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Current status of and future opportunities for digital agriculture in Australia

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ABSTRACT

In Australia, digital agriculture is considered immature and its adoption *ad hoc*, despite a relatively advanced technology innovation sector. In this review, we focus on the technical, governance and social factors of digital adoption that have created a disconnect between technology development and the end user community (farmers and their advisors). Using examples that reflect both successes and barriers in Australian agriculture, we first explore the current enabling technologies and processes, and then we highlight some of the key socio-technical factors that explain why digital agriculture is immature and *ad hoc*. Pronounced issues include fragmentation of the innovation system (and digital tools), and a lack of enabling legislation and policy to support technology deployment. To overcome such issues and increase adoption, clear value propositions for change are necessary. These value propositions are influenced by the perceptions and aspirations of individuals, the delivery of digitally-enabled processes and the supporting legislative, policy and educational structures, better use/conversion of data generated through technology applications to knowledge for supporting decision making, and the suitability of the technology. Agronomists and early adopter farmers will play a significant role in closing the technology-end user gap, and will need support and training from technology service providers, government bodies and peer-networks. Ultimately, practice change will only be achieved through mutual understanding, ownership and trust. This will occur when farmers and their advisors are an integral part of the entire digital innovation system.

Keywords: agricultural data, data analytics, digital literacy, digital maturity, internet of things, interoperability, precision agriculture, remote sensing, robotics, sensors.

Introduction

It is well known that agriculture faces enormous challenges now and in the future with the need to feed a rapidly-growing global human population at a time of declining arable land, water and soil resources caused by ongoing environmental degradation and climate change (Schneider *et al.* 2011; Rockström *et al.* 2017). Global human population projections of nearly 10 billion people by 2050 will require a 70% increase in food production (Kopittke *et al.* 2019). To meet this rapidly-growing demand for food will require the sustainable intensification of agriculture (Rockström *et al.* 2017) including improving crop yields, increasing agricultural production in developing countries, improving food distribution and reducing waste (Ray *et al.* 2013; Shepherd *et al.* 2020). Digital agriculture is promoted as the fourth agricultural revolution and has the potential to meet future food requirements, but is not without limitations (Barrett and Rose 2020).

Australian farmers have a reputation for innovation and use of technology (Lowenberg-DeBoer and Erickson 2019). Digital agricultural innovations are deployed in some form or another across the whole agricultural sector and some notable innovations have originated from Australia, for example, application of soil moisture sensors, grape yield monitoring and grain protein mapping (Lamb *et al.* 2008). Yet the overarching state of digital agriculture in Australia is considered immature and adoption *ad hoc* (Baker *et al.* 2017).

Digital maturity can be viewed as a process that converts manual tasks to digital by way of digitisation of data, digitalisation of process and ultimately, digital transformation (Savić 2019). Many players in the Australian agri-food value chain use digitised data by way of platforms (e.g. software applications and online decision-support tools), but few have evolved to digitalisation of process, let alone digital transformation (Skinner *et al.* 2017).

Australia agriculture has some notable differences to other countries in terms of farm management, government priorities, the policy environment and the climate. Dominated by family farming businesses, Australian farmers tend to be the decision-makers in a farming enterprise but often rely on advisors who are private operators (Llewellyn and Ouzman 2014). The Australian agricultural workforce is an 'aging demographic' relative to the general workforce (Binks *et al.* 2018), while employment costs are high compared to other countries (https://worldpopulationreview.com/country-rankings/minimum-wage-by-country). Australian agriculture operates on commercial principles with minimal financial intervention from government and is dominated by commodity production for an export market (Perrett *et al.* 2017). Generally, farm size and enterprise scale are large and human resources per hectare low, a product of the positive relationship between farm size and profitability (Sheng and Chancellor 2019). Farm and enterprise size reflects Australia's geographical and geological uniqueness as the oldest, flattest and driest permanently inhabited continent on earth, with a principal land mass of 7.69m km^2 and a wide range of climate zones including tropical, arid, temperate and alpine (Beck *et al.* 2018). Approximately 55% of Australia's landmass is used for agricultural production, with the gross value of agricultural, fisheries and forestry production increasing to AU$67billion GDP in 2019–20 (ABARES 2021) including the dominant industries of red meat (cattle and sheep), arable crops and horticulture. Australian agriculture, fisheries and forestry sector aims to achieve AU$100billion in annual farm gate output by 2030 (DAWE 2020) and embracing digital agriculture could contribute approximately AU$20.3 billion each year (Perrett *et al.* 2017). However, achieving this uplift requires work to deliver the value proposition of digital agriculture specific to Australian requirements (Baker *et al.* 2017).

Review process and objectives

Here we provide a narrative about the state of digital agriculture in Australia from the perspective of increasing digital maturity in Australia. This review is not intended to be exhaustive and there are others that have comprehensively reviewed a range of technical and social topics (e.g. Kamilaris *et al.* 2017; Tzounis *et al.* 2017; Wolfert *et al.* 2017; Bahlo *et al.* 2019; Kirkegaard 2019; Klerkx *et al.* 2019; Fielke *et al.* 2020; Shepherd *et al.* 2020; Cook *et al.* 2021; Durrant *et al.* 2021). Instead, we approach the topic from the viewpoint of the hallmarks of increasing digital maturity (converting manual to digital) and provide insights into bridging the gap between the technology providers and end users (farmers and their advisors). We used an unstructured review process, starting with the peer-review and grey literature we had from previous research, and guided by keyword searches of literature ('Australia', 'digital agriculture', 'digital adoption', 'digital maturity') in various search engines, and a 'snowball' approach to obtain further literature. We combined our review of peer-review and grey literature with Australian examples collated from the authors' collective knowledge and experience. We used this information to provide an overview of three interlinked concepts that influence digital adoption and how they combine to provide value: (1) enabling technologies and processes (and their value); (2) governance, and (3) the people. On this basis, we explore some key factors that will help improve the value proposition for digital adoption. We conclude by providing commentary on the roles of agronomists, early adopter farmers and government organisations in enabling technology-mediated change.

Overview of enabling technologies, processes and their value

There is a broad range of enabling technologies currently available to the agriculture sector (Table 1) and each type demands a range of competencies and skills, underpinned by both formal and informal learning. Together these technologies can support efficient and sustainable farm management and create value for customers, supply chains and the broader community through data and information sharing. The following section provides an overview of some of the key enabling technologies that have experienced widespread development and deployment in Australia via the research and commercial sectors.

Proximal sensors, robots and the internet of things

Sensing technologies and robots are underpinned by cyber-physical systems (CPS) and the Internet of Things (IoT), which are essentially equivalent (Greer *et al.* 2019). Connecting sensing devices through the Internet (i.e. IoT) allows multi-directional sharing of data, analytics, insights and applications across the network (Elijah *et al.* 2018; Zhou *et al.* 2021).

Australian CPS development and deployment research has focused on grain, tree crops, wine grapes and sugar, from the perspective of weed, pest and disease management, water use efficiency and yield forecasting (for example: Anderson *et al.* 2018; Wang *et al.* 2018; Brinkhoff and Robson 2021). IoT soil moisture sensing plays an important role in monitoring spatio-temporal variability in soil water availability, particularly where water limitation is a greater constraint

Table 1. Enabling technologies and processes for digital agriculture (modified from Van Es and Woodard 2017), and their potential benefits and adverse impacts (which can lead to the creation of, or are themselves barriers to digital agriculture) in Australia.

Enabling technology or process	General benefits/value	General barriers, adverse impacts or risks	Examples of benefits/value for Australian agriculture	Examples of adverse impacts or risks for Australian agriculture
Computational decision-support tools	Use data to develop recommendations for management and optimise farm tasks	Expertise required for development of maps and interpretation of results. Lack of baseline data	More efficient use of resources like water, as water limitation is a major challenge for Australian farms, particularly for sustainable agriculture (and social licence) in places like the Murray–Darling Basin. In Great Barrier Reef catchments, optimisation of nitrogen application (e.g. Thorburn *et al.* 2019) can support participation in incentive schemes as well as help reduce costs to farms and nutrient runoff into waterways Precision application of fertiliser using spatial data, autosteer and rate controllers can support input and fuel use efficiency e.g. in cropping and sugar cane industries (Bramley and Ouzman 2019 and Bramley *et al.* 2019)	Fragmentation/lack of interoperability of tools and systems due to prevalence of single use-case solutions over platforms (Nolet 2018) Better tailoring of tools and systems for mixed enterprises, which are common (ABARES 2021) Barriers to adoption of precision application of fertiliser including technical issues with equipment and software and the incompatibility of equipment with existing farm operations (Robertson *et al.* 2012)
The cloud	Provide efficient, inexpensive, and centralised data storage, computation, and communication to support farm management	Access to essential information may be prevented due to network connectivity Proprietary systems may lock users in even when systems are no longer fit-for-purpose, i.e. technical debt	PairTree provides a universal dashboard by accessing data through the cloud (with data privacy controls), facilitating effective use of multiple tools/services through centralising coverage data from several devices and facilitating data comparison and analysis (Marshall *et al.* 2021), which is useful in Australia where integrated/platform solutions are still lacking (Nolet 2018)	Reliance on cloud-based systems across remote farm networks is an issue due to poor and unreliable network connectivity (Lamb 2017), and can disrupt fundamental business management across multiple farming enterprises
Data analytics (including AI and ML) and cyber security	Information processing that converts raw data to a form suitable for decision making (underpins many technologies in digital agriculture)	Collecting data for the sake of data	Ability to obtain insights from broader sources of information, e.g. through aggregation of complementary datasets for remote-sensed pasture biomass estimation. This may be especially valuable in Australian dairy where forage can account for more than 50% of costs (Gargiulo *et al.* 2020)	Sensor error leading to inappropriate irrigation schedules, which has implications for soil and crop health. Water rights are also a significant cost and social licence issue in Australia
	Ensure data integrity at the source and negate the capability of nefarious actors to impact the digital agriculture system	Privacy and trust concerns especially around data sharing	Machine learning for cattle identification (Mahmud *et al.* 2021), which can benefit large-scale farms and/or those with relatively few workers	
Digital communication tools (wireless, wired and low	Allow frequent, real-time communication between farm resources, workers, managers, and computational resources in support of management	Exacerbated social divides and power imbalances between digital users and digital illiterates	Cost-effective and/or enhanced knowledge exchange and learning, particularly where location of people and plant is remote (e.g. Mushtaq *et al.* 2017)	Poor network connectivity in Australia presents major barriers to digital tools (including IoT deployment) (Lamb 2017)

(*Continued on next page*)

Table 1. (*Continued*).

Enabling technology or process	General benefits/value	General barriers, adverse impacts or risks	Examples of benefits/value for Australian agriculture	Examples of adverse impacts or risks for Australian agriculture
power wide area networks)		Poor network quality	Remote monitoring of water infrastructure and availability for livestock in large pastoral systems (e.g. farmbot.com.au) with benefits including reduced labour and fuel costs and improved OHS	
Distributed ledger systems	Demonstrating provenance of food through the supply chain	Increased cyber-security risks	Integrated provenance, blockchain security and payments platform for premium products e.g. Australian beef (BeefLedger 2021) Compliance with global food safety initiatives e.g. Safe Quality Food programs (Freshcare 2021), which supports access to export markets	Barriers from lack of digitisation and digital infrastructure e.g. connectivity is required to automatically capture and enter data for distributed ledger systems (DISER 2020)
Internet of things (IoT)/sensors	Collects and integrates data and information through a network of devices. connected to the internet. Gather information on the functioning of equipment and farm resources to support management decisions	Lack of technical guidance and support to undertake operations relying on digital technology including installation and maintenance	IoT and sensors can be deployed as part of cyber-physical systems for frost monitoring (Zhou *et al.* 2020), which can support crop production in regions of southern Australian where frost season length has increased (Crimp *et al.* 2016)	Sensor malfunction caused by susceptibilities to physical and environmental challenges from remote deployments and extreme environmental conditions. This can be exacerbated when technology providers adopt fragile commodity technology (not originally destined for agricultural applications)
			Tracking livestock health and condition through animal GPS-enabled sensors in intensive livestock operations or in remote areas e.g. accelerometers for remote detection of bovine ephemeral fever (Tobin *et al.* 2020)	Inadvertent animal welfare problems e.g. reliance of devices that removes human observation/judgement element
Remote sensing	Acquires information at a distance, complements manual data collection and proximal sensing	Resolution and accuracy of remote-sensed data and predictions not reliable or useful at a farm or paddock scale	Yield estimation/prediction using satellite remote-sensed data e.g. to support harvest/orchard management and forward selling for avocados and macadamias (Robson *et al.* 2017), or feed budgeting and setting stocking rates for pasture biomass (Crabbe *et al.* 2019)	Satellite coverage and image resolution are poor in some remote areas Remote sensing using UAVs may be limited by airspace regulation, weather conditions etc. Visual line-of-sight requirements limit UAV use over large areas
Robots (fully and semi-autonomous)	Implement tasks with efficiency and minimal human labour	Inadvertent animal welfare problems, e.g. reliance on robotic interactions with animals that removes the human observation element	Robots (e.g. SwarmFarm) can be used to manage resistant weeds and reduce reliance on chemical control (Ball *et al.* 2017)	Large fleets of robots may become expensive and/or time-consuming to monitor/control/maintain
	Reduction of human errors and OHS risks – use of AI and ML to reduce repetitive tasks. Use of drones and robots to work in dangerous situations, e.g. steep embankments, silos	Loss of farming skills, intuition and farming knowledge normally derived from interaction with farming elements, learning by doing	Reduced reliance on and cost of labour	Robots need to be integrated with the rest of the farm systems and connectivity will remain important

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Table 1. (*Continued*).

Enabling technology or process	General benefits/value	General barriers, adverse impacts or risks	Examples of benefits/value for Australian agriculture	Examples of adverse impacts or risks for Australian agriculture
		Loss of local community and rural cultural fabric caused by job losses through automation		Potential for negative impacts on fragile soils and/or biodiversity, unless explicitly considered during design and testing.

Table compiled based on references consulted for literature review.
AI, artificial intelligence; IoT, internet of things; OHS, occupational health and safety; UAV, unmanned aerial vehicles; ML, machine learning.

than nutrient management (https://smarterirrigation.com.au/). IoT-enabled horticultural production includes systems that can detect and identify fruit fly in real time (Moraes *et al.* 2019) and measure the effectiveness of precision application of insecticide (e.g. RapidAIM 2021).

IoT and sensor applications in livestock are dominated by tracking, control and animal health monitoring (Farooq *et al.* 2019; Chang *et al.* 2022), which have particular value for geographically large pastoral systems (Bahlo *et al.* 2019). In the dairy sector, digital deployment is characterised by technologies such as rotary automatic milking systems developed to meet the specific needs of Australian milk harvesting (https://futuredairy.com.au/publications/).

Autonomous harvesting and crop manipulation robots could significantly reduce reliance on and the cost of manual labour and improve overall efficiency (Lowenberg-deBoer *et al.* 2020). Lowenberg-deBoer *et al.* (2020) note that there is a scarcity of research on the economics of robotics technologies, when use of robotics is likely to improve the consistency and resilience of Australian supply chains, which have been notably disrupted by COVID19-related labour shortages (Bulgari *et al.* 2021). Outside the dairy industry, on-farm robotics have focused on broadacre grain and horticultural crops specifically for chemical application, weeding and harvesting (e.g. Sukkarieh 2016; https://www.swarmfarm.com/applications/).

Despite Australia being an early leader in the development and adoption of precision agriculture (Bramley and Trengove 2013), limitations of connectivity technology both across and between farms has hampered widespread uptake of IoT. Many remote farming enterprises must rely on satellite solutions which offer inferior data allowances and speeds, or pay to install their own infrastructure (Lamb 2017). Several state governments have been investing in a range of initiatives aimed at increasing uptake of IoT, for example, New South Wales' Farms of the Future program (NSW Government 2021), Victoria's On-farm IoT trial (State Government of Victoria 2021), Western Australia's eConnected Grainbelt program and IoT DecisionAg grants (Government of Western Australia 2021) and South Australia's AgTech demonstration farms (Government of South Australia 2021).

Remote sensing

The cost of farm field sampling and monitoring can be prohibitive, especially at large scales and in remote locations. Remote sensing is the acquisition of information about an object or phenomenon from a distance and provides an alternative (often cheaper) means of collecting data. Improvements in computing and processing power, the resolution of satellite data and improved access to platforms, such as Cubesats (Akyildiz and Kak 2019) and unmanned aerial vehicles (UAV), have driven increasing popularity of remote sensing methods for production and other land management practices (Scarth *et al.* 2019).

In Australia, digital agriculture has historically been constrained by limited access to, and the useability of, satellite imagery. Organisations such as CSIRO have been working alongside Geoscience Australia to create an Earth Observation Data Hub that will provide 'data cubes' of satellite information for applications in digital agriculture (Lewis *et al.* 2017). Several companies have capitalised on the availability of high spatial and temporal resolution data from Sentinel satellites (ESA 2021) and are at the forefront of commercial remote sensing services, e.g. CiboLabs (CiboLabs 2018).

In the current state, the data collected *via* remote sensing systems are often complemented by proximal sensing systems, such as handheld devices, vehicle mounted devices or even cameras on smartphones (e.g. Trotter 2010). In precision irrigation, for example, there are exciting possibilities of linking satellite information, weather forecasts and crop models with ground-based, spot sensing of crop canopy temperature. This involves static infrared thermometers (wireless IoT devices) giving precise warnings of the need for irrigation over whole farms and the consequences of delay (Bange and Jamali 2018). At the time of writing there was still no remote sensing system that can non-invasively measure soil fertility, biotic stressors in crops nor diagnose animal health.

Data, analytics and information flow

Digital agriculture offers the opportunity to collect data remotely and at a greater resolution in space and time, then integrate, analyse and generate actions from these data in new and improved ways. The pace of monitoring and measurement in digital agriculture is leading to the generation of unprecedented volumes of data, particularly in the private sector. These data require more sophisticated treatment and analyses in order to derive insights for making farming decisions (Wolfert *et al.* 2017). For example, while cropping and horticulture make a substantial contribution to Australian production value (ABARES 2021), crop yield forecasting is challenging due to high production, environmental and climate variability. To address these forecasting challenges, increasingly sophisticated crop modelling approaches are being used to improve certainty for cropping production systems. CSIRO-developed system GrainCAST™ has helped increase the accuracy of near real-time wheat yield predictions (Hochman and Horan 2019). The Agricultural Production Systems sIMulator (APSIM) model (Holzworth *et al.* 2018), also developed by CSIRO and a predominantly Australian team, has seen widespread uptake (APSIM 2021), for example, in tools like Yield Prophet® which provides paddock-scale forecasts (https://www.yieldprophet.com.au/). Remote data collection, analysis and visualisation offers opportunities for new supporting services, but not without the challenges of disruption (Fielke *et al.* 2020).

The volume of data generated in agriculture (and other disciplines) is driving the practice of 'big data analysis' (Kamilaris *et al.* 2017; Newton *et al.* 2020). This is matched by increasing use of artificial intelligence (AI) and machine learning (ML), and many new research programs and companies in digital agriculture seek to utilise these approaches for analysis, prediction and decision making. Sensor/AI based microclimate forecasting systems (Nolet 2018) are expected to drive productivity gains through increasing operational efficiency and optimising resource use (see for example Baker *et al.* 2017; Llewellyn *et al.* 2017). Use of ML regression methods applied to remote sensing data have increased the accuracy of wheat yield gap mapping (Kamir *et al.* 2020). However, despite a growing list of reviews published on the potential or current state of AI in relation to sustainable and/or precision agriculture (e.g. AgriFutures 2016; Peters *et al.* 2020; Linaza *et al.* 2021), there remains a paucity of detail on the use of such capability to support decisions based upon business rules at the farm or operational level. This is an ongoing impediment to actual, and impactful adoption of AI/ML, not only in Australia but worldwide.

The way the industry engages with digital data can be affected by the perceptions of who the end users are (Fleming *et al.* 2018). The implementation of technologies to translate data to decisions is largely the domain of the commercial sector, and agricultural technologies companies and their investors are at the centre of efforts to integrate data sources and scale up analytics to predictive platforms for farmer decision making (Nolet 2018).

The role of Australian AgTech in implementing digital technologies

Agricultural and agri-food technology ('AgTech') companies play an important role in customising enabling technology, developed through research, to digital solutions for producers. As such, AgTech is expected to continue to grow as a domain and support achieving (and surpassing) the $100b target for the sector (Baker *et al.* 2017).

AgTech research is strong in Australia and Australian innovators producing world-leading digital technologies (Hudson and Wood 2017; Nolet 2018). Some of the leading examples are direct from the research sector, like CSIRO (virtual fencing, Cerestag) and the University of Sydney (Australian Centre for Field Robotics), with products and services that have subsequently been commercialised (Campbell *et al.* 2021; Aquilani *et al.* 2022). Other examples come from the corporate and farming sectors (e.g. Farmbot, Pairtree and Farmers2Founders). The Australian Agritech Association (ausagritech.org) and AgTech Finder (agtechfinder.com) are intended to help expose and link the technology industry to end users.

Unlike countries like the United States of America that have invested heavily in AgTech development, Australia lags in investment despite an expanding AgTech industry and a doubling in size of Australia's venture capital market between 2016 and 2017 (Maughan *et al.* 2018; Nolet 2018). This lag reflects a disconnect between the expectations of Australian farmers and technology companies in terms of the perceived value of technology (Nolet 2018). This disconnect has resulted in many AgTech tools being developed without a good understanding of the needs of the next-(advisors) and end-users (farmer), which can differ. This is a significant problem for the Australian AgTech industry with a myriad of digital solutions available that are largely isolated and lack the socio-technical foundations to make them interoperable (Nolet 2018).

The value of digital solutions

The pace of digital innovation and deployment in agriculture is overwhelming. It is clear that some technologies will be greatly beneficial for end users, particularly given the unpredictable nature of climate and markets in Australia. Export market demands, consumer expectations in relation to sustainability and traceability, and COVID-19 pandemic impacts on supply chains and labour all add increasing pressure on Australian food production to improve processes and efficiencies (Snow *et al.* 2021). Digital agriculture is well placed to help address these challenges and even solve some, for example, increased digital maturity in Queensland sugarcane farming has improved water use efficiency as well as making labour and cost savings (Fig. 1). However, digital disruption can have adverse impacts in terms of time, cost,

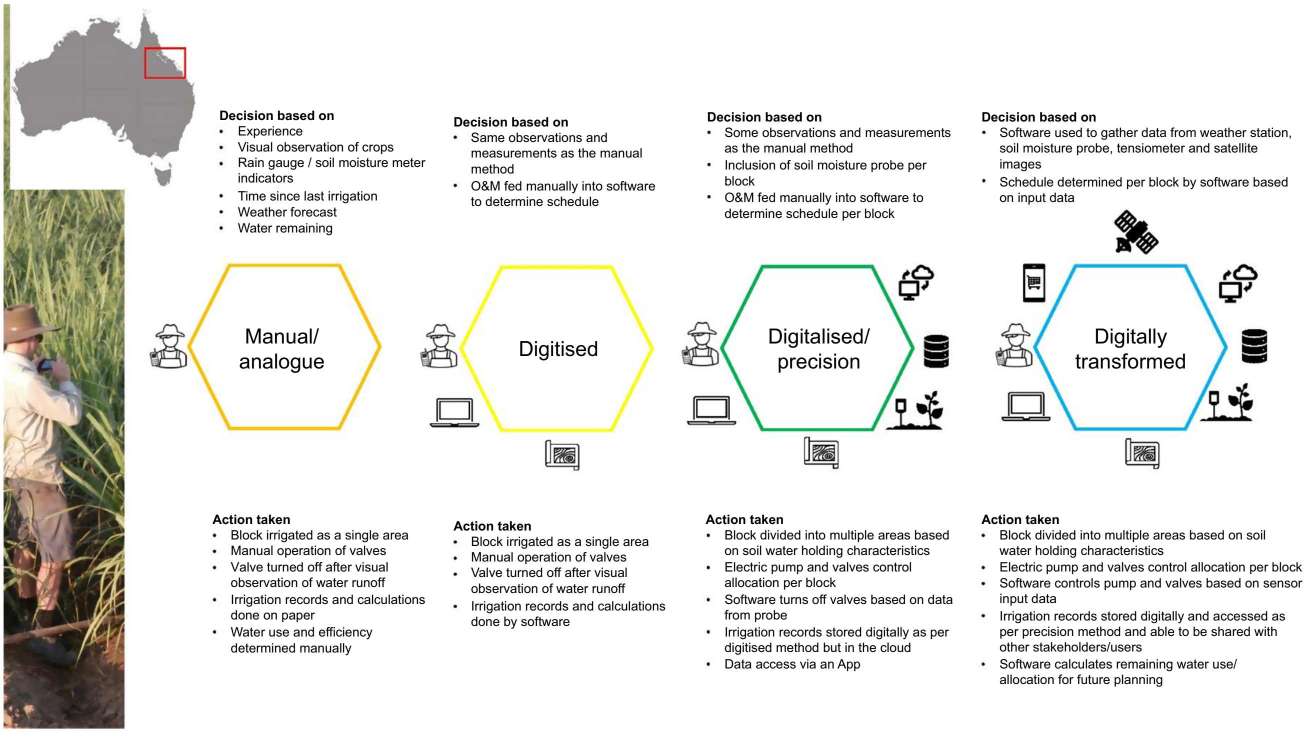

Fig. 1. Conceptualisation of the tasks associated with flood irrigation, relating to the level of digital maturity. This is based on a case study farm on the Burdekin River in Far North Queensland, which was used for sugarcane production. The conversion of the farming operation to an automated furrow irrigation system ultimately resulted in labour savings (farmer time), cost savings (reduced water tariffs), and yield improvements. This presents a strong value proposition for adopting digital transformation in other similar enterprises. Figured created based on material in Leonard (2019) and Wang *et al.* (2019). O&M, operations and maintenance.

technical expertise required, insufficient technical support, trust, inequality and regulatory lags (Fielke *et al.* 2019) (Table 1).

Maturity encapsulates a number of elements: strategic leadership, governance, technology, availability and use of data and the digital capability of users in the agricultural sector (Baker *et al.* 2017). These elements are interrelated such that low maturity in one factor can limit all others; therefore, all elements are considered necessary to influence the value proposition of digital agriculture (Leonard 2022). For example, connectivity is a key enabling technology for digital agriculture. The value of many digital solutions relies on adequate network connectivity and poor connectivity in Australia diminishes the value of deploying sensor networks in remote rural areas. In a survey of 1000 Australian farmers (Lamb 2017), of those who owned sensor networks, more than 75% of them rated their networks as moderately to extremely challenging to maintain. This type of overarching issue will require external drivers such as legislation or consumer demand to address and accelerate digital uptake (Klerkx *et al.* 2019). Where potential adverse impacts outweigh the relative benefit of digital solutions, the case for adoption is likely to be weak.

Governance and people

Governance and legislation

Governance structures and processes are essential for providing certainty in the sector to invest in and adopt digital technologies (Wiseman *et al.* 2019). However, Australia lags in providing appropriate regulation and governance frameworks for the sector, and there is little government guidance for responsible development and deployment of digital innovations (Fielke *et al.* 2019).

Data is a key area for improvement across the sector. In the United States of America, the Department of Agriculture (USDA) facilitates access to a wide range of data and information for entrepreneurs and researchers to develop technologies upon (Keogh and Henry 2016). Australia has instead focused on mechanisms to provide more certainty around data exchange and access via industry bodies, for example, the National Farmers Federation Farm Data Code (NFF 2020*b*) and the *Get Australia Growing* strategy (NFF 2020*c*), but has so far failed to provide appropriate regulatory standards for many parts of the industry. Governance for data ownership, use of robots on public roads and animal welfare approval for virtual fencing all remain at an immature stage, with some issues dealt with differently between states (NSW Farmers 2022). This problem is not peculiar to Australia, for example, regulation in cellular agriculture lags behind technology innovation, which is effectively acting as barrier to developing alternative innovation pathways (Chiles *et al.* 2021). The recent announcement of the Australian Agrifood Data Exchange (www.integritysystems.com.au/ozdata), has been met with mixed responses from the farming sector (www.abc.net.au/news/rural/programs/landline/2022-02-20/data-doubts:-harvesting-big-data-from-farmers/13762796) partly because of the lack of government regulation in relation to consumer data laws and mistrust in how farm data are used (Zhang *et al.* 2021).

People

In Australia, digital maturity and thus, digital adoption in general remains low (Baker *et al.* 2017). Motivation to adopt digital technologies will be limited by the time required to select, and skills to implement, appropriate digital technology (Ayre *et al.* 2019). Trust associated with reliability of technology, and ownership and use of data present additional barriers (Baker *et al.* 2017). Adoption theory is littered with examples of the human elements of innovativeness and social influence helping or hindering adoption. This is specifically true for family farming businesses where utility is found to be a greater driver of change than profit (Leonard 2022). Yet the characteristics of the technology only become relevant once the decision to adopt has commenced as attitude to change and external support for change are most influential (Streuer 2020).

Establishing robust measures of agricultural adoption is limited by a lack of comprehensive models (Montes de Oca Munguia *et al.* 2021). Of those that exist the ADOPT model (Kuehne *et al.* 2017) is highly regarded in Australia as it considers the individual's attitude to a new technology in relation to an established or incumbent technology. However, the ADOPT model is weak when measuring attitude to the use of data. As data use is pivotal to the use of technologies, the ADOPT model fails to distinguish between the uptake of a precision versus a digital technology. Beyond the quantitative approach offered by the ADOPT model, there are few studies that have quantified adoption (but see Zhang et al. 2017; Bramley and Ouzman 2019). Where adoption measures are specified they include examples like greater collection/use of more data types, use of modelling products and software solutions for decision making, the installation and use of sensors and technology infrastructure on farming enterprises, and use of software solutions in irrigation cotton growing (Baker *et al.* 2017; Ayre *et al.* 2019; Cook *et al.* 2021). We consider adoption here in terms of uptake of digital tools by next- and end-users, and generation/use/sharing of data (and by inference, investment from various parts of the sector in shifting to digital solutions over analogue), although we do not attempt to quantify it.

Improving the value proposition for digitial agriculture in Australia

The success of agricultural technology innovation to drive sector-wide change hinges on next- and end-user adoption (Shepherd *et al.* 2020), which in itself depends most strongly on the value proposition presented by the technology and the digital maturity of the sector to engage with technology innovations (Annosi *et al.* 2020; Ball *et al.* 2021). To increase digital maturity will require a range of simultaneous strategies (Kirkegaard 2019), focused primarily on closing the gap between the technology development and end users. At the same time there need to be improvements to supporting legislation and education, knowledge brokering and exchange, conversion of data to decisions, and to the enabling technologies themselves.

Closing the gap: individual perceptions and the suitability of technology

Many digital solutions are immature and not always fit for purpose because of a disconnect between developers and users. Individual users perceive and interact with technology differently and therefore, technology adoption needs to address cognitive, emotional and contextual concerns (Straub 2009). The value proposition is often expressed as a financial benefit. In reality, users adopt when there is a need, and that need is serviced by a technology that is easy to use and provides a cost benefit. Yet, technologies such as mobile phones, internet banking and autosteer primarily offer utility, which may or may not provide a financial return (Leonard 2022). Within family farming businesses digital capability and aspirations can diverge, therefore understanding the demands of all individuals and their potential to influence a business's purchasing and adoption decision is vital to achieve change. The value is tightly entwined with users' personal perceptions, goals and priorities (Leonard 2022).

People, not the technology, are at the heart of digital agriculture adoption, but technology providers tend to focus on promoting the functions and applications of the technology (Leonard 2022). The ongoing failure to unlock the value proposition of digital agriculture is considered to be due to digital solutions being offered at a task level, rather than a process level, and failure to align digital solutions with human influences on adoption (Leonard 2022). Technology developers need to work directly with end users using a co-design process (Ayre *et al.* 2019; Stitzlein *et al.* 2020). This helps reduce the time and cost required to set up and use a new digital practice, builds end user confidence in the technology and their skills to operate it, and establishes systems to place full control of the data with the end users (Streuer 2020). To support on-farm digital change, co-design approaches need to bring together all members of the family, farm and support team of the business to capitalise on skills and knowledge (Leonard 2022). This will be essential to break down the digital divide and help remove barriers to the communication of clear value propositions (Lamb 2017).

Delivery of supporting legislation and education

A long-term strategy is needed for the Australian agriculture sector that generates confidence in farmers to invest in digital solutions and recognise value in the digital opportunities for the sector (see also Fielke *et al.* 2019). High priorities for national legislation are the creation of regulations around farmer data rights, the use of robotics and animal welfare implications of remote management methods, e.g. virtual fencing and sensors for health monitoring. New and existing regulations require improved enforcement and compliance monitoring (e.g. drones; Commonwealth of Australia 2020). Furthermore, differences between state legislation need to be reconciled with stronger leadership from the Australian national government (a problem which plagues other sectors, e.g. environmental legislation: Hamman *et al.* 2021).

Stronger oversight of the agricultural knowledge and advice network, which is mostly privatised and lacks regulation, is required (Fleming *et al.* 2021). There is a crucial need for developing skills and knowledge in end users to engage with data and available digital platforms. Policy-driven education and skills training play a role in meeting this need and should be supported and expanded, for example, through government initiatives like AgSkilled 2.0 which is being rolled out by the NSW State Government. TAFE/University courses, advisor accreditation and in-person training programs are recommended as mechanisms to address awareness and knowledge gaps in the sector (NFF 2020*a*). Government policy guidance on responsible digital agricultural innovations for the sector is also needed (Ayre *et al.* 2019; Fielke *et al.* 2019), and could be linked to and used in conjunction with commercial solutions like digital directories (e.g. AgTech Finder).

Knowledge brokering/exchange

Knowledge and advice networks will be essential to diffusing digital innovations across the sector (Ayre *et al.* 2019; Fielke *et al.* 2020). This centres around several approaches: workforce integrated learning and training, building and supporting social networks, smart farm demonstrations, and well-evidenced case studies. Government and corporate organisations need to support the creation of a workforce of digital agriculture professionals with relevant domain expertise, and support social agricultural networks for knowledge exchange and upskilling, for example, grower groups like North Australia Beef Research Council and Birchip Cropping Group (e.g. Anil *et al.* 2015). Social networks will help lift the capabilities of people of all genders in businesses, as they may activate practice change in different ways (e.g. in livestock production rural women use most components of technology three times more often than men: Hay and Pearce 2014). Social networks will also help facilitate participatory technology design (Stitzlein *et al.* 2020). Building and supporting citizen science initiatives provides an alternative and under-utilised avenue, not only for collecting data, but also for encouraging knowledge exchange between different stakeholders across the value chain (e.g. Ryan *et al.* 2018). Strengthening linkages between farmers, agronomists and knowledge providers (Rijswijk *et al.* 2019) and the promotion of key influencers, opinion leaders and experienced farm advisors creates an information rich environment, which will help sustain and expand farming networks.

Farmers generally prioritise learning from their peers and in-person events (NFF 2020*a*). Given that many farmers prefer to be provided with practical facts in a logical sequence rather than lots of information (Nicholson *et al.* 2015), field days, demonstration and smart farms play an important role in increasing farmer awareness, knowledge and skills, and exposing the economic value propositions through well-evidenced use of technology (Ayre *et al.* 2019). Demonstration farms help test and de-risk the practical implementation of new agriculture technology for farmers, as they can learn from others' mistakes and understand the return on investment.

Better data, access and interoperability of digital systems

Access to, and custodianship of data is both a barrier and enabler of digital adoption (and farming productivity more generally: NFF 2020*a*). A fundamental issue for digital agriculture is whether the necessary data exist and are fit-for-purpose, and how to access these data to inform and improve decision making (Darnell *et al.* 2018; Durrant *et al.* 2021). All elements of data (standards, storage, exchange, security and conversion to information products) need to be aligned to build confidence in stakeholders and end users to engage in digital agriculture (Bahlo *et al.* 2019). Early steps to achieve this are development of policies for data use (nff.org.au/programs/australian-farm-data-code and www.farmdatacode.org.nz) and autonomous machinery (Grain Producers Australia (GPA), Tractor and Machinery Association (TMA) and the Society of Precision Agriculture Australia (SPAA) 2021).

Data sharing practices that aim for greater interoperability of data systems with clear governance and stewardship arrangements should be the focus for future development of the agricultural data sector (Box *et al.* 2015). Open data exchange systems, data cooperatives and data trusts will need to have technical and legal mechanisms to ensure the data provider (farmer or other party) retains full control of access to their data, regardless of where those data are hosted (Box *et al.* 2015; Jouanjean *et al.* 2020; Agricultural

Research Federation 2021; Durrant *et al*. 2021). Data supply chain infrastructure should be underpinned by semantic and syntactic web technologies, distributed ledger technologies, and privacy preserving technologies (Durrant *et al*. 2021), with dataset access linked to electronic licences, smart contracts and data sharing agreements. Even greater certainty for data custodians is provided *via* analytical processes and systems that do not require local copies of data (e.g. federated learning: Zhou *et al*. 2021). Deployment of multi-stakeholder cooperative models (e.g. Cultured Meat Modelling Consortium for cellular agriculture innovation: Chiles *et al*. 2021) would have multiple benefits in terms of addressing data control and privacy concerns of custodians, but also brokering knowledge and advice on appropriate application of digital innovations.

Across all sectors there is increasing recognition that data should be FAIR: Findable, Accessible, Interoperable and Reusable, in order to increase efficiencies in conversion of data to knowledge for end users (Wilkinson *et al*. 2016). This is an ambitious but necessary goal for the agri-foods sector to maximise value from vast quantities of (often) disparate data being collected (Darnell *et al*. 2018) and ensure data are analysis-ready. Without better access to fit-for-purpose data and the insights from data to inform farming decision making, it will be very difficult to demonstrate the value proposition for agricultural data sharing between many actors.

Improvements to enabling technologies

One fundamental reason for using technology in agriculture (e.g. IoT) is to sense or collect information about phenomena in an attempt to create a deeper understanding of the full agricultural system. Doing so aims to move away from reactive responses/systems and toward proactive, predictive and prescriptive systems for supporting decision making (Zhou *et al*. 2021). Therefore, improving the design of cyber-physical systems (CPS) and the underlying sensing technology that generate data will be necessary to help farmers achieve efficiencies and production growth at scale. Developing and deploying new sensing technologies and CPS suitable for Australian agriculture, particularly large-scale farms with remote connectivity (Jawad *et al*. 2017), will need to focus on solutions for power, sensing, connectivity and security.

New power-related technologies that will enhance existing sensor usage and enable new uses include hybrid energy storage (Ongaro *et al*. 2012), ambient energy scavenging (Kim *et al*. 2014) and simultaneous wireless information and power transfer (SWIPT) (Zhang and Ho 2013). Conversion of freely available ambient radio frequency (RF) energy (e.g. solar, wind, thermal) to electricity offers a novel and sustainable approach for recharging super capacitors (Collado and Georgiadis 2013). This can be achieved by combining antennas and rectifying circuits to create a rectifying antenna (rectenna), which harvest RF energy from a focused beam (wireless power transfer) and ambient energy sources (Shariati *et al*. 2015). This is a matter of paramount importance for autonomous systems in remote or climatically-harsh areas where accessibility for servicing and data retrieval is a problem. Ultimately, this technique can introduce more robust and trusted autonomous monitoring systems (Shariati *et al*. 2015; Keshavarz and Shariati 2021) than otherwise possible.

Enhancement of sensing technology will require research into metamaterial-based and multi-band-based RF sensing technology, synthetic and indirect sensing and calibration (Amiri *et al*. 2020). The fundamental need to get data from sensors and where those data are destined, which is typically the cloud, ultimately requires internet connectivity. From a technology improvement perspective, advanced antenna design can lower the cost and enhance long range communication while enabling greater system integration beyond the use of off-the-shelf antenna technology. As systems supported by IoT technologies present several attack vectors e.g. biosecurity, data security, and cyber-physical system security (sensing and actuation), these vectors need to be addressed and continually negated to not only protect economic success but to ensure 'Brand Australia' safety (Zhou *et al*. 2021).

Closing remarks

Increasing digital maturity and adoption in Australian agriculture heavily relies on the knowledge brokering role of agronomists and early adopters, supported by industry organisations that are themselves supported by government (e.g. Agrifutures, National Farmers Federation), rather than directly by government. Agronomists are generally in a better position to invest time in understanding how the technology works and the value proposition it will provide, as it will help improve their existing client service. Agronomists are seen as trusted, key actors, in educating the broader farming community on digital maturity and adoption. Therefore, despite the current trend of corporate-level digital transformation, in order to get grass-roots traction in Australia, knowledge transfer remains critical, and digital systems and tools need to provide personalised advice and come with ongoing technical support to agronomists and farm management consultants. Ultimately, practice change will only be achieved when researchers, technology developers and suppliers, farmers and their advisors collaborate across the entire digital innovation system.

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