruitment, are made while the project is in the very act of becoming, forged out of practicality but also conditioning the very futures the project can potentially create. Our evaluation data show clear tension among the researchers on the team with our collective work very much encompassing a process rather than a product. Components of the project are assembled without full consideration of deliverables, often inherent in open collaborations with broad-ranging goals. This is a big difference from one's individual expectations depending on their disciplinary training and experiences on past projects.

Yet, we find that these tensions regarding competing interests and expectations within a team can provide valuable lessons for other social scientists involved in interdisciplinary RI projects. From the perspectives of 'the science of team science' (Stokols, Hall, and Taylor 2008) and knowledge brokerage (Turnhout et al. 2013), social sciences offer a bridge between the natural sciences and science communication and policy. We have found that social scientists can build a research ecosystem that fosters responsibility in innovation by informing technology and policy goals, and harnessing trust between users and technology. Our experiences highlight that an integrative approach guided by social scientists can (1) blend different knowledge, perspectives, and approaches to innovation, education, and training; (2) bridge diverse perspectives, such as between graduate students and team leaders; and (3) provide opportunities for the team to be more reflective of their agency.

Our contributions to extant RI literature

Traditionally, innovation governance models have leaned on responsibility in its 'reactive' form, which is predicated on eliminating barriers to adoption after the fact, weighing between benefits and risks (Figure 1). RI encourages us to acknowledge people and organizations that have a collective responsibility for protecting each other and the environment.

A proactive version of responsibility in PA research idealizes responsibility to embody foresight, production of a space for a full suite of affected actors to participate and voice their matters of concern (Latour 2005), inquiry of how participating stakeholders are

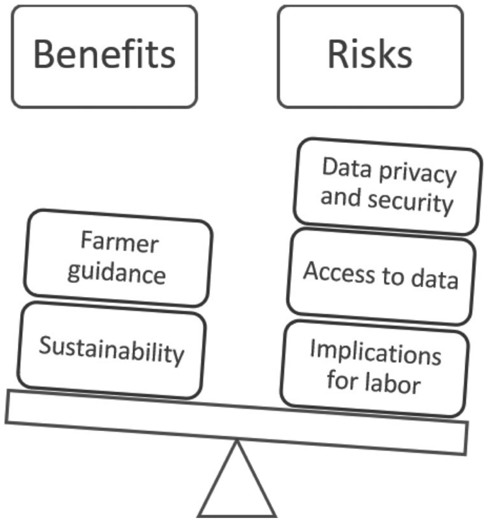

Figure 1. Reactive responsibility in PA.

affected differently given how distributed the impact of technology is, and consideration of long-term impact on people and the natural environment (Figure 2). Indeed, there are subtle differences between whether we are in it together to design a common future or whether we are united in the effort to learn from collective experiments in the laboratory of society. The collective experimentation approach envisions that researchers and innovators are both subjects and objects. They are the object of research as well as those who are researching (Nordmann 2019). In collective experimentation, there are fewer clear divisions between those who conduct the experiments and that which is observed (Nordmann 2019). According to Delgado and Åm (2018), in this different conceptualization of

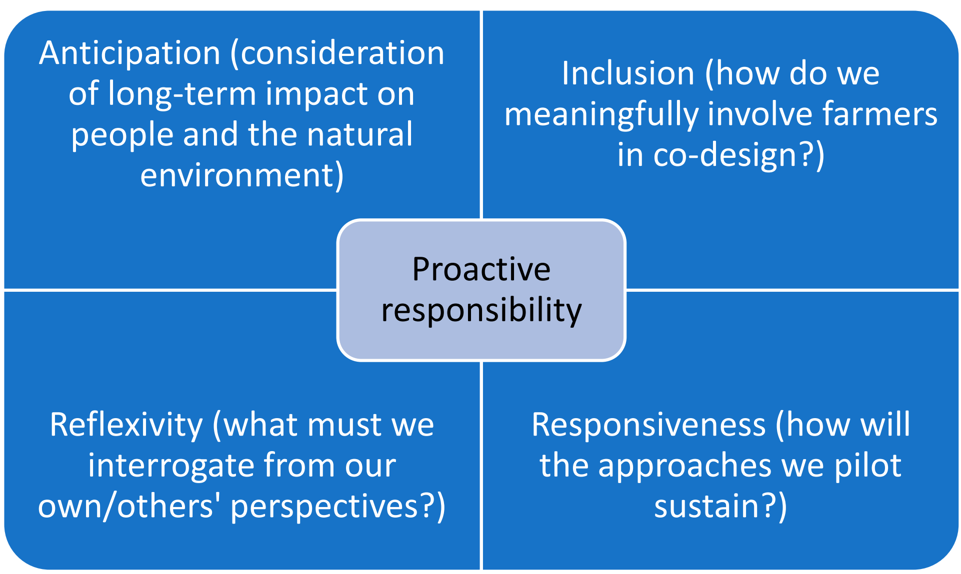

Figure 2. Proactive responsibility in PA.

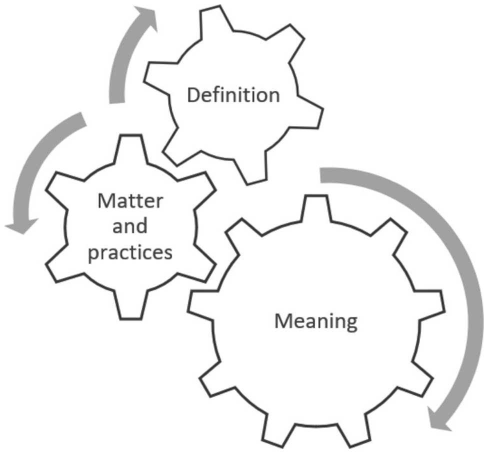

Figure 3. A new materialist vision of responsibility in PA.

responsibility, how people think about what responsibility is, or what the public good is, are undefined (apriori), and such definitions are emergent. They occur within the context of specific interdisciplinary collaborations and remain an empirical question (Delgado and Åm 2018).

Our paper demonstrates how a new materialist vision of responsibility in PA can enable an interdisciplinary team to see concepts, nonhuman actors, material processes, and pre-existing meaning-making dynamics as mutually constructed and as forces setting each other in motion (Figure 3). For response-ability, actions matter in meaning and materially. It considers our ability to understand how our actions/practices affect beings (and what we may not be considering) to be important. While response-ability inherently cannot serve as an explanatory framework that demystifies said relations, it does allow the possibility to notice how they are situated in particular contexts and how they diffuse. Burch and Legun (2021) point toward how this can bring additional reflexivity: 'This awareness can support researchers in more consciously participating in processes of mattering (i.e. in navigating and bringing together materials and meanings to actively influence a project's ongoing shape and potential to achieve its stated aims).' This new materialist approach presents a bold challenge to the current assumptions of innovation processes. Rather than innovation processes existing in relative isolation, they are in fact contributing to – and built by – a wide range of 'stakeholders' (human and more-than-human), each with their own intentions, experiences, knowledge, skills, and limitations. Those actors are themselves influenced by larger material, epistemological, and ontological approaches and systems. An interdisciplinary RI project should aim to harmonize knowledge, approaches, and perspectives across multiple disciplines.

Conclusion

This paper provides an overview of challenges and opportunities for innovation governance of new agricultural technologies by an interdisciplinary project team. When it comes to the agricultural sector, the stakes are high. Recent research on digital agriculture has shown it is difficult to ascertain whether new PA tools, through automation, might lead to mass rural unemployment (Sparrow and Howard 2021; WEF 2016), power asymmetry with regards to data ownership and access by large agricultural technology corporations (Bronson 2018; Bronson and Knezevic 2016; Carolan 2018; Rijswijk et al. 2021; SHERPA 2019; Van der Burg, Wiseman, and Krkeljas 2020), challenges with privacy and security (Nguyen-Duc and Chirumamilla 2019), and at the same time also improve crop yield, reduce environmental degradation, and help national and global food security agendas (Bronson 2018; Rose and Chilvers 2018; Shepherd et al. 2018; Wolfert et al. 2017). This ambiguity in how to develop and govern these technologies can sometimes lead to inaction, a mismatch between regulatory procedures and human capacity, or regulations that target different levels of risk tolerance that people and organizations have.

This project aims to responsibly innovate PA technologies with farmers by harmonizing knowledge, approaches, and perspectives across multiple disciplines. This paper offers two main insights. First, we draw on our experiences to contribute to the challenges of RI in interdisciplinary collaborations for research on PA technologies. Second, we reimagine these challenges not as limiting RI research, but as a point of departure for re-imagining RI as an experimental research approach. Our paper shows it can be challenging to reach consensus about the definition of RI. Instead, we argue this multiplicity of RI conceptualizations can lead to different interpretations of responsibility, a process that can spark creativity and ingenuity. Indeed, as Delgado and Åm (2018) see, this process is

> a necessary condition for experimentation … RI can be seen as an experimental approach to science governance, in the sense that it demands that research be oriented toward producing a certain result (i.e. better technological futures or the public good). But the means to reach the goal must be set up under conditions of uncertainty, as in experimental design.

While our team has a shared commitment to advancing societal goals, we have started to think of project team members and leaders themselves as ‘participants’ in innovation.

There are several lessons from our paper that can be relevant for other interdisciplinary teams working on RI projects. First, a RI project team at the outset, needs to acknowledge innovation as a complex, collaborative process where inventions are developed within a larger network of power and privilege. The project team needs to imagine ‘innovation’ as a long-term process from beginning to end – from original conception to the creation to the eventual marketing and implementation into larger society. This process should be imagined to continue well into the future, beyond the end date of the project. We encourage project team to collectively define the ‘end’ in RI research and what time period may be considered sufficiently ‘long-term.’ Second, any RI project should acknowledge that technology is embedded with values and politics. Thus, the project team should focus on innovation processes as an opportunity to create a collaborative and constructive approach not only with human actors, but also non-human actors, such as plants, soil, climate, and technologies. We advocate for locating democratic governance upstream, involving a diverse array of relevant actors. Rather than forcing actors to adapt their motivations and needs, the project team should play a central part in determining the direction of innovation by collaborative and inclusive means. The purpose of

RI should not be restricting innovation to serve the public or the user, but the project team should collectively open innovation as developed in tandem with the public to better address public desires and concerns. It is a matter of bringing these concerns to the table through researchers dialoging with publics rather than trying to decipher publics in isolation. This requires the team to be flexible to what emerges from deliberations with the publics, but also in the project team discussions.

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