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Global Adoption of Digital agriculture

Simon Cook
Elizabeth Jackson
Davide Cammarano

Introduction:
Digital Agriculture – what does it signify?

The term digital agriculture instigates equal measures of excitement, confusion and scepticism amongst investors and scientists alike. It is a new term, appearing only since about 2015 and we understand it as the "use of detailed digital information to guide decisions along the agricultural value chain" (Shepherd et al. 2020). The term Agriculture 4.0 is also used by some to portray a system revolutionized by digital technology in the same way that digital technology has totally transformed many sectors of our economic and social life (Trendov, Varas, and Zeng 2019). Reports from the McKinsey consultancy, however, suggest that agriculture is lagging the least digitized sector of those economies (Manyika et al. 2015; Blackburn et al. 2017).

Rapid growth in the use of digital technology seems inevitable, if only because agriculture must, at some stage, accelerate adoption simply to match that of other sectors. Readers who search the internet will find an impressive array of technologies to support adoption. Further investigation will reveal that many organizations, including the World Bank and FAO, see digital technologies as vital to agricultural development to meet future demand (FAO 2022; S. E. Cook and Jackson 2019; World Bank 2021). Economic analysis from Australia anticipates an additional 20B annually in agriculture there though the adoption of digital technology over the next few years (Australian Farm Institute 2018).

But what pathways will adoption follow, and how will these appear in vastly different systems that comprise global agriculture? While blind optimism, of the type we read from some commercial proponents, seems unhelpful, so too is blanket pessimism. We therefore consider four different types of food system (commodity, high-value; subsistence and nature-based) to identify the contrasting forms that Digital Agriculture is likely to be adopted within a global wave of digital technology growth.

Digital Agriculture offers a substantial portfolio of technologies

A casual search for digital agriculture will reveal a substantial portfolio of technologies on offer to agriculture. While some of these are basically 'rebranded' from precision agriculture, we note that Digital Agriculture is actually quite different in scope to PA (Baker et al. 2021; S. Cook et al. 2021). While some technologies such as satellite remote sensing have been repurposed for new uses, others, such as robotics, value chain modelling, blockchain or the 'omics are new in agricultural practice. So, too are many of the ways in which technology is applied, in particular a shift from a focus on production to much broader applications within food systems.

To make sense of these changes, we suggest that readers consider four aspects of the adoption of digital agriculture to anticipate change:

1. Think where Digital Agriculture will operate within food systems, because change occurs in different locations within food systems, depending on the relative value of change and ease of technology use;
2. Consider the range of digital technologies that is available or emerging, because many are new to agriculture and their use is likely to grow with experience;
3. Identify how technology is expected to create value, because the process of adoption is driven by value creation, and finally
4. Consider who will benefit from the IP, because sustained adoption is supported by value sharing amongst partners who enable endogenous change of the system.

Where will Digital Agriculture operate within food systems?

While PA focusses on production gains, through precision management of variable production systems, Digital Agriculture targets gains at loci *throughout* food systems, largely within value chains. About half of the investments in Digital Agriculture occurs downstream from the farmgate, and seek opportunities to acquire value through responses to consumer demand (Burwood-Taylor et al. 2021). Other applications of Digital Agriculture are growing to support management of soil, water and other natural capitals. Yet others are being used to support financial and other systemic support We found it useful to consider change in 4 domains: Production domain; Market domain; Capitals and Control (S. Cook et al. 2021).

What range of digital technologies is available?

A cursory search on the internet reveals the deployment of a bewildering array of technology, much wider than that associated with PA. We find it useful to organize these technologies into four classes - data; control; modelling and comms [see box]. Together substantially expanded the power and reach of digital technologies throughout food systems.

Box 1: Examples of Digital Agriculture Technologies	
Data (D) . Cheap and plentiful data. Yield and quality sensors, high resolution satellite, airborne or UAV sensor platforms. GPS, Within--stream sensors (e.g RFID).	Control (C) Variable rate technology, robotics, selection technology, processors, decision tools
Modelling (M) Multi-dimensional modelling of large complex datasets to characterize complex production, processing or environmental systems. VR/AR. Near real-time predictive modelling of climate effects. Product quality monitoring and control	Communication and networking (N) Social media networking for disruptive business models. Distributed ledger technologies.

How is technology expected to create value?

Change is driven by the identifiable value opportunities created by the technology. Value is created when digital technology clearly improves processes within the food system. Improvement can occur in a variety of ways, such as greater productivity; improved selectivity leading to better product quality; preserved value through digitally enabled tracking or certification, reduced environmental costs though monitoring and evaluation. Digital Agriculture can be said to have been adopted when it identifiably changes one or more steps within value chains.

Who will benefit from the IP digital technology creates?

As we have commented, the range of value sharing arrangements on which change is supported is broader than PA, which was commonly a deal between machinery suppliers – who supply technology - and farmer purchasers – who believe they can manage better as a result. We now understand more about the complexity of change and technology driven innovation and the wide range of business models that can emerge (Lajoie-O'Malley et al. 2020; Klerkx, Jakku, and Labarthe 2019). While many observers stress the potential for digital technology to disrupt, (Spanaki et al. 2022; Bryan et al. 2020), we observe - in developed economies at least- that incumbents may seek to use digital technology to strengthen their positions within value chains through the process of IP accumulation. (Malerba 2006) explains the range of behaviours for adopters of technology. Distinct patterns of technology adoption have been observed in manufacturing according to the size and knowledge content of organizations that are adopting (Pavitt 1984).

What these factors mean for the global adoption of Digital Agriculture in four types of food system

Most reports of digital agriculture focus on change within specific geographies or type of farming system. Alternatively, reports attempt to fouc on a discipline such as innovation. Neither approach can explain the diversity of change that Digital Agriculture represents globally.

We suggest using a food system approach to organize concepts. Food systems are increasingly used as a concept to direct science and political action (von Braun et al. 2021). Food systems are extremely diverse so balance is required to ensure that the concepts they assemble are sufficiently broad to identify global or national targets, but precise enough to define specific actions necessary for change (von Braun et al. 2021)

Béné (Béné et al. 2019) identifies the dynamics and complexities of such systems. Here we apply the framework above to describe plausible future scenarios for the adoption of digital agriculture in four different types of food systems that together account for an important large sector of global activities.

We select four systems to characterize the diversity of adoption patterns for digital agriculture that we label as commody; high-value; subsistence and nature-based.

1. Commodity: Systems dominated by production of tradeable commodities such as wheat, maize, milk rice or meat. These systems have developed to meet global demand for major foodstuffs and are characterized by high levels of labour productivity, input use and capitalization. They predominate in North America, parts of Latin America, Europe and Australasia. The value chains are highly agglomerated to handle bulk commodities through relatively few intermediaries that diminish somewhat the sensitivity to consumers.
2. High value: Systems producing value products such as coffee, cacao, quality meat and dairy products for urban markets. These systems respond to specific demands of consumers and handle small or moderate quantities of product through well-defined value chains. Such chains can change rapidly to meet consumer preference or specific value opportunity. Production tends to be

restricted to suitable production areas distributed throughout the world, rather than the extensive regions observed for bulk commodities.

3. Subsistence: Systems in which production is predominantly used to support the needs of farmers, with uncertain or insignificant production capacity for markets. Such systems predominate in large areas within lower and middle income countries in which agriculture still accounts for a large proportion of GDP (Byerlee et al. 2007). While development and market opportunities can shift people out of subsistence agriculture quickly, even here, many people may be left behind (Byerlee et al. 2007). Farmers are often highly vulnerable to risk, input use if often minimal (Dixon et al. 2001; Kemp-Benedict et al. 2011).
4. Nature-based: Systems which provide environmental services, through carbon, water or biodiversity. These are seen as increasingly important to the resilience and sustainability of global food systems (World Bank 2020; UNEP 2021; Costanza et al. 2017; Rockström et al. 2020). The focus in these systems is the balance between production natural and human capital (UNEP 2018).

What are the scenarios for digital agriculture in these four types of food systems?

Commodity systems

For systems dominated by commodities most change is expected in the production domains. The major goals are to increase increasing efficiency of input use, including fertilizer, labour, agrochemicals and germplasm. Highly mechanized production systems provide platforms on which to embed digital technology to monitor outputs (yields) inputs (variable applications) and performance.

Demands for plant and animal protection provide opportunities for patented chemicals and germplasm (including GMOs) that embed digital technology in advanced research and production techniques.

In addition to moves to increase production efficiencies for bulk producers, digital grain trading will provide opportunities for some diversity of supply chains to specialist commodities. But incumbents within value chains seem likely to benefit most from digital technologies as they use it to manipulate logistics between closely monitored production and demand.

For Food Systems characterized by High Value Chains

Images of digital agriculture often show lettuces, tomatoes or similar high value chains that clearly demand the use of digital technology for ultra precise control - and have done so for decades. The most emblematic examples are vertical production systems, which are clearly high value, low volume systems to supply specific urban consumers. But there are many other examples that exemplify the use of data technologies to connect producers with specific consumers, such as Cropster.org, which connects coffee consumers with roasters and producers to preserve value through product tracing. About half of the Digital Agriculture investments recorded by the annual AgFunder reports (e.g.. (Burwood-Taylor et al. 2021)) are oriented towards consumers.

The types of agtech they deploy include data acquisition, modelling and analysis; product certification and tracing. Some high profile start-ups also use social media to communicate with clients and intermediaries.

These applications tend to be more agile. Opportunities for disruption are greater in this type of food system, since economies of scale are less powerful where product and consumer diversity is greater.

Digital Agriculture in Subsistence Food Systems

The World Bank and CGIAR have substantial expectations of the power of Digital Agriculture to support development on behalf of the world's poorest (World Bank 2021; CGIAR, n.d.). Subsistence agriculture is understood to provide basic human requirements as a pre-requisite for development of market productivity, opportunities for Digital Agriculture in subsistence agriculture focus on support for food security and protection of capitals for livelihood support. While some high profile applications of Digital Agriculture indicate an important move towards markets, the much greater challenge remains for Digital Agriculture to support smallholder productivity. Examples do so through applications to manage climate risk (e.g. data-rich financial instruments (Amarnath, Malik, and Taron 2021; Nieto et al. 2012; Hazell, Pomareda, and Valdés 1986; World Business Council for Sustainable Development 2021), fertilizer input (Webb et al. 2011) seed selection or crop protection ("AgTech Accelerator Formed by Bayer, Syngenta, Other Investors" 2016).

Data, data modelling and comms networking are the major agtech contributions. Substantial weight of expectations are loaded on mobile phone networks to support change, even though network coverage remains patchy and smartphone ownership even more so.

The value from Digital Agriculture is expected largely from improvements in risk management – for farmers and suppliers, access to markets, access to credit and financial services and farmer-to-farmer networking. The World Bank and others anticipate the process to be highly disruptive, with many start-ups anticipated where conventional businesses have failed to invest.

NBS

The final type of food system we discuss is one in which nature based solutions (NBS) are emerging with the support of digital agtech. Such systems are described as "agriculture to deliver nutrition for people worldwide while restoring nature and the climate" (Miralles-Wilhelm 2021). While the areas dedicated to NBS are currently modest, we include them because such areas are likely to increase as people wake up to the urgent need to re-invest in natural capital, even while pursuing goals of food and income security.

A role for Digital Agriculture technology in such systems includes monitoring change of land use and soil condition over large areas using remote sensing or proximal soil measurement and the use of such data to support valuation of ecosystem services.

Such processes are likely to rely on existing financial institutions to scale up, so the acquisition of IP is likely to be cumulative. Data and modelling technologies will also support regulation and governance at national or global scales. .

	Loci for change	Main agtech class	Value propostion	Predominant BM type
C	Production	D, C,	Increased productivity	Cumulative
HV	Market	D, C, M, N	Increased value	Disruptive

	Processing		per unit	
Sub	Production Capitals	D, M, N	Reduced risks Market access	Disruptive
NBS	Natural and human capitals	D, M	Natural capital growth	Cumulative

Table 1 Summary of characteristics of adoption pathways in four types of food system.

Role of Science to Support Adoption of Digital Agriculture Technologies

Finally, what is the role for science and research to support the growth and use of diital technologies in agriculture? We ask this because – if our experience of precision agriculture is repeated – some of the most capable scientists, who also happen to be the most deeply embedded in existing scientific paradigms, will struggle to adapt to the new opportunities offered by digital agriculture. Conversely, we take issue with those from the data sciences, who discount what conventional science, especially that grown from field experience, has to offer Digital Agriculture. We propose that advance occurs in the space between three disciplines: data sciences; social sciences and agricultural sciences, according to the following general 'rules':

- Data sciences offer unparalleled depth, breadth and precision of observations to agriculture, and the capability to control processes as never before.
- Social sciences explain how the human systems around the technology organize and adapt in order to acquire sustainable and inclusive change within food systems
- Agriculture sciences provide knowledge of the biological processes within food systems that determine its performance in an uncertain and changing world.

We suggest that for scientists to contribute substantially to the development of Digital Agriculture, they must explore the linkages between at least two of these domains.

Summary

Digital Agriculture is exciting investors and scientists who see the massive scope for improvement of food systems through digital technologies. It is also disappointing some, because the adoption pathways are rarely clear or progressive and many are new to experienced scientists.

We explore possible adoption characteristics for Digital Agriculture within four contrasting types of food systems to illustrate the diversity of change that is likely to occur globally and suggest that for many scientists, the change will demand inter-disciplinary exploration that will place many outside their comfort zone.

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