Journal of Agriculture, Food Systems, and Community Development
ISSN: 2152-0801 online
https://foodsystemsjournal.org

Understanding the social implications of digital agricultural technologies

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Submitted September 13, 2024 / Revised December 3, 2024, and February 18, 2025 /
Accepted February 18, 2025 / Published online June 3, 2025

Citation: Melo-Velasco, J., Wilson, K., Hendrickson, M., & Valdivia, C. (2025). Understanding the social implications of digital agricultural technologies. *Journal of Agriculture, Food Systems, and Community Development*, *14*(3), 173–188. https://doi.org/10.5304/jafscd.2025.143.010

Abstract

The current digital agricultural revolution presents significant possibilities, promising transformative changes in agri-food systems. While advocates foresee enhanced efficiency, profitability, and sustainability, social movements and social critical scholars have concerns about its potential to perpetuate existing inequalities in the food system. The current conversation on the social implications of digital technologies often lacks a balanced perspective, either too broad and generic in scope or too narrowly focused on specific technologies. This imbalanced approach makes it difficult to inform meaningful policy debates or guide stakeholders

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Author Note

This manuscript is based on one of the papers from the corresponding author's doctoral dissertation (Melo-Velasco, 2023). Portions of it were presented at the National Conference on Next Generation Sustainable Technologies for Small-Scale Producers in September 2022.

Funding Disclosure

The corresponding author is thankful to the Fulbright Program and the Colombian Institute of Educational and Technical studies Abroad (ICETEX) for providing support through the Scholarship Fulbright-Pasaporte a la Ciencia on its specific focus of "Society."

who want to harness digital technologies to create more equitable and inclusive food systems.

This paper contributes theory-based applied research to this discussion. We offer applied scholars and practitioners a Socio-Ethical Awareness Framework for Digital Agriculture, which recognizes the non-neutrality of technology, the central role of power, and the importance of data governance. The framework advocates for analyzing digital technologies based on the services they provide to farmers, while prompting questions about access, technology governance, and power distribution. Focusing on these aspects of digital technology can help ensure that these innovations support, rather than marginalize, small and limited-resource farmers.

Keywords
digital agriculture, social implications, smallholder farmers, rural sociology, socio-ethical awareness framework, applied research

Introduction

The current digital agricultural revolution offers impressive possibilities and the promise of a profound transformation in the way agri-food systems operate (Trendov et al., 2019). Contemporary digital agriculture innovations contribute to existing digital technology interventions that are already reshaping agricultural and food systems. The digital landscape includes, among many possibilities, farmers using autonomous tractors, receiving specific technical advice on pests through mobile phones, deciding where and when to use fertilizers after considering data provided by sensors, custom grazing with animal collars linked to a virtual fence mobile phone app, buyers verifying through platforms powered by blockchain that farmers are properly receiving the premium price they pay, and consumers and farmers bargaining directly through marketplaces (Digital Agri Hub, 2022). The general rationale for digital technologies is that they enhance cost-effectiveness and efficiency, either by automating processes or by enabling data capture and access for streamlined decision-making (Schroeder et al., 2021). The narrative promoted by multilateral organizations and media around digital technologies is generally technically driven and optimistic. In this view, technology is presented as a straightforward solution to global food shortages, with the promise of increasing yields and incomes while mitigating issues related to current input application methods in agriculture (Abdulai, 2022; Lajoie-O'Malley et al., 2020; Mohr & Höhler, 2023). Digitalization in agriculture—the integration of digital technologies, data-driven solutions, and interconnected systems into farming practices (Klerkx & Rose, 2020)—is often also framed through a techno-optimism lens. This perspective aligns with the traditional value-neutrality thesis, which holds that technology is inherently neutral—neither good nor bad, neither morally nor politically biased (Miller, 2021).

However, reducing digitalization to a mere opportunity for willing farmers oversimplifies its complex socio-technological dynamics, limiting both our understanding and capacity to shape its trajectory. The effects of technology are shaped not only by its use but also by its inherent design, which often embeds power asymmetries. Precision tractors illustrate this dynamic: they collect granular farm-level data that corporations exploit for algorithmic improvements and agribusiness partnerships, while farmers face restricted access to their own data due to software agreements. These imbalances reinforce the dominance of large agribusinesses, excluding smaller farmers and exacerbating existing agricultural inequities. (Bronson & Knezevic, 2019). While for advocates and enthusiasts digital agricultural technologies will mainly bring increased efficiency, profitability, and sustainability (Lajoie-O'Malley et al., 2020), social movements and activist scholars emphasize the potential risks and unexpected social consequences that digital technologies may bring to disadvantaged actors in agriculture and the food sector (Bronson, 2019b; Klerkx & Rose, 2020; Mooney, 2018; Nyéléni Forum for Food Sovereignty, 2019; Grupo de Trabajo sobre el Campo y el Agro, 2019). Identifying and understanding these social and ethical implications is crucial for making informed decisions on how to promote digitalization that is inclusive and equitable.

Maintaining an apolitical stance on digital technologies in food systems is problematic. First, technology is never neutral; the interests and intentions of developers and funders shape every stage of its development, from design and implementation to its intended users and applications. Digital technologies are inherently value-laden (Bronson, 2022). Second, digital agriculture technologies are being introduced into a food system that is highly concentrated, centralized, and globalized (Clapp, 2021; Hendrickson et al., 2019). The existing power asymmetries in the system raise significant concerns about technology's potential to further marginalize small farmers. When embedded in already unequal societal structures and relationships, digital technologies risk amplifying existing disparities by concentrating power among dominant agricultural actors while eroding the agency and opportunities of vulnerable farmers (Mooney, 2018). Identifying and addressing the social dimensions of these technologies is essential to ensuring that they serve small and limited-resource farmers and contribute to more equitable food systems.

Current discussions of the social implications of digital technologies tend to be either too broad or too overly focused on specific technologies, making them inadequate for informing political debates or guiding stakeholders. To foster more informed conversations, we offer applied scholars and practitioners a framework for identifying and systematically exploring key questions when designing, promoting or analyzing digital agricultural technologies, a Socio-Ethical Awareness Framework for Digital Agriculture to be discussed later.

This paper was guided by three core questions: What falls under the umbrella of digital agriculture? What are the socio-ethical implications of digital agricultural technologies? What knowledge is needed to open possibilities for a different approach to digitalization in agriculture? The following sections explore each of these questions, concluding with a discussion of advancing digitalization responsibly while remaining aware of its broader implications.

Methodology

This study employs a theory-based applied research approach, drawing on critical theory to examine power asymmetries in digital agriculture, while integrating innovation systems frameworks (Klerkx et al., 2019) and responsible innovation governance perspectives (van der Burg et al., 2019). The research applied a systematic snowball sampling method to map literature within interconnected academic networks (Greenhalgh & Peacock, 2005). The process involved three phases: (1) Reference Analysis: Systematically examined citations in foundational reviews, emphasizing studies that explored power dynamics, data ownership, privacy, and ethical concerns in digital agriculture; (2) Forward Citation Tracking: Using Google Scholar, identified studies that cited the seminal works of Klerkx et al. (2019) and van der Burg et al. (2019) to capture emerging discussions and theoretical advancements; (3) Systematic Database Search: Conducted targeted searches in Scopus and Google Scholar, using multilingual Boolean strings to minimize language bias: English: "digital agriculture" AND ("social implications" OR "ethical issues" OR "power dynamics"); Spanish: "agricultura digital" AND ("implicaciones sociales" OR "preocupaciones éticas" OR "desigualdades de poder").

Thematic matrices identified patterns and critical gaps in interdisciplinary literature. A total of 52 peer-reviewed articles across multiple disciplines were analyzed to gain deeper insight into the socio-ethical implications of digital agriculture, with a focus on power asymmetries and farmer agency. By combining a systematic review process with theory-based analysis, this research provides actionable insights to inform digital agriculture policy and governance frameworks. The iterative process ensured both academic rigor and practical applicability, identifying key themes for addressing inequities and ethical challenges in the sector.

What is Under the Digital Agriculture Umbrella?

Terms such as Agriculture 4.0, digital agriculture, e-agriculture, smart farming, and Agtech are commonly used by scholars and industry professionals to describe digital innovations in agriculture and food production. While these terms often overlap in meaning, scope, and the innovations they encompass, they all broadly refer to the "digitalization of agriculture," a process in which all sorts of activities conducted to produce, commercialize, and consume food may at some point use digital technologies (Klerkx et al., 2019).

In simple terms, digital technologies are "tools that collect, store, analyze, and share information digitally, including mobile phones and the Internet" (Townsend et al., 2019, p. 4). This broad definition encompasses earlier approaches, such as information and communication technologies (ICT), which include computers, the internet, mobile phones, radio, and television. These technologies, developed under e-agriculture—information and communication technology (ICT) for development (ICT4D) (Flor & Jimenez, 2015)—were primarily used for one-way communication with farmers. More recent precision agriculture includes technologies like drones, autonomous vehicles, Global Positioning System (GPS) guidance, robots, sensors, soil sampling, and automated hardware and software, offering more control over farming activities (Karunathilake et al., 2023). Smart farming builds on these technologies by integrating cloud computing, the Internet of Things (IoT), and geographic information systems (GIS) which enable data collection, integration, and visualization (Lytos et al., 2020). The rise of Big Data techniques allows the capture of massive, varied, contextual data in real time, facilitating advanced analytics for predictive modeling and decision-making (Wolfert et al., 2017). The complexity and sophistication of these new technologies make them potentially "game-changing" (Klerkx & Rose, 2020).

The wide range of digital technologies aimed at agricultural production can be categorized based on their degree of technological sophistication (Trendov et al., 2019), their position in the commodity chain (Prause et al., 2020), or the specific services they offer to farmers (Porciello et al., 2021). Each approach emphasizes different aspects of these technologies.

Considering the level of technological complexity, Trendov et al. (2019) classify digital technologies into five segments: (1) mobile devices, (2) precision agriculture and remote sensing technologies, (3) big data, cloud, analytics, and cybersecurity, (4) integration and coordination systems such as blockchain, financing and insurance systems, (5) intelligent systems such as deep learning, machine learning, and artificial intelligence. While this classification recognizes the variety of sophistication within technologies, it does not account for their overlapping use in specific digital products and services, as digital products often simultaneously incorporate several technologies. For instance, the Tumaini Mobile App, developed by the International Center for Tropical Agriculture (CIAT) to identify major banana diseases worldwide, is accessed via a mobile application and utilizes machine learning, big data, cloud-based services, field sensors, and diagnostics equipment (Alliance of Bioversity International & CIAT, n.d.).

Examining the position of specific technologies along the steps of the food commodity chain reveals how digitalization impacts food production, distribution, and commercialization. Prause et al. (2020) identified 280 specific products and services already available in the global market, categorizing them into 20 groups. These categories include data-based insurance, precision agriculture equipment, farm robotics, digital marketplaces, and digital tools for commodity chain traceability and transparency. While this classification illustrates how technologies can be applied across the value chain, it does not fully capture their dynamic nature.

Porciello et al. (2021) and Digital Agri Hub (2022) offer a different approach, focusing on the specific services digital technologies provide to farmers. Porciello et al. identified four types of services: advisory, farm tools, financial services, and market linkages. Similarly, Digital Agri Hub's open dashboard, which shares innovative digital agricultural solutions, employs a taxonomy of five categories: advisory, market linkage and e-commerce, supply chain management, finance, and ecosystem support.

We argue that focusing on the type of service provided to farmers through digital technology facilitates cross-dialogue among stakeholders (e.g., farmers, extension practitioners, consumers, entrepreneurs, researchers). This approach helps to fully explore how these technologies operate, the conditions under which they can fulfill their promised benefits, and whom they benefit. Additionally, it enables consideration of how varying degrees of technological complexity can be integrated within a specific type of service. Building on Porciello et al. (2021) and Digital Agri Hub (2022), and examples of digital products and services discussed in reports by international organizations, Table 1 provides an overview of the service types and corresponding digital products and services under the digital agriculture umbrella.

Socio-ethical Implications of Digital Agricultural Technologies

Amid the optimistic narrative surrounding digital agriculture, an emerging scholarly literature critically examines its implications and unintended con-

Table 1. Service Types for Digital Agriculture

Service types	Service definition	Examples of digital products and services
Digital Advisory & Extension	Information delivered digitally to farmers, covering various topics aimed at enhancing decision-making, productivity, and quality. Information includes: ● General advisory information on agronomic best practices, on pest and disease management, ● Recommendation tailored to agroclimatic conditions ● Market prices	● Mobile-based information services ● Generic apps: e.g., WhatsApp Groups ● Regular mobile features: e.g., SMS ● Specifically designed ● Web-based information service
Digitized Farm Tools	Products and services that enable the collection, synthesis, and interpretation of farm-level data to optimize farming practices and production. The data includes: ● Crop extension, crop health (e.g., nitrogen prescriptions), density of vegetation ● Soil analysis, farm environmental parameters ● Livestock health and mobility	● Precision agriculture equipment (e.g., sensors, drones, satellite images) ● Farm management platforms doing data analytics ● Mobile-based ● Web-based ● Farm robotics ● Applications to control livestock movement (e.g., virtual fencing) ● Automated warehouses
Digital Financial Services	Digital products and services that provide access to financial services aiming to improve farmers' yields and income. They can include: ● Digital payments, digital transactions ● Credit, credit scoring ● Insurance, savings, subsidies, and policy incentives	● Fintech for credit evaluation and payment services ● Data-based insurance ● Services for digital application to cost-share programs
Digital Market Linkages	Digital services that enable farmers to engage in transactional interactions across the food chain, connecting them with agricultural input suppliers, market buyers, and service providers. They can include: ● Suppliers of agricultural inputs, buyers in different markets, service providers	● E-commerce platforms ● Marketplaces
Supply Chain Management	Solutions within the food system that support different actors in facilitating the flow of information. Information can include: ● Prices along a transaction ● Engagement of people, organizations, places or things in an exchange	● Digital tools for traceability and transparency (e.g., Blockchain, QR code) ● Software for supply chain operations

Source: Service types based on Porciello et al. (2021) and Digital Agri Hub (2022). Examples of products and services are based on Prause et al. (2020), and reports published by international organizations such as Inter-American Development Bank (Viton et al., 2019), Global System for Mobile Communications Association (Phatty-Jobe, 2020), FAO (Trendov et al., 2019), World Bank (Schroeder et al., 2021) and the open dashboard published by Digital Agri Hub (2022).

sequences beyond simplistic technological diffusion (e.g., Ayris & Rose, 2023; Bronson, 2022; Fielke et al., 2020; Hackfort, 2021; Jakku et al., 2019; Rotz, Duncan, et al., 2019; Rotz, Gravely, et al., 2019). Researchers emphasize that these technologies function within existing social and economic inequities, potentially exacerbating systemic disparities. Economically, the high upfront investment, infrastructure requirements, and operational costs disproportionately burden small-scale farmers with limited financial resources (Hackfort, 2021; Karunathilake et al., 2023; Shukla et al., 2023). Socially, digital technologies often overlook critical access barriers: for example, women farmers face restricted decision-making power and financial access, and youth lack land ownership, capital, and training (Rola-Rubzen et al., 2020; Zulu et al., 2021). Ethically, concerns about data ownership, privacy, and corporate data monopolization demonstrate the need for responsible governance (Bronson, 2019a; Rotz, Duncan, et al., 2019). This multidimensional perspective underscores that digital agricultural technologies are not neutral; rather, they risk reproducing and intensifying existing structural inequalities in the agricultural sector.

Adopting a political economy perspective and building on our review of literature on the socio-ethical implications of digital technologies, we determine that there are three interlinked practical factors to guide conversations among practitioners and farmers on design, access and governance: power distribution; inclusion and exclusion; and data ownership, accessibility, sharing, and control.

Power Facets: Shaping the Narratives and Maintaining Current Imbalances

For critical social scholars, power relationships are central to understanding social processes. They shape how the trajectories of new digital technologies can reproduce power imbalances (Bronson, 2019b; Bronson & Knezevic, 2016; Hackfort, 2021; Marquis, 2020). Power is a complex and contested concept. Despite different approaches, sociologists generally agree on the relational nature of power. Roscigno explains it in terms of social relationships: power is an "unequal relation, or inequality, based on personal attributes, institutional positioning, and statuses that are defined, codified and acted upon within historical and cultural contexts" (2011, p. 353). Power has a reciprocal and asymmetrical character, and the relative power of an actor is expressed *in relation to* and in *interaction with* (Roscigno, 2011).

Unequal power relations are evident both structurally and discursively in the increasing digitalization of the agricultural sector. The structural approach analyzes power as embedded in broader political, cultural, and economic systems that constrain individual actions and perpetuate social inequalities and injustices. In contrast, the discursive approach frames power as a productive force that shapes social norms and individual identities through knowledge, truth claims, and narratives, with individuals and institutions acting as instruments of power (Shackleton et al., 2023).

We identified three intertwined ways in which power is evident in the implementation of digital technologies in agriculture. The first involves how the narrative around these technologies is shaped. This is linked to discursive power, defined as the "power to achieve visibility, to shape knowledge, to frame narratives, and to influence policy" (International Panel of Experts on Sustainable Food Systems, 2016). From this perspective, dominant actors in the current food system, such as large firms, major retailers, and international organizations, promote the narrative that intensive, industrial food production, dependent on advanced technologies, chemical fertilizers, and pesticides, is crucial to feeding the growing global population (Clapp, 2021). Their influence is tied to their market power, economic capacity to lobby, and ability to finance research (McNeill, 2019).

The second dimension highlights how structural power is embedded in the technological development pipeline, from design to market implementation. This power manifests through a web of decisions that determine who has agency in this landscape: who make the choices, who designs, who sells, who buys, who can afford at what price, who can repair, who owns data, who can profit from it, which crops are prioritized, who benefits —and under which circumstances—are central to the sites where power is exerted. These decision points represent the concrete mechanisms through which structural power operates in digital agriculture. As the most direct manifestation of power, the structural dimension presents clear opportunities for intervention and transformative action.

The third form of power emerges at the intersection of discursive and structural power, visible through changes in relationships and dependencies. This hybrid power becomes apparent when examining how the design, deployment, and use of digital technologies potentially amplify the control and influence that large companies already exert over producers. This is especially significant within the prevailing neoliberal food regime, in which free market policies and corporate dominance shape development paths (Prause et al., 2020). The interplay between discursive elements (how digital agriculture is framed and promoted) and structural mechanisms (how it is implemented and who controls it) creates new power dynamics that can reinforce existing hierarchies in the agricultural sector (Hackfort, 2021). A more specific and tangible manifestation of these inequalities is seen in identifying who is included and who is excluded.

The next section will explore the different layers of the access gap, examining who benefits from digital agricultural technologies and who is excluded from accessing them.

Factors Shaping Access: Who Is Included and Who Is Not?

The digital divide, understood as the unequal access to the internet and digital technologies across populations worldwide, is a central concern in discussion about the development of digital technologies. Reports published by multilateral organizations (Townsend et al., 2019; Trendov et al., 2019; United Nations Economic Commission for Latin America and the Caribbean, Food and Agriculture Organization of the United Nations, Inter-American Institute for Cooperation on Agriculture, 2021) consistently assert that lack of infrastructure and related capabilities are a major reason why farmers are not able to fully benefit from digital technologies. However, the question of who is included and who is excluded encompasses a complex and pluralistic range of factors. It goes beyond the gap in access and requires a multilayered, intersectional perspective that explains how interconnected identities and social relations influence access to resources and opportunities (McCall, 2005).

The gap in access

Lack of infrastructure to support access to digital technologies, recognized as the first layer of the digital divide, is a deeply concerning problem. For example, estimates of access to 5G cellular networks—the latest generation of mobile broadband, offering the fastest speeds for internet access and data transfer—are that in 2025, access in the U.S. will be 55%, but in low- and middle-income countries only be 7%. The 2025 estimate for 4G is somewhat better, at 52% for low- and middle-income countries (GSMA, 2020; Phatty-Jobe, 2020).

Data from the 2021 Agricultural Digitalization Index (Schroeder et al., 2021) illustrate this gap more dramatically. The availability subindex measures the percentage of farmland with mobile coverage (2G, 3G, 4G) in a country, combining these coverage types into a single score between 0 and 100 to indicate the extent of digital connectivity available to support agricultural activities. In this subindex, Israel scored 95.9, Australia 84.6, New Zealand 90.3, the U.S. 87.6, Honduras 42.9, Uganda 33.7, Mexico 33.6, Brazil 30.0, Argentina 26.3, Nigeria 22.3 and Bolivia 18.1. The well-known gap between Global North and South countries exposes a predictable reality: some countries are better positioned to deploy digital technologies and reap their benefits.

While the lack of access is crucial, it is not the only gap worth addressing when discussing digital technologies. The digital divide is a multifaceted phenomenon with three layers. First, there are disparities in access to and availability of information and communication technologies. Second, socio-demographic factors influence individual decisions to use or not use available technologies. Third, there is an unequal capacity to benefit from access to and use of technologies (Ragnedda & Gladkova, 2020). A comprehensive view of the digital divide must account for inequalities in access, skills, and the capacity to gain benefits.

The gender gap and data gap

The gender digital divide and the data divide are two additional gaps that are crucial for digital technologies in agriculture (Rijswijk, 2022). The digital gender divide consists of gender differences in access to digital technologies. Data from International Telecommunication Union (ITU), the United Nations specialized agency for information and communication technologies, indicate significant gender divides in internet usage across countries with varying income levels. In 2022, internet usage among women was 21% in low-income countries, compared to 32% among men. In lower-middle-income countries, 51% of women used the internet, compared to 61% of men. The gap narrows in upper-middle-income countries, where 79% of women and 80% of men accessed the internet. In high-income countries, 92% of women and 93% of men accessed the internet (ITU, 2022). These differences reflect the numerous barriers women face in the offline world, such as limited access to education, traditional gender roles, unequal distribution of resources (e.g., land ownership, credit), restricted access to infrastructure, and laws limiting women's rights and opportunities. In this sense, the gender digital divide mirrors a broader social, political, and cultural condition in which women have unequal access to resources, opportunities, and, in the case of agriculture, participation.

Data divides can be understood in three categories: access, data as representation, and control of data flow (Cinnamon, 2020). Data access refers to the extent that data is available, relevant and reliable. Data representation implies that when data is produced choices are made that reflect specific worldviews, often privileging certain ones over others. Data control inequalities refer to the asymmetric relationships between those who possess data—collecting, storing, and mining it—and those whose data is being collected (Andrejevic, 2014).

The gaps in capabilities, motivations and opportunities

Another way to identify gaps is through an individual's capacity to use a particular digital technology: their capabilities, motivations, and opportunities (McCampbell et al., 2023). Capabilities refer to both psychological and physical abilities required to use digital technology. For example, physical skills include handling a smartphone, while psychological capabilities involve e-literacy and understanding how different phone functions interrelate. Opportunities are external social and physical factors that shape the ability to use technology. Social opportunities include mindset, social cues, cultural norms, and expectations, such as gender roles influencing access to devices. Physical opportunities involve access to time, money, and infrastructure like network coverage or device availability. Motivation refers to the internal processes that drive action both reflective (e.g., intentions, perceived, or goals) and automatic ones (e.g., habits, emotional responses, or routine behaviors such as checking a phone first in the morning). This framework helps to understand how individual and contextual factors enable or hinder the use of digital tools, and it brings attention to the often-overlooked role of infrastructure readiness.

To summarize, the question of who is included and who is not involves more than selecting specific individuals or groups for inclusion in the digitalization process. Effective inclusion efforts must consider the many factors reinforcing inequalities in digital technologies. Gendered access, for example, should be understood through intersectional factors such as gender combined with education, class, and career, as these intersections significantly influence access to resources.

Factors on Technologies Governance: Who Governs Technologies and How?

Broadly, governance in digital technologies covers how relationships and interactions are organized, structured, and regulated (Gorwa, 2019), in areas such as data privacy, cybersecurity, intellectual property rights, accessibility, and regulatory compliance. Governance also addresses the social, economic, and ethical implications of technologies and their impact on stakeholders.

Discussing governance of individual digital technologies, a wide range of practical questions emerge: Who has the authority to make decisions, and how are they made? Who designs the technology and who is consulted? How are users defined and engaged? What is the rationale behind profit generation? What changes are expected in farmers' practices or outcomes, and who decides those changes? How are pricing decisions made? How will future scenarios and potential economic, social, and environmental implications be addressed? What are the definitions of data ownership and privacy, and how are they enforced? Answers to these questions reflect specific values and interests. Depending on how these features of governance are defined, they may empower some actors while disempowering others.

Below, we summarize governance dimensions that present practical opportunities for technology developers to reflect on the situating of their work and for users to hold developers accountable.

Data and its challenges in ownership, access, and privacy

Data is the lifeblood of the digital economy. In agriculture, data is both generated and used on-farm and off-farm. There are four data streams in farming (Maru et al., 2018). The first stream, "localized data," consists of data created and compiled on a farm for its exclusive use there, and includes information on soil, seed, fertilizer use, sowing date, production practices, water use, and equipment use. The second stream, "imported data," involves data generated and acquired off the farm for on-farm use, and includes market prices and climatic information, typically analyzed and tailored by a third-party entity that owns, manages, and controls the data. The third stream, "exported data," consists of data generated and compiled on the farm for off-farm use, and can be gathered by farmers or obtained through advanced external tools. It is often processed, clustered, or merged with other information, and is issued by various actors such as governments for targeting services and subsidies, banks and insurance companies for offering targeted products, and researchers for specific projects. The fourth stream, "ancillary data," involves both on-farm and off-farm data used off-farm, including, for example, government statistical and research data on agriculture (Maru et al., 2018).

Those with access to data ownership of it, along with the ability to interpret it, are in a stronger position to make decisions and profit in the digital economy. In digital agriculture, key aspects of data are related to ownership, accessibility, sharing, and control (van der Burg et al., 2019). Each type of data brings its own set of challenges. Imported data raises concerns about its availability, accessibility, and usability, while exported data raises issues of privacy, ownership, and monetization (Maru et al., 2018). Examples help illustrate nuances of these issues. Localized data provides insights into a farmer's specific situation, their productive system and land management practices. Ownership disputes can arise when farmers' data, considered their property, is used by third parties without clear agreements on ownership rights. Monetization issues emerge when valuable agricultural data, essential for decision-making and commercial strategies, is exploited for profit without adequate compensation to the farmers who generated the data. Addressing these issues is crucial to safeguard farmers' interests and ensuring ethical and equitable use of agricultural data. This remains an ongoing conversation in the political arena, with no final solutions yet. As stated in a report published by the World Bank, in the digital transformation of the agrifood system, "laws addressing the ownership of data from digital agriculture are frequently either missing or inadequate" (Schroeder et al., 2021).

Conflicts arises with imported data. For example, it can include market prices and tailored climate information provided by third-party entities for on-farm decision-making. Access challenges may occur when this information becomes unavailable due to access issues, changes in infrastructure, fluctuating subscription fees, or formats that are incompatible or not user-friendly for producers.

Effective data governance requires understanding the specific types of data in question, the ownership rights in place established through contractual agreements, and the interests protected through these arrangements. Data privacy, ownership, and control are interconnected topics whose interaction presents risks and uncertainties (van der Burg et al., 2019). For example, farm data—specifically, localized data (Maru et al., 2018)—is often seen by agribusinesses and technology companies as trade data rather than personal data; how it is produced and used lack clear regulations and are characterized by unequal power dynamics. Van der Burg et al. (2019) discussed the risks with two examples. Input suppliers such as seed dealers may use data analysis to offer farmers different prices or terms based on predicted yield or other data points, which could lead to potential price discrimination. Second, big companies that provide smart farming technologies, data analysis algorithms, and recommendations while also selling inputs such as seeds may have privileged access to farmers' data, which can be exploited to gain an unfair competitive advantage.

Big data refers to the vast volumes of data collected from digital communication devices and stored in organized datasets and analyzed with algorithms. The data is not limited to localized information but encompasses all four streams of farming data, including climate and weather data, soil data (e.g., pH, nutrient content, moisture levels), crop data (e.g., yield, growth patterns, pest infestations), livestock data (e.g., growth rates, feed intake, health information), machinery and equipment data (such as usage patterns and maintenance history), market data (such as pricing and demand trends), financial data (e.g., input costs, labor costs, profitability), satellite imagery, aerial drone data, social media and consumer data (e.g., food preferences, purchasing behavior), and sensor data from IoT devices (such as moisture and temperature sensors in greenhouses).

Big data in agriculture raises critical concerns about data ownership and control. Agricultural data can be sold to third parties for unknown mining purposes, often aligning more with corporate interests than societal benefits. In this increasingly concentrated digital landscape, large corporations' access to and ownership of farmer-generated data can create a "digital lock-in" effect, disproportionately benefiting the corporations over smaller producers (Bronson, 2019a). This power imbalance has sparked resistance movements, exemplified by initiatives such as the First Nations Information Governance Center (FNIGC) in Canada, championing Indigenous data sovereignty (n.d.). Such models demonstrate how vulnerable populations can protect and maintain control over their data, offering valuable frameworks for how to empower all farmers in the digital agriculture landscape.

A Socio-Ethical Awareness Framework for Digital Agriculture

To assist practitioners and farmers in considering these critical factors affecting equity, we present a Socio-Ethical Awareness Framework for Digital Agriculture (Figure 1), which poses practical, broader questions that spark and guide discussions on power distribution, inclusion and exclusion, and data ownership, accessibility, sharing, and control.

What Do We Need to Know to Open Possibilities for a Different Digitalization in Agriculture?

Critical scholarship on agricultural digitalization reveals significant socio-ethical challenges that span issues of access, data representation, privacy concerns, and governance frameworks. While the impacts vary across different farming scales and regions, the implications for small-scale farmers remain particularly uncertain. Addressing these knowledge gaps is crucial to ensure that digital agricultural technologies serve as tools for empowerment, rather than sources of further marginalization for smallholder farmers globally.

Potential for a Responsible Innovation Framework

Responsible innovation offers a way to foresee potential impacts and shape the trajectories of digital agricultural technologies (Bronson, 2019b; Eastwood et al., 2022). Responsible innovation explicitly considers social and ethical aspects during the innovation process, including four dimensions: anticipation, reflexivity, inclusion, and responsiveness (Stilgoe et al., 2013). Anticipation identifies future innovation scenarios and minimizes their potential unintended economic, social, and environmental consequences. Reflexivity involves critically examining and evaluating one's activities, commitments, and assumptions, including assessing the motivations and assumptions of developers. Inclusion seeks to expand participation beyond top-down approaches by engaging the public and incorporating a diverse range of stakeholder concerns into innovation. Responsiveness adapts the innovation process based on feedback from the wider community and evolving perspectives, views, and norms (Stilgoe et al., 2013).

Scholars have used elements of, or the entire responsible innovation framework, to analyze and extract lessons from smart dairy projects (Eastwood et al., 2022), understand how apple orchard producers engage with the prospects of AI robotics (Legun & Burch, 2021), determine how inequity is present in the design of digital farming innovations (Bronson, 2019b), and build a research agenda in France to foster an agroecology-based digitalization of agriculture (Bellon-Maurel et al., 2022). These examples demonstrate the potential for a responsible innovation lens to activate discussions about the future of digitalization and critically analyze current digital products and services.

Trajectories in Different Regions, Types of Production, and Types of Crops

Few critical studies have explored how digitalization unfolds in low-and middle-income countries. Empirical work has focused on New Zealand, Australia, North America, and Europe (Hackfort, 2021; Klerkx et al., 2019), with little empirical evidence from Africa and Latin America through a critical lens (Abdulai, 2022; McCampbell et al., 2022; Melo-Velasco, 2023; Steinke et al., 2022).

Understanding the varied effects of digitalization on different production systems and crop types requires careful monitoring of its progress. This empirical evidence will help to address and provide nuanced perspectives on the questions raised by van der Burg et al. (2019), who suggest exploring the advantages and disadvantages of different power distributions in relation to goals, the allocation of burdens and benefits, farm sustainability, farmer and consumer autonomy, and values such as fairness, justice, equitable distribution, transparency, and trust.

Understanding the Different Stages of Technological Developments and Potential Outcomes

The umbrella of digital agricultural technologies is extensive and varies in complexity. Despite the hype, not all technologies are at the same level of market readiness or maturity across sectors. For example, while robotics, IoT, and data analytics in

Figure 1. Socio-Ethical Awareness Framework for Digital Agriculture

Power facets: Shaping the narratives and maintaining current imbalances	Factors shaping access: Who is included and who is not?	Factors in technologies governance: Who governs technologies and how?
Aspects of inquiry:		
• How and by whom is the narrative about these technologies shaped? • What interests are at play, and how do they influence the distribution of benefits and risks in the development and use of digital agricultural technologies? • How does the process of designing, testing, and deploying technologies in the market unfold? • Are there shifts in relationships as a consequence of using a digital technology?	• How does infrastructure support access to digital technology, and to what extent? • What are intersectional factors limiting or extending access to digital products? • What are the relationships between an individual's capabilities, motivations, and opportunities to use a digital technology? • What worldviews, livelihoods, productions systems, and crops are being represented in available data? • What are the relationships between those who possess data—collecting, storing, and mining—and those whose data is collected? • How are gender and cultural barriers addressed in relation to access to digital technologies, and who is working to overcome these challenges?	• What types of data are being gathered, and what challenges do they involve regarding ownership, access, and privacy? • What data is being collected, and what challenges exist regarding availability, accessibility, and usability? • What relationships and exchanges are encouraged in the business model supporting the expansion of this technology? • What ethical frameworks are used (or should be used) to ensure that the development, deployment, and regulation of agricultural technologies respect farmers' rights, particularly in vulnerable communities?

livestock are closer to scaling, they are more at a prototype level in aquaculture (Food and Agriculture Organization of the United Nations, 2022). A deep understanding of the nuances of what specific technologies do, with which crops, in which region, and producing what outcomes would lead to a better understanding of their potential and limits, as well as more focused interventions. Beyond categorization, paying attention to the heterogeneity of agricultural technologies is needed: "What works well for technologies for goats follows different development trajectories than that for cattle, or round bales, for that matter" (Stræte et al., 2022, p. 9).

Interactions of Digital Agriculture with Ecosystem Challenges

Although narratives of digital agriculture assert that sustainability is linked to a better allocation of natural capital, this can be considered a superficial perspective since most of the discourse is overly focused on technical and economic benefits. Considering that agriculture (as primary production), broader food-related activities (such as processing and distribution), and deforestation are major drivers of climate change (Intergovernmental Panel on Climate Change, 2022), it is imperative to understand how digital agricultural technologies impact environmental challenges, such as deforestation and consumption of natural resources. Digital technologies have been analyzed as associated with ecosystem services in two ways: making farm management more precise (e.g., sensors, AI, robotics) and increasing connectivity in the food system (e.g., supply chain management technologies, blockchain, expansion of ICT) (Green et al., 2021). Much more empirical research is needed to explore how this link unfolds in specific territories, crops, and production systems. A deeper understanding of how digital agricultural technologies function will provide evidence to either challenge or support dominant narratives about the benefits of digitalization, and will inform more targeted accountability efforts in their development.

Conclusion

This paper makes three significant contributions to the literature on agricultural digitalization. It challenges the prevailing techno-optimist narrative rooted in the notion of technological neutrality, emphasizing that this perspective limits efforts to make digitalization a more inclusive and responsible process. It argues for reframing discussions on digital technologies by focusing on the services they provide, which opens space for cross-sectoral dialogue among diverse stakeholders—farmers, extension workers, consumers, entrepreneurs, and researchers—while highlighting the conditions, functionalities, and beneficiaries of these technologies. It offers the Socio-Ethical Awareness Framework for Digital Agriculture, a tool for analyzing the socio-ethical dimensions of digitalization, fostering dialogue on power dynamics, inclusion, exclusion, and governance, and enabling comparative analysis across various technologies.

The Framework holds substantial practical relevance, serving as a bridge between research and practice. It provides a common language for engaging diverse actors, from policymakers to practitioners, in discussions about digitalization's socio-ethical implications. For technology developers and promoters, it underscores critical considerations regarding inclusion and governance that can be addressed throughout the stages of design and deployment. By structuring the examination of these issues, the framework supports informed decision-making and promotes more equitable food systems. Additionally, it offers tools for collaborative exploration of the emergent challenges of power asymmetries and governance structures while drawing lessons from real-world technological developments. Specific recommendations include initiating and guiding sectoral conversations in concrete cases in order to ground discussions in local realities, analyzing cases to understand how digital technologies reshape relationships and influence farmers' actions, and using the framework to facilitate dialogue aimed at fostering responsible innovation. These efforts can help ensure digital tools are designed and implemented in ways that consider unintended consequences and prioritize equity.

Future research should apply the framework in specific agricultural contexts to understand its real-world implications. This includes analyzing diverse business models and organizational arrangements in designing and deploying digital agricultural technologies, focusing on how these structures shape relationships, affect farmer agency, and produce varied socio-economic outcomes. An applied research approach should emphasize practical interventions to address inequities in digital agriculture, generating actionable insights for designing inclusive technologies, and proposing governance structures that mitigate power imbalances. These analyses can reveal pathways for fostering responsible innovation, ensuring that digitalization processes are equitable, situation-sensitive, and transformative.

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