This is an accepted manuscript of an article published by Taylor & Francis in International Journal of Agricultural Sustainability on 3/7/2021 available online at http://www.tandfonline.com/10.1080/14735903.2021.1937881

Embedding digital agriculture into sustainable Australian food systems: Pathways and pitfalls to value creation

Authors
Simon Cook1*,
Elizabeth L. Jackson2,
Myles J. Fisher3 (In Memoriam),
Derek Baker4 and
Dean Diepeveen1,5

Author affiliations
[1] School of Veterinary and Life Sciences, Murdoch University, Murdoch, Western Australia 6150. Australia.
[2] School of Management & Marketing, Curtin University, Bentley, Western Australia 6102. Australia.
[3] Centro Internacional de Agricultura Tropical, Cali. Colombia
[4] University of New England Centre for Agribusiness, UNE Business School, UNE, Armidale, NSW 2351. Australia.
[5] DPIRD, South Perth, Western Australia 6151. Australia

*Corresponding author.
Email: simon.cook.ag@gmail.com ORCID: 0000-0003-0902-1476

Acknowledgments
This work was supported by the Western Australia Fellowship for Agriculture and Food. The Fellowship was the centre piece of the Science and Agribusiness Connect initiative, made possible by the State Government's Royalties for Regions program. Myles Fisher's input was supported by funding from the Food Agility CRC.

Declaration of interest
The authors declare that they have no conflict of interest.

Authors contributions.
SC, ELJ, DB and DD wrote the manuscript, MJF reviewed and edited the submission.

Abstract

Digital agriculture is exciting attention because of an expectation that food systems will be disrupted by new digital technologies through improvements in precision, efficiency, volume, speed of process or identity of product. This is against the background of the drive for sustainability in food systems.

A diversity of technology applications is unilaterally emerging in all food chains with benefits realized through human acceptance and adoption in business processes.

This paper focuses on Australia but the lessons apply to digital agriculture globally. We propose that sustainable food systems frameworks identify the relation of individual changes to broader systemic change, to relate individual changes to one another and to understand how multiple changes within a system can trigger major shifts in entire agri-food chains. With this rapidly-changing landscape in mind, we argue that food system frameworks cover five domains: production, market, capitals, governance and data technologies.

We analyse experience from agricultural systems, compare it to digitization in non-agricultural systems and conclude that change will be both disruptive and cumulative. We consider the role of systems governance to be under-reported. Governance will prove critical in areas of IP legislation, policy harmonization and targeted investment.

1 Introduction

1.1 The introduction of digital technology to agriculture and food systems

Digital technology is influencing all aspects of economic and social life (Trendov et al., 2019a). The widespread adoption of digital technologies such as smartphones, the internet-of-things and cloud-based technologies has changed everyday life for rich and poor alike. Disruptors in the digital context, such as the iPhone, Uber, and AirBnB, are examples of changes that are happening or will soon occur in all sectors of the global economy. We therefore subscribe to the following definition of digital disruption (Skog et al., 2018: 432): "The rapidly unfolding processes through which digital innovation comes to fundamentally alter historically sustainable logics for value creation and capture by unbundling and recombining linkages among resources or generating new ones." Digital transformation as a goal, and as a process, has been variously defined as the incorporation and uptake of digital technologies. It also includes the reorganisation of firms and their business models to take best advantage of digital technologies while networking within value chains and the broader society (Bowersox et al., 2005).

Digital agriculture has been defined as "the use of detailed digital information to guide decisions along the agricultural value chain" (Shepherd et al., 2020: 5084). The proportion of management processes in agriculture that are digital is the lowest amongst all sectors in both the US and the Australian economies (Blackburn et al., 2017; Manyika et al., 2015; Trendov et al., 2019b). While we note that their methods may underestimate the degree of digitization currently present through technologies embedded in germplasm, farm machinery or agrochemicals, these authors imply an almost inevitable growth of digital agriculture merely through the opportunity to catch up. Globally, there are high hopes that digital technology will bring deep changes in sustainable agriculture through demand (Government Office of Science, 2011), although the changes are mostly yet to happen. Nevertheless, the rapidly changing parts of the agri-food supply frameworks attract investment by venture capitalists (Burwood-Taylor et al., 2020, 2021). As yet, the investment has reached about US$30 billion (in 2020), which is a fraction of the global value of food chains of over US$3 trillion. Commentators anticipate roles for digitally-empowered food systems to address challenges of future food security in the face of increasing population, while maintaining a plethora of factors like food quality, environmental sustainability, equity and a host of surveillance, value addition and management tasks (Klerkx et al., 2019). Interest in the potential of digital agriculture in Australia is heightened by its sensitivity to changes in global value chains (Greenville, 2019), as well as its degree of vertical coordination (Lammers et al., 2018) and broad stakeholder group (Janssen et al., 2017). A roadmap for Australian agriculture to reach a value of A$100 billion (US$78 billion) by 2030 (Thomas, 2018) sees innovation using digital technology playing a substantial role, building on the industry's current strengths.

It has been estimated that improved decisions resulting from digitally-generated information will increase the value of Australian agriculture by over A$20 billion (US$15.6 billion) annually, with additional benefits generated in the downstream food and fibre sectors; notably, in some sectors, the gain was envisaged primarily from "improving trust" (Perrett et al., 2017). These authors identify particular "practice areas" with high returns to the successful implementation of digital transformation. Implementing it, however, raises major challenges, including deficient infrastructure with poor connectivity and deficient internet service (Keogh, 2019), skills shortages (CSB-SYSTEM, 2020; Darnell et al., 2018), and a lack of appropriate decision tools (Banhazi et al., 2012; Keogh & Henry, 2016; Rojo-Gimeno et al., 2019) particularly those embracing the new business models offered by digital agriculture (Griffith et al., 2013; Leonard et al., 2017).

1.2 The need for a clearer vision in embedding digital agriculture into sustainable Australian food systems

Although numerous reports have been published on aspects of digital agriculture, the formal research literature is both dispersed in its purpose and selective in product coverage (Klerkx et al. 2019) and has focused little on impact. Most reports rely on surveys or case studies, both of which may be biased by pre-existing expectations of change, and indeed the stage of change undergone by participants. The above-mentioned lack of appropriate decision tools further obscures incentives. While digital agriculture takes a value-chain approach to technology in food production systems (Shepherd et al., 2020), precision agriculture is very much in the domain of pre-farm gate production and focuses on the understanding of temporal and spatial variability to improve sustainability (International Society of Precision Agriculture, 2019; National Research Council, 1997). The meagre adoption of some forms of precision agriculture highlights the dangers of misreading change processes and of assuming that technical capability leads automatically to development.

The change we seek is more effective management processes enabled by digital agriculture, rather than the development of the technology itself. Reports that encourage investment in agriculture, such as Burwood-Taylor (2020), promote an optimistic narrative around digital agriculture in terms of innovative thinking and the eagerness of users to adopt new ways of agri-food production. This oversimplifies what is a complex and uncertain opportunity, and can lead to unachievable expectations. Given the power of narratives to influence investors' opinion (Goldfarb & Tucker, 2017; Schiller, 2017), it is important to clarify the opportunities and risks digital agriculture represents.

The changes that digital agriculture brings will have consequences for investors, farmers, managers of components of the supply framework and consumers. Each group has different, and sometimes competing, objectives and will seek different information. To address the problem of increasing complexity from growing market demands for safe food from secure, sustainable sources, coupled with the need for investment into new technologies, we present an overview of the change process that digital technology will bring to Australian agriculture. We achieve this through addressing the following objectives: 1) Identifying the potential for digital agriculture to contribute to sustainable growth and 2) Identifying how this transformative change will occur.

2 Digital technology, practice change and a sustainable food framework

Change in food frameworks will occur in response to demand, but the change must be sustainable. How will technologies support change within and around sustainable food frameworks?

In this section, we propose a concept of global change in response to demand and a picture of change in Australian food systems in response to demand and capacity. A vision for change must explain how technology will move food systems towards a sustainable future. Jevon's paradox suggests that digital technology may have adverse effects by promoting profits over sustainability. Commentary on the sustainability of economic activity (Solow, 1991; UNI-IHDP & UNEP, 2012) explains the need to consider not just gains of production but also the human and natural capitals that underpin and sustain them. We consider this from global, and then Australian, perspectives.

2.1 Global challenges

The World's population is projected to increase until 2050, stabilizing at almost 10 billion (United Nations et al., 2019). Meeting the demand for more food will require more from the natural capital that supports food production (Godfray et al., 2010; UNEP, 2014). Several authors point to emerging evidence of failures in agricultural systems to provide basic needs of food, and express concern about the ability of global ecosystems to balance the pressure to providing a range of ecosystem services demanded without inflicting irreversible damage (Millennium Ecosystem Assessment, 2005; Rockström et al., 2009). The sharp spike in global food prices in 2010 indicated the challenges that confront food systems (Government Office of Science, 2011). FAO estimate that if recent trends continue, more than 840 million people will be affected by hunger by 2030, mainly in sub-Saharan Africa (FAO, 2020). Tension is anticipated within river basins due to competing demands for food, water and energy (Molden et al., 2007). Others identify the ongoing loss of biodiversity due to agricultural growth (Benton et al., 2021). Above all, growth in food systems must contend with the threats posed by Global Climate Change (Pachauri et al., 2015).

The dominant source of production growth will need to come from intensification of agriculture, either through increased cropping intensity (13–15%) or, more importantly, through yield increases from the process of sustainable intensification (75–76%) (Bruinsema, 2009; Godfray & Garnett, 2014; Pretty et al., 2018; Pretty, 1997; Rockström et al., 2017). However, while the capacity to meet demand appears to exist within food systems globally (Cassman & Dobermann, 2021; Foley et al., 2011), food systems may not respond in ways that are considered sustainable. Yield gains in high-yielding systems may have slowed (Grassini et al., 2013) while those in areas such as sub-Saharan Africa - which have the significant potential to contribute to the global solution - remain stubbornly slow (Figure 1). While the technical means to improvement may exist (Cassman & Grassini, 2020), the intensification of food systems under competing drivers is understood to be a complex process, involving institutional and infrastructural barriers

(Fischer & Connor, 2018) and entailing multiple entry points, trade-offs and feedbacks (Béné et al., 2019; Herrero et al., 2021).

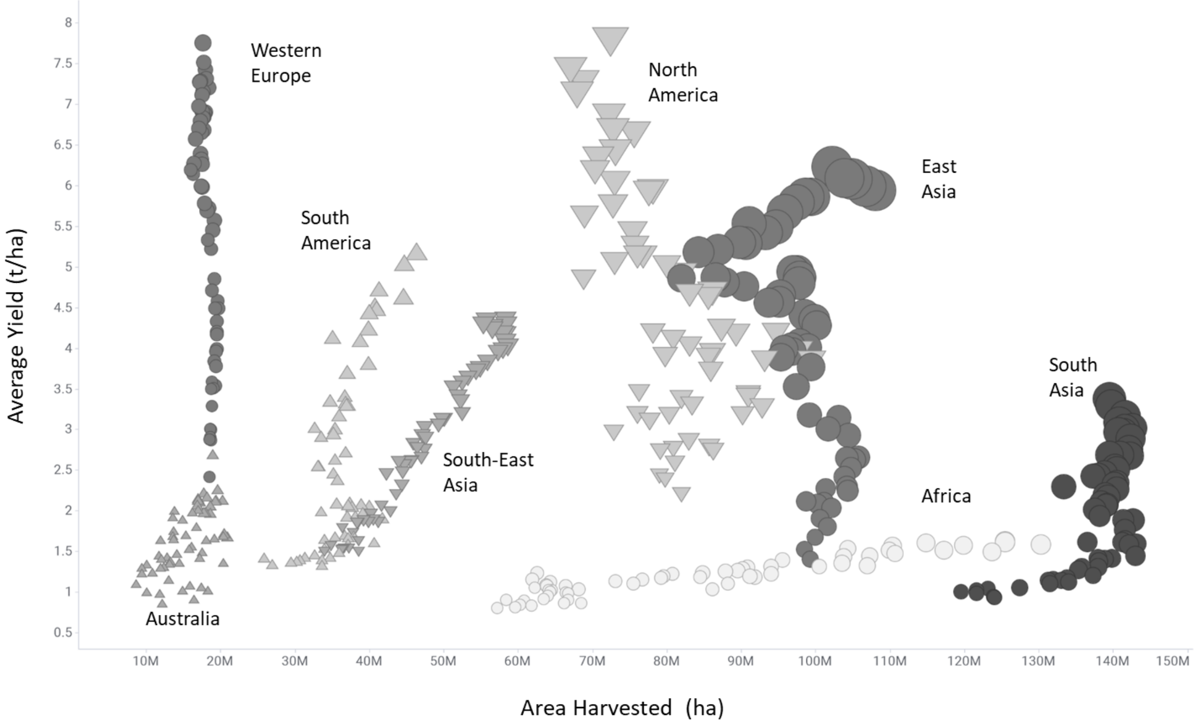

Figure 1: Comparison of production statistics from different regions (1960-2019) suggests contrasting patterns of cereals intensification. The size of bubble indicates gross production. A hesitant intensification in Australia compared to other areas. Difficult growing conditions and exposure to world markets explains a lack of consistent progression of productivity in Australia Data from FAOSTAT.

Producing enough food to feed the future global population on a sustainable basis will be insufficient. Food must be safe and nutritious (Willett et al., 2019), it must be desirable to the consumer, and it must offer appropriate incentives along the supply chain for investment and for participation by stakeholders. In addition to facilitating food supply chain operation, information is itself in demand to certify the attributes for which consumers are willing to pay (Gao & Schroeder, 2009). This, taken with the major growth of international trade, led the FAO, WHO and WTO to call for a new approach, sometimes called OneHealth (Mackenzie & Jeggo, 2019) involving globally co-ordinated food supply chains to meet the demand for more nutritious food of known attributes and provenance.

A global reassessment of sustainable intensification identifies three stages in the transition towards sustainability: efficiency, substitution and re-design (Pretty et al., 2018). Digital agriculture technologies can support all three processes: Precision agriculture aims to improve production efficiencies through the use of spatial technologies. Digital agriculture accelerates substitution within food systems through the application of technologies, including phenomics and metabolomics, which link genetic, environmental and management aspects of production systems, through global nutrient budgeting or product certification driven by consumer demand. Re-design is supported by the capacity of digital agriculture technology such as remote sensing; field-robust technologies, high-dimensional modelling and communications media to link components and actors within the food system as governments and individuals explore options for change through local adaptation. The outcome is to link the four components that we mention below of production, consumer, capitals and governance through tools such as data-rich valuation of natural capital, social networking of farmers, IP policy to support human capitals amongst farmer groups and evidence-based policy

With this in mind, the framework we propose in this paper includes the role of digital technologies to support the range of changes that define sustainability. But first, we examine the Australian context of our research agenda.

2.2 The Australian setting

While Australian agribusiness is dominated by commodity export, we observe digital agriculture to have contrasting roles of supporting productivity gains in commodities while also enabling opportunities for value in a quality product. Although Australia ranks only 23rd as a global food producer, it ranks 12th in terms of exports (Greenville, 2019), which is about two-thirds of the value of production. The OECD (OECD, 2015) highlights the need for improvements in productivity in Australian agricultural systems, for which Keogh (2019) details some of the technical challenges, particularly in rural Australia. Digital agriculture is often associated with close-to-market, low-volume, high-value products, but a more important role in Australia will therefore be to drive productivity growth for land, labour and water in a changing environment: some of the elements of sustainable intensification are discussed below. The variability of typical Australian growing conditions can be viewed as an asset if better data allow smarter management of the risks involved. Australian risks often include weather uncertainty, variable market prices, and institutional changes in their business management (Nguyen et al., 2007). However, the current yield gap of about 50% for most Australian crops (Lawes et al., 2018) suggests that substantial scope remains for improvement in production efficiency, in addition to gains in value. Australian cereals farmers deal with risk by avoiding it ((Nguyen et al., 2007); Figure 1). Digital technology will provide a better understanding of the risks so that producers can exploit them rather than avoid them.

Despite Australian farmers' general characteristic of risk avoidance, they are noted innovators (OECD, 2015), which is an essential factor in the adoption of new technologies, such as those of digital agriculture (Ernst and Young, 2019; Thomas, 2018). Yet, there are major obstacles to the expression of such innovation (Keogh, 2019; Leonard et al., 2017; Wiseman & Sanderson, 2018a), with multiple opportunities hindered by a lack of industrial organization, inconsistent policy on issues such as data governance, and the lack of scale (Leonard et al., 2017). Nevertheless, overall expectations are substantial, and the gains from digital agriculture are anticipated to generate more than A$20 billion [US$15.6 billion] annually for Australian agribusiness (Heath, 2018; Perrett et al., 2017). The majority of advances are expected in the grains and livestock industries, primarily because of their scale, but rapid growth is also sought in high-value export products for which Australia has a competitive advantage (Agrifutures Australia, 2021). A different layer of uncertainty surrounds the gains from digital agriculture as Australian agribusiness moves from established value chains towards more dynamic market arrangements and opportunities. Many see this to be the future for Australian food systems, but uncertainty arises because few can explain how the changes will sustainably occur and how investment opportunities must be approached. The rest of the paper focuses on the Australian context of digital agriculture with recognition of the influence of global players and innovations.

3 Growth of digital agricultural technology

3.1 Historical growth

Digitally transformed agriculture emerged around 2014, although precision agriculture globally dates from the 1980s and in Australia from the 1990s (Cook & Bramley, 1998). Use of digital technology in agriculture has grown over recent years (KPMG & Skills Impact, 2019). Data from Google for 2015-21 (Figure 2) show that while interest in precision agriculture continued to grow to 2020, the interest in digitally transformed agriculture accelerated over the period, but from a lower base.

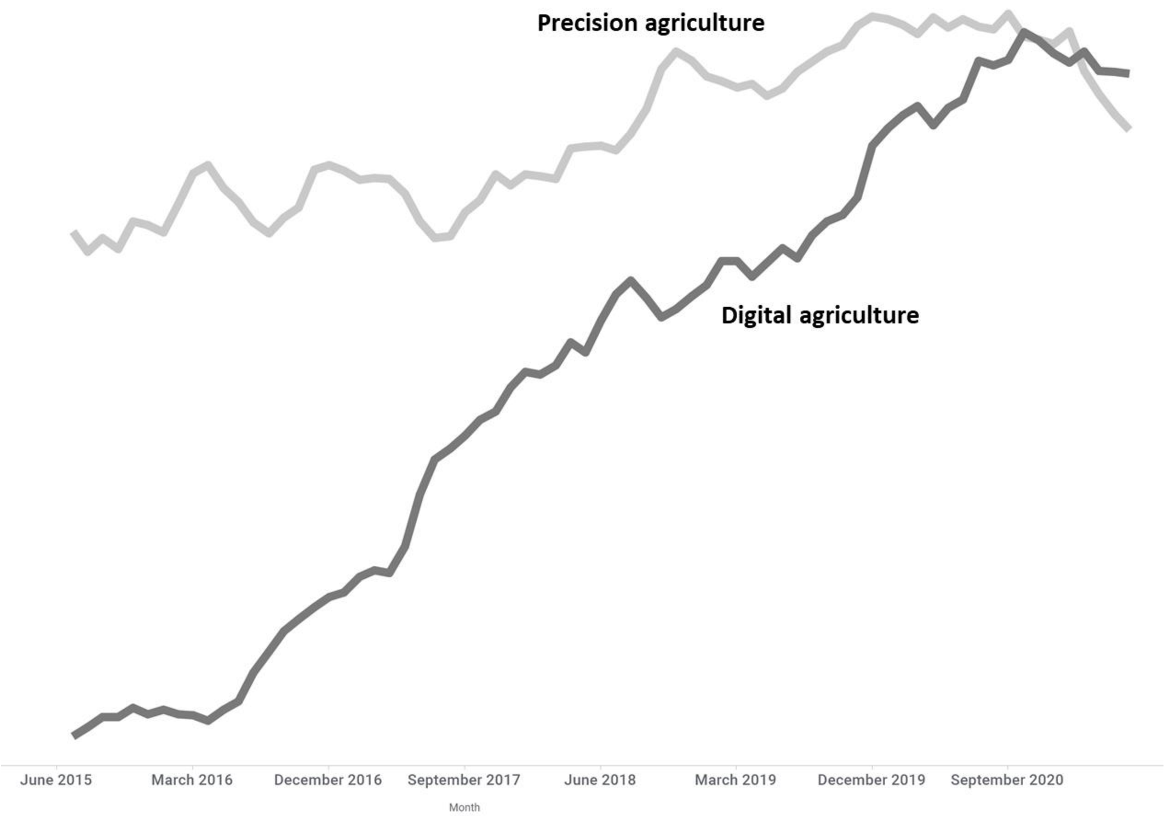

Figure 2: Global interest reported by Google Trends in the terms "digital agriculture" and "precision agriculture" 2015-2021. Weekly data are normalized to the average for 2020 and presented as ten-week running means.

3.2 How does digital technology introduce change in agriculture?

Digital technology generates value by means of data creation and sharing which enables better business process (Keogh & Henry, 2016; Leonard et al., 2017; Wolfert et al., 2017). We view digital technologies' functions in food systems as having four general "classes" (see Box 1). Throughout the paper we describe the types of outcomes that technologies enable. Following an analysis of digital technology, blockchain technology is considered and we provide a reflection on what has changed from the advent of the technologies discussed in this section.

Box 1: Classes of technology

1. **Data:** Sensing the system.
2. **Control:** Responding to insight.
3. **Modelling:** Working out what complex multi-sensor data means.
4. **Networking and Communication:** Increasing the flow of data and insights.

3.2.1 Data

Digital technology in agriculture provides primary data, from a vast array of sensors, internet of things (IoT) and data from secondary sources, including data of physical and socio-economic condition. Together these provide information on many different parts of the food systems. The sensors directly measure the condition of components or aspects of entities of interest such as cells, soils, climate, plants, animals, products, and their packages, location and condition as they pass from production through processing to consumers. Secondary data include those from omics (omics data include chemistry information describing plant or animal genomics, phenomics, proteomics or metabolomics), monitors, remote sensing whether from satellite, airborne or ground-based devices, radio frequency identification (RFID) scanners, and other data such as GPS. Other secondary data are those used to monitor and adjust activities within value frameworks, such as those that support trading, inventory management, certified product information, e-commerce or management of the supply framework.

Protected cropping systems have traditionally been more data-centric than broadacre cropping (Klerkx et al., 2019) and have been partially digital since the 1970s. The volume of data collected in broadacre cropping systems lagged until the 1990s, when it jumped dramatically with the introduction of precision agriculture (National Research Council, 1997). Yield sensors on grain harvesters, coupled with GPS, gave precise geo-referenced yield data at a resolution of a few meters. These data were then expected to guide fertilizer application. Geo-referenced sensors are now available to provide on-the-go estimates of machinery position, grain protein, reflectance, and absorption of crop canopies, weeds, soil geophysical properties, and machinery performance. While the costs of technology have reduced dramatically, in broadacre cropping, issues remain regarding the conversion of data into information of sufficient value to promote widespread adoption for complex field management operations, although adoption of spatial guidance has been very high (Lowenberg-DeBoer & Erickson, 2019).

The dairy industry has used sensors of individual milk yield and quality for decades to measure cow performance and adjust feeding accordingly. Data technologies were developed later in other livestock systems because of technical difficulties with field-robust sensors (Wathes et al., 2008). Recently, RFID technology has allowed producers to adopt robust sensors, which has dramatically increased data flow in many livestock systems (Barge et al., 2013; Zhang et al., 2020). A range of technologies, including animal tracking (Barge et al., 2013), DEXA carcase analysis (Connaughton et al., 2020; Delgado-Pando et al., 2021), electronic noses for profiling of meat quality (Wojnowski et al., 2017) and blockchain technologies (Cao et al., 2021) are being explored to promote objective measurement and to stimulate information sharing throughout livestock systems. Summarising recent research on the motivation for uptake of digital technologies in food and agriculture (CSB-SYSTEM, 2020; Demartini et al., 2018) we suggest that the roles of digital technology in value creation include:

- Data-enabled valuation of equity
- Production efficiency through precision agriculture, by varies inputs to meet variations in the land's capability to produce.
- Product streaming to increase value
- Preserving value through environmental control during logistics
- Increasing value by precision processing and
- Certifying origin of products using distributed data ledger technology

Direct, proximal or remote sensing of field growth environments has developed in parallel to support an interpretation of these data. Satellite imagery dates from the 1970s (Weiss et al., 2020), but recent substantial increase in the spatial and spectral resolution, which, together with data from various airborne and ground sensors, has improved the precision and utility of remote sensing for digital agriculture.

A further wave of data technologies is arriving through the internet-of-things (IoT), which has the potential to provide real-time data from a wide range of sensors on equipment, animals, water tanks, gates and elsewhere. The wide deployment of this technology will depend on better and more widespread internet connectivity in rural areas (Nirmalathas, 2016; United Soybean Board, 2019). Downstream within food systems, blockchain technologies will support incentives for reducing food waste and managing uncertainty. IoT monitoring of food products through the value framework is expected to reduce losses by 1%-4% (World Economic Forum, 2019). Despite the need for fitness of telecommunications to support growth, there remains a lack of appropriate quantitative data supporting data use 'behaviour' by food producers and the capability of existing or planned network infrastructure to cater for that data use; producers in Australia continue to express frustration about the lack of development of rural telecommunications (Lamb, 2017). The conclusion can therefore be drawn that adoption of rural innovations requires user buy-in as well as numerous positive product attributes.

3.2.2 Control

Digital technology generates value when it improves an action through better control of an activity or process. Desired effects include machinery guidance, animal control, selection of input type or quantity, control of processing action, or modified value of product or attribute. Table 1 lists a selection of technologies that are either in use or at advanced stages of development.

Table 1: Current agricultural technologies that are either in use or at advanced stages of development; these are examples of technologies that provide improved control of an activity or process.

Innovation	Use
Auto-steer	High-resolution GPS guides farm machinery precisely to avoid overlaps or misses
RFID selection of livestock (often referred to as EID)	Individual animals are selected on basis of weight gain or other diagnostic criteria for differential feeding, treatment or cull
Virtual fencing	Animals are controlled by digital fence lines in the field based on GPS
Variable rate technology	Equipment is capable of changing rates during operation in accordance with a digital field map and GPS. Applicable to fertilizer, spray or irrigation
On-the-go spraying	Real-time detection and treatment of weeds or nutrient deficiency
Robotics	Machine operations in the yard or processing to improve precision and reduce labour costs. Selective harvest. Product quality is differentiated within-management units to increase total value
Digital trading	Data intensive valuation to account for differential quality, consumer preference, and provenance
Data-driven financial and insurance instruments	Precision financing of product and components of natural capital

3.2.3 Modelling

Modelling provides the linkages between data and control. For example, auto-steer – widely used in no-till farming in developed countries, uses GPS to estimate the current location of a machine, a digital model then compares that to the desired location, and a response to correct the steering if needed. This is an unusually simple example. Analysis often requires several sources of data, which are then combined to represent complex processes as they vary over space and time. The results that appear to the user conceal the complex calculations of the model and the effort that went into its development.

From a model design perspective, a review of the next generation of models revealed the need to characterize systems up to the farm gate (Antle et al., 2017). Advice on the technological advances necessary to model systems beyond the farm gate is available (Jones et al., 2017) and associated digital technologies have developed in four ways to support advances in modelling. These are:

- Software has become capable of analysing more complex problems. It has also become more accessible in open source software (e.g. QGIS Development Team (2021) and R Core Team (2020)), which encourages collaboration and co-development of models.
- Database management is now more competent to handle large datasets from multiple sources and with more flexible formatting. Through GODAN and other programs, systems are developing to facilitate networking of large databases for both public and private benefit (Kretser et al., 2015).
- Visualization of large, linked databases is easier (Charvat et al., 2018) but requires specialist data managers.
- Continued expansion of data storage and computing power at much reduced prices.

3.2.4 Networking and communications

Communication and networking technologies promise new patterns of disruption to existing agricultural systems through their effects on the distance that separates people. Economists believe innovation conforms to the gravity model (the premise that trade "gravitates" more towards size or scale) through processes of knowledge sharing, matching and knowledge spill over (Carlino & Kerr, 2014). These would seem to relegate agriculture – by definition non-agglomerated – outside the innovation mainstream. In Australia and elsewhere, agricultural organizations are attempting to improve agglomeration by coordinating grower groups.

There are documented examples of the digital mobilisation of cooperative action both along the food supply chain (Berti & Mulligan, 2016) and amongst farms (Lev & Stevenson, 2011) which address traditional problems of farmers' lack of coordination, scale and market power. In addition, many cooperatives have adopted advanced information technology for market intelligence and other decision support, often to overcome spatial separation. These developments are often described as "hubs".

Further development in digitally-enabled collaborative action is in data platforms that serve some collective or individual need on a service provision basis. Platforms can take various forms and associated governance structures ranging from in-house and proprietary through to being stand-alone service providers (Wolfert et al., 2014). The requirements for their effective operation in an Australian context are reviewed by Darnell et al. (2018); these include the well-understood constraints on more conventional collaboration, such as shared ownership and its relationship to control and decision making. Studies of agri-food trading platforms in well-developed online environments such as China have also emphasised the importance of strong physical and operational networks which can ensure satisfactory delivery and certify product safety and quality, alongside the virtual network (Montealegre et al., 2007; Wei et al., 2020).

The rapid global growth of mobile phone and data coverage still has major deficiencies for rural areas in many countries (United Soybean Board, 2019), including Australia (Nirmalathas, 2016). This is a clear priority for government intervention, discussed later in this paper. Nevertheless, social media is an essential vehicle for P2P (person-to-person) or B2P (business-to-person) communication, for understanding customer preferences and adapting products to meet the demand and overcome the problems incurred by relying on traditional extension pathways. Cloud computing allows simple local devices to use remote computing and storage resources at low cost, allowing the data to be shared easily.

3.2.5 Shortening value chains using blockchain technology

Distributed ledger or blockchain technology (BCT), introduced to agriculture after 2008, offers secure methods to transfer information between parties. BCT could improve relations between actors in food frameworks who are isolated, insecure, externally controlled or data-poor. For example, food fraud which is avoidable by way of enhanced connectivity between consumer and producer costs the food industry tens of billions of dollars per year, leaving aside the consequences to health and brand damage (Rocchi et al., 2020). The potential impact is substantial for Australia, which aspires to export high-quality products (Greenville, 2019). There are many other applications for BCT, such as land registration, smart contracts and access to financial products (FAO et al., 2019).

The advantages BCT offers include security, transparency, independence and speed (Mearian, 2018; Yiannis, 2019). Challenges include a lack of regulation conformity, scope of security and time needed for participants to learn unfamiliar technology.

It remains to be seen if BCT can be implemented satisfactorily as part of digital agriculture. There remains some scepticism with statements that there is no example in agriculture with “wide adoption and which is truly run as a shared system. And . . . if the real issue is market structure – technology won’t solve that." (Martha Bennett, cited in Mearian (2018).

3.3 What has changed?

Several recent reports suggest that the move to digital agriculture and food is occurring and that the pace of its adoption will increase in the near future (Keogh, 2019; Keogh & Henry, 2016; Perrett et al., 2017; Ramasubramanian, 2010; Trendov et al., 2019b; US FDA, 2019; World Bank (2021). From these, we summarise six underlying reasons for this:

1. Technology has become much cheaper.
2. People and sensors are more connected, and the connections will become faster and capable of conveying more complex data.
3. Society has changed in ways that accept the technology, which has become commonplace.
4. Labour costs have increased, and labour has become scarce in many rural areas.
5. Modelling capacity can now represent complex realities and is no longer limited to large dedicated computer facilities.
6. Data have become more embedded in business models, increasing the number of stakeholders who may seek digital connections to products, firms and supply chains as part of their decision support.

4 New food value frameworks: Digital agriculture’s role in a paradigm shift

Thus far, we have outlined the situation of digital agriculture from global and national perspectives. We have also made a case for the need for a clearer vision of digital agriculture. Evidence has been presented to claim a rise in the interest of digital agriculture and we have outlined several methods of how digital agriculture will stimulate change in agriculture and associated value frameworks. In this section, we discuss digital agriculture’s role in the creation of new food value frameworks and comment on how digital technologies will drive efficiencies in sustainable food systems as they become increasingly complex.

Early data applications focused on improvements in agricultural production efficiency, which we refer to as the *production* domain. More recently there has been emphasis (Burwood-Taylor et al., 2021) on the role of technology in creating value beyond the farmgate: the *market* domain.

Addressing sustainable food systems requires, in our view, three further domains. The first and second are in the *capital* and *governance* domains, which concerns the role of technologies to protect and govern investment in human and natural capitals that underpin sustainable production (UNEP 2014). The third is in using *data technologies* to help govern complex food systems through data-enhanced instruments for sustainability in terms of policy, finance, legislation or public investment. In this sense, data is an asset from which to generate value (Wiseman and Sanderson 2018). This section of the paper draws the capital and data technologies domains into the more-mature production and market domains of agribusiness.

4.1 Demand focus is the future; supply focus is the past

Food systems have reached a stage of development where their design is grounded in consumer satisfaction (Taylor & Fearne, 2006, 2009). They also show extreme concentration at retail, input and processing levels (Maglaras et al., 2015). Retailers control access to the consumer and dictate many aspects of the supply conditions (Hingley, 2005). Hence a variety of transaction mechanisms have emerged, all of which target delivery of customer value at minimum cost.

Digital transformation plays many roles in this change, at all stages of the value chain, and offers many opportunities. It offers a means to coordinate divergent mechanisms within food systems (Kramer et al., 2021; Kumar et al., 2020).

Consumer demand will be more important in the future and drive value in terms of demand for products with repeatable quality and quantity (Grunert, 2005; Verbeke, 2005). For example, developers of plant-based protein must meet consumer expectations for products that are like meat, while meat producers are focused on reducing carbon emissions. Other examples include the emphasis food retailers put on the repeatable quality of fresh fruit and vegetables. This emphasizes the need for channels to provide feedback information from retailers/customers to producers. Digital technology now allows feedback from consumers to all upstream actors in the supply framework (Shepherd et al., 2020).

Nevertheless, producers, logistics and value chains remain the focus of digital technology in developing value frameworks in agriculture. Although producers dominate food frameworks, in developed societies, most components of retail food are unusable by consumers in their raw state (fresh fruit and vegetables are exceptions).

To enable information flow through the value chain framework, a range of technologies new to agriculture are available. These include blockchain technology to provide assurance in the nature and provenance of products and their transaction history (Yiannis, 2018). A range of predisposing conditions have been identified for the implementation of blockchain for food products (Behnke & Janssen, 2020), and Australian implementations are in its early stages. In turn, such strongly curated information offers secondary uses such as the specification of “smart contracts” (Staples et al., 2017).

Use of social media in marketing and generating consumer feedback offers significant potential, particularly in developing value addition mechanisms that circumvent, or possibly complement, retailers' hold on consumer demand information.

New analyses (such as metabolomics) to assess food quality offer yet further opportunities (Kobayashi et al., 2015). The degree to which new digital processes interact within the value framework may determine how much extra value is created (see Box 3).

Natural, human and manufacturing capital must be maintained and nurtured when considering food production. Digital technology will enable new financial, administrative and social instruments to evolve. An early goal is the sustainability of food supply frameworks in which value accumulates throughout the process, including managing the waste that is produced (Shafiee-Jood & Cai, 2016).

Box 3: Creating value in meat processing

a) DEXA† technology identifies the characteristics of each sheep carcass as it enters the processing plant.
b) This information increases value when used to control meat-cutting robots to meet customer requirements.
c) It adds more value when fed back to the sheep producer, and more when it is used to modify feed characteristics.
d) The total value added far exceeds that of the original but depends upon integration within the supply framework.

†DEXA = Dual Energy X-ray Absorptiometry.

Some economists assert that the growth of human capital is the only true indicator of the sustainable use of natural resources (Solow, 1991). Food systems are therefore sustainable only when the processes they use increase a society's overall welfare. Economists debate how to measure the increase in human capital and how to establish what causes it. It is likely that food producers will adopt many new digital-based systems ranging from robotics to data sharing and artificial intelligence platforms. These will have as-yet unforeseen social consequences, some of which need new skills (KPMG and Skills Impact, 2019) that will take time to assimilate into the supply framework.

In Australia, producers' and processors' disclosure of product characteristics and attributes on the Sedex data sharing platform has been used to inform retailers, which in turn provide product assurance for their customers (*Sedex Australia*, 2018). Mobilisation of this data beyond the immediate food system holds promise, for example, in insurance and finance markets where data provision serves as proof of risk management implementation (Ruiz-Garcia et al., 2009; Tripoli & Schmidhuber, 2018), or from natural capital accumulation which in turn allows inference about risk and resilience in natural systems (Cong et al., 2014). The existence and potential for data transmission do not, however, necessarily occasion success. Food retailers' attempts to employ metrics based on a purposive collection of farm-level data of interest to the consumer have been shown to encounter constraints associated with communication, trust and perceived lack of relevance amongst chain members (Freidberg, 2020). Extension into certification faces many of the same limitations, including incompatibility of supply chain actors' media (Theuvsen et al., 2007).

4.2 Developments in farm and food systems within the new food value framework

Digital technology will enable the present agriculture-based sustainable food chains to transform into complex frameworks. This will occur as food production systems grow in volume and complexity to meet the multiple demands of consumers. Consumers' demands apply pressure at points within the framework that will move production, processing and waste management up the spiral (Figure 3).

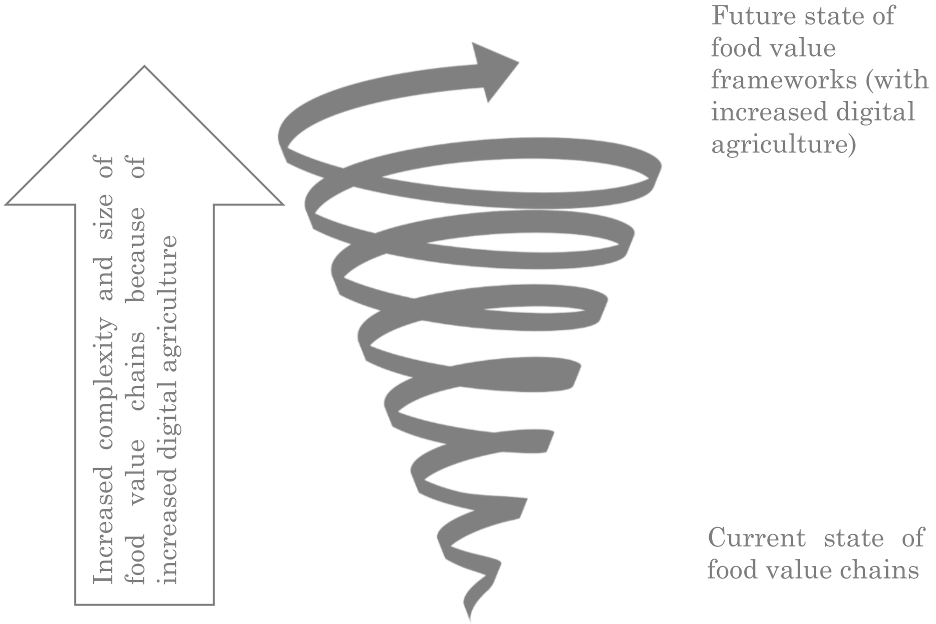

Figure 3: Food value chains will increase in size and complexity as they become frameworks and adopt digital technologies.

The mechanism for scalability of change within value frameworks determines how the investment will respond to change. The German Economist Schumpeter recognized two modes of economic development: disruption and accumulation (Fagerberg, 2003). In the case of disruption, scale is enabled through communications and networking technology if the business model allows some version of Metcalfe's Law (Briscoe et al., 2006) to operate whereby the value of telecommunications networks increases in proportion to the numbers of users. In the case of accumulation, existing entities will seek to modify processes that build on their commercial strengths. Both processes may operate concurrently and may be confounded (Malerba, 2006).

Connectivity between producer and consumer is important in both directions within the framework. Onward signalling maintains value in the product through its trusted identity as it passes through the framework, for example, through traceability. Backward signalling indicates consumer, buyer or processor preference back towards the producer (Spence, 2002). Blockchain packaging of information supports trading, and data transfer mechanisms that promotes innovation (Rejeb et al., 2020).

This section has argued that a new paradigm of agri-food value frameworks will emerge from the advent of digital agriculture. The next section of the paper continues with the theme of process innovation and the appetite for investment.

5 Business processes, innovation IP and social capital to adopt digital technology

Digital agriculture will attract more investors if they understand how the technology will drive innovation. Innovation in agriculture has become less deliberative (Hall et al., 2006) and more complex and collaborative (Satell, 2019). This change is costly. Of the US$1.3

trillion invested in new digital projects in 2018, US$900 billion was wasted because of an inappropriate emphasis on strategic goals and organizational cultural problems (such as mindset towards change and speed of decision making) (Tabrizi et al., 2019). Innovation brings together new ideas with new mixes of existing elements, including novel products and new ways of producing existing ones (Edquist, 2006). Therefore, we should look at changes in business processes that new technology make possible.

Food industry firms' innovation capacities have been found to be enhanced by networked relationships amongst firms, mainly where firms' networks include third parties beyond immediate suppliers, customers and peers (Kühne et al., 2015). Such third parties could well include digital and data service providers, and platform operators and members.

The factors that affect the investment decision to adopt agricultural technologies have been synthesised into three interacting drivers (Annosi et al., 2019). These are "capabilities" (especially in information acquisition and processing); "cognition" (regarding awareness of innovations' availability and of the benefits they deliver (Leonard et al., 2017); and "external factors", particularly the vertical linkages which are increasingly both an initiator and a consequence of digital transformation in food systems.

The different condition of these factors within food systems as they attempt digital transformation influences how benefits are recognized and realized (Fielke et al., 2020). Benefits of digital transformation may be more recognised by, and more available to, large and powerful firms and those engaged with structural change. Others (van der Burg et al., 2019) anticipate policy challenges associated with the distribution of power not only along the conventionally defined food supply chain but also within networks mobilised by data exchange in the food system.

As has been the case historically for the value chain, farmers' information networks operate on cooperative principles. Communities of Practice and Networks of Practice wherein farmers' weak organisational interlinkages are overcome so as to "collude on information sources" have been investigated (Oreszczyn et al., 2010). Furthermore, it has been identified that contextual economies of scale has benefits to farmers of such collusion in data collection and management (Sykuta, 2016). Examples have been reported where cooperatively-owned data has been used to exercise countervailing market power within the supply chain via horizontally oriented food hubs which collect and share data (Berti and Mulligan, 2016) and vertically co-ordinated food processing and marketing complexes built on seamless data transmission (Lev and Stephenson, 2011).

So how is this working? Facilitation of farmer collective action accelerates progress toward digital transformation by groups of farmers (King et al., 2019; Oreszczyn et al., 2010). At the production level in Australia, innovations arising from transdisciplinary science have been such an accelerator (Polk, 2015), and their translation and extension via the multiple stakeholder organisation Landcare (and more recently Grower Groups) are seen as a driver of innovation from within the food system rather than imported from outside (Baumber et al., 2018). Looking more broadly at innovation that crosses sectoral boundaries and bridges supply chain stages, it has been suggested that innovation platforms that focus on actors' shared interests at the micro-level of "innovation ecosystems" are the way forward (Pigford et al., 2018). The work targeted innovation in sustainable agricultural practices, but many of the same principles apply to digital agriculture transformation: interactions amongst actors within "regimes" of commercial practice. In the absence of external facilitators, these regimes emerge from the farmers' own networking (Sligo & Massey, 2007).

Technological innovation (e.g. machinery, equipment, plant and animal breeds) has long been critical to more productive agriculture together with operational efficiency (Ernst and Young, 2019). As discussed in previous sections, value creation drives this process. Innovative business processes can apply to a small part of the value framework or occasionally span the entire framework. Measuring and monitoring performance against metrics allows process efficiency projects to be targeted towards production problems. Bottlenecks, delays or areas displaying poor utilisation of resources are initial targets for digital technologies.

The pathway of adoption of technology is strongly determined by the pattern of accumulation of intellectual property (IP) because this dictates who gains most value in the process. As we have witnessed in precision agriculture, farmers do not adopt the technology if they perceive no value from adoption (Lowenberg-DeBoer and Erickson 2019). Digital agriculture is far broader and offers the potential of value to farmers, suppliers, advisors, distributors, processors and others within food value frameworks.

The pattern of technology growth varies markedly, depending on who derives the value from its use. This is explained clearly by Malerba (2006), who uses analysis of change in different organizations to identify four contrasting patterns of technology growth (Pavitt, 1984). The different types show contrasting patterns of innovation and IP generation. They vary from disruptive, agile activities focussed on small specialist actors to large organizations that aim to protect their power and influence.

IP law is a relatively new issue for many in agriculture and presents several emerging issues concerning who owns the value from the data generated in digital agriculture (Sanderson et al., 2017; Wiseman & Sanderson, 2018a). Patenting a new or improved process is complex, and the technology use must be substantial, not incidental, which can be hard to prove (IP Australia, 2020). IP has become increasingly important to Australian agriculture as the value of food exports to China grows. Weak property rights increase the risk of the loss of IP.

6 Role of Government in Digital Agriculture

We have provided evidence thus far to suggest that digital agriculture is a process led by the private sector. Despite this, the public sector has important and often understated functions to support the resilient and equitable growth of digital food value frameworks. These include:

- Maintaining a competitive environment for digital transformation: particularly across services and data. This would include regulating the value chain ecosystem to encourage development through trading policy, intellectual property legislation, and taxation policy.
- Overseeing financial and insurance institutions to ensure their fitness to support development through licensing and regulation.
- Stimulating value frameworks by prudent investment in public goods such as communication and transport infrastructure.
- Maintaining human capital by investment in rural education, because digital capability of the workforce is a key factor in preparedness for change (Trendov, 2019b; KPMG and Skills Impact, 2019).

The public sector faces major challenges to support digitization (Dilmegani et al., 2014). It can support digital agriculture in three areas in addition to its traditional support of research and development (Keogh, 2019):

1. Harmonize policy that affects the sectors that support the change to digital agriculture;

2. Invest in mechanism for correcting market and institutional failure; and
3. Provide a legislative and regulatory environment to support rapid change.

Federal and state government policy in Australia supports sustainable growth with the policy environment favourable to rural innovation (OECD, 2015). Digital technology in agriculture can interact with these processes in several ways:

1. Policy influences transport, trade, rural education and communications, which affect the feasibility of options available for digital agriculture;
2. In marketing, demand for products will be influenced by policies that target trade, biosecurity and public health (Greenville, 2019);
3. Digital agriculture can aid policies that target sustainable growth as a component of agricultural productivity called "management of the ecosystem"; an important term not to be confused with the study of the interrelation between organisms in classical ecology.

6.1 Investment

Investment in innovations was briefly touched on in a previous section, but from a public sector perspective, most governments are reluctant to invest in areas seen as the private domain. Recently, however, Australian states have invested public funds in innovation precincts or food hubs (Australian Government, 2018), hoping that private investors will also support the innovation. In some cases this has supported regional leadership and identity (Ernst and Young, 2019) and in others it has addressed the need for cross-subsidisation of services to sparsely populated areas (Keogh & Henry, 2016).

6.2 Regulation and legislation

Scale and networking effects increase the tendency for the winner-takes-all to occur in the digital economy (Bughin et al., 2018). The imperative is on entrants to dominate market share or prepare to be dominated: this can have serious consequences for others in the ecosystem. Farmers and cooperatives enter this ecosystem with understandable trepidation. Often their only defence is government regulation.

Legal aspects of the ownership of agricultural data ownership in Australia focus on commercial sensitivity (Cho, 2018; Keogh & Henry, 2016) of IP which generates competitive advantage. The Australian National Farmers' Federation (National Farmers Federation, 2020) has addressed this aspect of farm level data to some extent in a Farm Data Code. A central purpose of such codes, seen also in the US and New Zealand is to generate trust amongst value chain actors through instruments such as business law and trademarks (Wiseman & Sanderson, 2018a).

7 Lessons from Precision Agriculture

The premise and potential value of digital agriculture have now been discussed at length, so it is prudent to consider lessons from similar technology that arguably have under-performed in adoption.

The expected benefits of precision agriculture in the 1990s did not materialize to the extent expected. For example, it has been shown that a pattern in which simple-to-apply precision agriculture technology such as GPS guidance is adopted very widely amongst crop farmers while more complex management processes such as yield map interpretation struggle to exceed 20% adoption and depends strongly on external technical support (Llewellyn & Ouzman, 2015). Similar patterns have been reported in the U.S. and Europe

(Lowenberg-DeBoer & Erickson, 2019). If we can understand why adoption failed, we can aim to avoid repeating the errors with digital agriculture.

7.1 The need to demonstrate early value from technology

Precision agriculture was envisaged fundamentally as a management change enabled by spatial technology (National Research Council, 1997). It has developed largely as a toolbox of technologies from which farmers seek immediate benefit (Lowenberg-DeBoer and Erickson 2019).

Its main problem in the Australian grain industry has been a lack of clear value to adopters (Leonard et al., 2017). It proved hard to gauge big gains from variable rate technology, which is often confounded with precision agriculture even though it is just one use of the data. Longer term gains from interpretation of complex data has proven much less attractive than the clear and immediate benefit of a technology such as auto-steer. The full benefits of data-based learning may take years to acquire and are subject to many uncertainties such as weather and markets. As such, at this early stage of digital agriculture, its value throughout the food system must be demonstrated for success to be enjoyed.

7.2 Technical innovation must become management practice

Business processes are interactions between people producing goods or services and, as demonstrated in this paper, are critical for value creation in food systems. In contrast, precision agriculture technology is fragmented. This obstructs the flow of data and hence the growth of management processes that could use it.

Patchy internet connectivity makes the problem worse. Connectivity in rural communities is a global problem and remains so in rural Australia (Gregory, 2020). It can be difficult to make the technology work in the field. In precision agriculture, the separate technologies have not communicated seamlessly with one another. Attempts by technology developers to address this issue further raises questions surrounding intellectual property (Wiseman & Sanderson, 2018b). Farmers may be wary of passing their data between machines through third parties using cloud-based data management systems. Lack of technical support was and remains a major barrier to the adoption of precision technology in Australia and elsewhere (Cook & Bramley, 1998; Fiocco et al., 2021). Most farmers who adopt precision agriculture did so through the agency of consultants (Llewellyn & Ouzman, 2015). We envisage that digital agriculture will need to address similar issues of control and training.

7.3 Institutions must support long-term change

Scaling is important to widespread adoption. Any technical innovation requires institutional support over the long-term for successful adoption. The success of a technology depends on the growth of know-how throughout the sector. Short-term, local successes may make the news, but they do not spread widely without industry-wide organizational capacity to invest in human capital and maintain progress. The need to develop sufficient organizational capital to achieve resilience and absorb the inevitable failures that occur. A failure to address organizational and social requirements results in the 'technology fallacy' (Kane et al., 2019) which could threaten the advancement of value created from digital agriculture.

8 Conclusions

Digital agriculture describes the introduction of a wide range of technologies – many new to agriculture - that promise substantial change in the operation of food systems through the use of data (Shepherd et al., 2020). Investors in digital agriculture are being attracted by expectations of substantial gains as agriculture strives to catch up with other more highly digitized sectors in a sustainable manner. To a degree, such a process is inevitable because the need for digitization in food systems is irresistible and because agriculture is considered to be the digital laggard in amongst economic sectors (Blackburn et al., 2017; Manyika et al., 2015), hence a strong candidate for change. Access to digital technology is increasing everywhere and is penetrating food systems globally.

Ultimately, digital technology promises changes in food systems through improvements in farm productivity, connectivity between farmers, consumers or intermediaries and through better control of processes throughout food systems. These changes offer prospects for improvements in global sustainability by connecting farmers better with consumers, intermediaries and the system in which they operate. By learning from the patchy adoption of precision agriculture, we acknowledge the need for adopters to realize value early from technology adoption. Learning from the patterns of technology led innovation in different industry sectors we also recognize the need to understand how adoption pathways differ according to who, in the food system, is likely to realise the value from digital technology adoption, as well as who owns the IP from its use. Failure to recognize the complexity of the changes will ultimately retard adoption.

8.1 Three principles for change

Identifying the potential for digital agriculture must first consider a sustainable food system framework which views food production not as an independent activity but linked inextricably to consumer and societal demands, and reliant on natural and human capitals that sustain it. A further aspect is how people will govern such systems, through a range of digitally enhanced policies, financial and administrative instruments.

Food systems vary enormously, and to understand the scale of potential change, we propose evaluating the role of digital technologies in all systems, rather than focussing on symbolic examples such as robotics which, while of undoubted long-term potential, promise change currently in only a small subsector of the agricultural economy. We propose to learn lessons from the smaller agile sectors while also attending to the ‘megalithic’ commodities, which will have a greater impact, albeit more slowly.

Second, we propose to learn from the patchy adoption of precision agriculture and realize that digital technology use will grow through the value of the processes it enables. Value is not a resource waiting passively to be harvested but an improvement in function that needs to be learned with partners inside complex systems. Failure to realize the social and organizational requirements for this to occur results in the technology fallacy (Kane et al., 2019) – seen in many sectors.

Digital technologies enable levels of data acquisition, transfer and control through space and time that were impossible prior to its introduction. Currently, the scale of activity is very small, but the potential is very large, but it needs to consider the realities of the market. For example, what may work well for a high-value food product may be too expensive for a low-value product like export grain. Conversely, remote sensing technologies that are useful for big-paddock systems over large areas will likely not work for the intensive production of high-quality fruit. Similarly, customer-centric frameworks for high-value products are likely to move quickly in response to consumer demand. But Australian agriculture and its food networks will remain dominated by extensive production of export commodities because of the long-standing and possibly irreversible surplus production of food. Therefore a broad scope for adoption of digital technologies but focussed on production efficiencies.

Third, there is a need to recognize the contrasting innovation pathways that will develop for digital agriculture. The creation of IP and its subsequent appropriation follows distinct patterns in industries according to fundamental characteristics such as product type, capitalization and time since innovation (Malerba, 2006). Sectors that already have well-established pathways, such as plant and animal breeders, machinery and agrochemical manufacturers, will be able to operate within larger value frameworks. Smaller start-ups will be able to move quickly within selected small-volume frameworks, but their impact on the whole sector is uncertain. While the word 'disruption' is often associated with digital technology, not all change will be disruptive.

8.2 The roles for digital technology in sustainable Australian food systems

To understand the transformative changes digital technology will bring to agriculture, we need to analyse it within a development context. While some developments are impossible to predict (who would have predicted Uber 20 years ago?), we do know how development trajectories work, which provide some insights.

Australian agribusiness is ripe for major growth. Digital agriculture is projected to support growth to an USD$78 billion industry by 2030 (National Farmers Federation & KPMG, 2018). The expectation is dominated by gains in productivity, automation, managing crops and livestock under challenging environment, and managing financial risk. Gains in value determined by volatile trading conditions are less predictable, and most rapid growth will be in small volume, specialist products rather than large commodity exports although these ultimately are likely to account for most of the gain. The scalability of success will be limited by the organization and the activation of institutions, in which governments will play an important part.

Digital technology will fundamentally shift some change dynamics, with duality between large incumbent organizations and smaller partners becoming important. Disruptive start-ups appear exciting, but most start-ups fail, largely through their inability to scale. Moreover, experience elsewhere shows that some of the bigger movers in the field will aim to dominate its space if governments allow them to do so, thereby squeezing out potential newcomers. Small-volume, high-value products look appealing, but how much innovation can they support in Australia without government intervention?

Attention to changes in food system function is also a vital issue. Traditional agri-food systems thinking need to be modified to capture the nuances of systems that are increasingly operating in new, more complex ways. Digital agriculture technology could support moves toward sustainability by connecting activities to changes in natural capitals through data-enabled land valuation or carbon financing. However such moves must first contend with existing interests that may not feel the need for change. Digital technology and innovation rely on connectivity between actors within the framework and functioning institutions to foster growth. Actors within food systems need not just utilise new technologies but apply better tools to assist planning, and to help them deal with the increasing complexity. New partners and business models can arise if connection is easy.

Governments play a major role in supporting resilient and sustainable food systems. Digital technology will help producers manage risk, but digital technology should also ensure appropriate investment in natural and human capitals on which resilience depends. It would be a serious error to overlook the biology that underpins complex food systems. Artificial intelligence and machine learning will provide new insights, but these will acquire value only when they are understood within their environment.

References

Agrifutures Australia. (2021). *Space-based technologies – opportunities for the rural sector*. Agrifutures Australia.

Annosi, M. C., Brunetta, F., Monti, A., & Nati, F. (2019). Is the trend your friend? An analysis of technology 4.0 investment decisions in agricultural SMEs. *Computers in Industry*, *109*, 59–71. https://doi.org/10.1016/j.compind.2019.04.003

Antle, J. M., Basso, B., Conant, R. T., Godfray, H. C. J., Jones, J. W., Herrero, M., Howitt, R. E., Keating, B. A., Munoz-Carpena, R., Rosenzweig, C., Tittonell, P., & Wheeler, T. R. (2017). Towards a new generation of agricultural system data, models and knowledge products: Design and improvement. *Agricultural Systems*, *155*, 255–268. https://doi.org/10.1016/j.agsy.2016.10.002

Australian Government. (2018). *Statement of Principles for Australian Innovation Precincts*. Department of Industry, Innovation and Science.

Banhazi, T. M., Lehr, H., Black, J. L., Crabtree, H., Schofield, P., Tscharke, M., & Berckmans, D. (2012). Precision Livestock Farming: An international review of scientific and commercial aspects. *International Journal of Agricultural and Biological Engineering*, *5*(3). Scopus. https://doi.org/10.3965/j.ijabe.20120503.00?

Barge, P., Gay, P., Merlino, V., & Tortia, C. (2013). Radio frequency identification technologies for livestock management and meat supply chain traceability. *Canadian Journal of Animal Science*, *93*(1), 23–33. https://doi.org/10.4141/cjas2012-029

Baumber, A., Metternicht, G., Ampt, P., Cross, R., & Berry, E. (2018). From Importing Innovations to Co-Producing Them: Transdisciplinary Approaches to the Development of Online Land Management Tools. *Technology Innovation Management Review*, *8*(8), 16–26. https://doi.org/10.22215/timreview/1175

Behnke, K., & Janssen, M. F. W. H. A. (2020). Boundary conditions for traceability in food supply chains using blockchain technology. *International Journal of Information Management*, *52*, 101969. https://doi.org/10.1016/j.ijinfomgt.2019.05.025

Béné, C., Oosterveer, P., Lamotte, L., Brouwer, I. D., de Haan, S., Prager, S. D., Talsma, E. F., & Khoury, C. K. (2019). When food systems meet sustainability – Current narratives and implications for actions. *World Development*, *113*, 116–130. https://doi.org/10.1016/j.worlddev.2018.08.011

Benton, T. G., Bieg, C., Harwatt, H., Pudasaini, R., & Wellesley, L. (2021). *Food system impacts on biodiversity loss: Three levers for food system transformation in support of nature*. Royal INstitute of International Affairs.

Berti, G., & Mulligan, C. (2016). Competitiveness of Small Farms and Innovative Food Supply Chains: The Role of Food Hubs in Creating Sustainable Regional and Local Food Systems. *Sustainability*, *8*(7), 616. https://doi.org/10.3390/su8070616

Blackburn, S., Gartner, D., Freeland, M., Kelley, A., Pickover, S., Thomassian, S., & Ubaldi, N. (2017). *Digital Australia: Seizing the opportunity from the fourth industrial revolution*. McKinsey & Company.

Bowersox, D. J., Closs, D. J., & Drayer, R. (2005). The Digital Transformation: Technology and Beyond. *SUPPLY CHAIN MANAGEMENT REVIEW*, *9*(1). https://trid.trb.org/view/751438

Briscoe, B., Odlyzko, A., & Tilly, B. (2006, 7). Metcalfe's Law is Wrong. *IEEE Spectrum*.

Bruinsema, J. (2009). *By how much do land, water and crop yields need to increase by 2050?* FAO Expert meeting on how to feed the world in 2050, 24–26 June, 2009. ftp://ftp.fao.org/docrep/fao/012/ak971e/ak971e00.pdf

Bughin, J., Catlin, T., Hirt, M., & Willmott, P. (2018). Why digital strategies fail. *McKinsey Quarterly*, 1–15.

Burwood-Taylor, L., Leclerc, R., Chauhan, R., & Inc, A. (2020). *2020 Farm Tech Investment Report*. 47.

Burwood-Taylor, L., Leclerc, R., Chauhan, R., & Inc, A. (2021). *2021 AgFunder AgriFoodTech Investment Report*. 58.

Cao, S., Powell, W., Foth, M., Natanelov, V., Miller, T., & Dulleck, U. (2021). Strengthening consumer trust in beef supply chain traceability with a blockchain-based human-machine reconcile mechanism. *Computers and Electronics in Agriculture*, *180*, 105886. https://doi.org/10.1016/j.compag.2020.105886

Carlino, G., & Kerr, W. R. (2014). *Agglomeration and Innovation* (p. 62). NBER.

Cassman, K. G., & Dobermann, A. (2021). Nitrogen and the future of agriculture: 20 years on: This article belongs to Ambio's 50th Anniversary Collection. Theme: Solutions-oriented research. *Ambio*, s13280-021-01526-w. https://doi.org/10.1007/s13280-021-01526-w

Cassman, K. G., & Grassini, P. (2020). A global perspective on sustainable intensification research. *Nature Sustainability*, *3*(4), 262–268. https://doi.org/10.1038/s41893-020-0507-8

Charvat, K., Junior, K. C., Reznik, T., Lukas, V., Jedlicka, K., Palma, R., & Berzins, R. (2018). Advanced Visualisation of Big Data for Agriculture as Part of Databio Development. *IGARSS 2018 - 2018 IEEE International Geoscience and Remote Sensing Symposium*, 415–418. https://doi.org/10.1109/IGARSS.2018.8517556

Cho, G. (2018). The Australian digital farmer: Challenges and opportunities. *IOP Conference Series: Earth and Environmental Science*, *185*, 012036. https://doi.org/10.1088/1755-1315/185/1/012036

Cong, R.-G., Hedlund, K., Andersson, H., & Brady, M. (2014). Managing soil natural capital: An effective strategy for mitigating future agricultural risks? *Agricultural Systems*, *129*, 30–39. https://doi.org/10.1016/j.agsy.2014.05.003

Connaughton, S. L., Williams, A., Anderson, F., Kelman, K. R., & Gardner, G. E. (2020). Dual energy X-ray absorptiometry precisely and accurately predicts lamb carcass composition at abattoir chain speed across a range of phenotypic and genotypic variables. *Animal*, *14*(10), 2194–2202. https://doi.org/10.1017/S1751731120001019

Cook, S. E., & Bramley, R. G. V. (1998). Precision agriculture—Opportunities, benefits and pitfalls of site-specific crop management in Australia. *Australian Journal of Experimental Agriculture*, *38*(7), 753. https://doi.org/10.1071/EA97156

CSB-SYSTEM. (2020). *From hype to implementation: Digitization in the food industry* (p. 20). https://info.csb.com/

Darnell, R., Moore, A., Barry, S., Bramley, R., Grundy, M., & George, A. (2018). The Current and Future State of Australian Agricultural Data. *Farm Policy Journal*, *15*(1), 9.

Delgado-Pando, G., Allen, P., Troy, D. J., & McDonnell, C. K. (2021). Objective carcass measurement technologies: Latest developments and future trends. *Trends in Food Science & Technology*, *111*, 771–782. https://doi.org/10.1016/j.tifs.2020.12.016

Demartini, M., Pinna, C., Tonelli, F., Terzi, S., Sansone, C., & Testa, C. (2018). Food industry digitalization: From challenges and trends to opportunities and solutions. *IFAC-PapersOnLine*, *51*(11), 1371–1378. https://doi.org/10.1016/j.ifacol.2018.08.337

Dilmegani, C., Korkmaz, B., & Lundqvist, M. (2014). *Public-sector digitization: The trillion-dollar challenge* (p. 4). McKinsey & Company.

Edquist, C. (2006). *Systems of Innovation: Perspectives and Challenges*. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199286805.003.0007

Ernst and Young. (2019). *Agricultural Innovation: A National Approach to Grow Australia's Future* (p. 166).

Fagerberg, J. (2003). Schumpeter and the revival of evolutionary economics: An appraisal of the literature. *Journal of Evolutionary Economics*, *13*(2), 125–159. https://doi.org/10.1007/s00191-003-0144-1

FAO. (2020). *The State of Food Security and Nutrition in the World 2020*. FAO, IFAD, UNICEF, WFP and WHO. https://doi.org/10.4060/ca9692en

FAO, WHO, & WTO. (2019). *Joint Statement: International Forum on Food Safety and Trade*. FAO, WHO, WTO.

Fielke, S., Taylor, B., & Jakku, E. (2020). Digitalisation of agricultural knowledge and advice networks: A state-of-the-art review. *Agricultural Systems*, *180*, 102763. https://doi.org/10.1016/j.agsy.2019.102763

Fiocco, D., Ganesan, V., Harrison, L., & Pawlowski, J. (2021). *Farmers value digital engagement, but want suppliers to step up their game* (p. 8). McKinsey & Company.

Fischer, R. A., & Connor, D. J. (2018). Issues for cropping and agricultural science in the next 20 years. *Field Crops Research*, *222*, 121–142. https://doi.org/10.1016/j.fcr.2018.03.008

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., … Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature*, *478*(7369), 337–342. https://doi.org/10.1038/nature10452

Freidberg, S. (2020). "Unable to Determine": Limits to Metrical Governance in Agricultural Supply chains. *Science, Technology, & Human Values*, *45*(4), 738–760. https://doi.org/10.1177/0162243919870234

Gao, Z., & Schroeder, T. C. (2009). Effects of Label Information on Consumer Willingness-to-Pay for Food Attributes. *American Journal of Agricultural Economics*, *91*(3), 795–809. JSTOR.

Godfray, C., Beddington, J. H., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., & Toulmin, C. (2010). Food Security: The Challenge of Feeding 9 Billion People. *Science*, *327*, 812.

Godfray, H. C. J., & Garnett, T. (2014). Food security and sustainable intensification. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1639), 20120273. https://doi.org/10.1098/rstb.2012.0273

Goldfarb, A., & Tucker, C. (2017). *Digital Economics* (No. w23684; p. w23684). National Bureau of Economic Research. https://doi.org/10.3386/w23684

Government Office of Science. (2011). *Future of food and farming. Final Project Report* [Science Report]. UK Government Office of Science.

Grassini, P., Eskridge, K. M., & Cassman, K. G. (2013). Distinguishing between yield advances and yield plateaus in historical crop production trends. *Nature Communications*, *4*. Scopus. https://doi.org/10.1038/ncomms3918

Greenville, J. (2019). Australia's place in global agriculture and food value chains. *Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra. CC BY 4.0*, 8. https://doi.org/10.25814/5d799a58db665

Gregory, M. A. (2020). *Rural and remote Australia and telecommunications and digital services*. https://regionaldevelopment.org.au/remote-rural-australia-dudded-nbn/

Griffith, C., Heydon, G., Lamb, D. J., Lefort, L., Taylor, K., & Trotter, M. (2013). *Smart Farming: Leveraging the impact of broadband and the digital economy* (p. 26). CSIRO and University of New England. https://hdl.handle.net/1959.11/13546

Grunert, K. G. (2005). Food quality and safety: Consumer perception and demand. *European Review of Agricultural Economics*, *32*(3), 369–391. https://doi.org/10.1093/eurrag/jbi011

Hall, A., Jansenn, W., Pehu, E., & Rajalahti, R. (2006). *Enhancing Agricultural Innovation: How to Go Beyond the Strengthening of Research Systems*. World Bank. www.worldbank.org/rural

Heath, R. (2018). An Analysis of the Potential of Digital Agriculture for the Australian Economy. *Farm Policy Journal*, *15*(1), 15.

Herrero, M., Thornton, P. K., Mason-D'Croz, D., Palmer, J., Bodirsky, B. L., Pradhan, P., Barrett, C. B., Benton, T. G., Hall, A., Pikaar, I., Bogard, J. R., Bonnett, G. D., Bryan, B. A., Campbell, B. M., Christensen, S., Clark, M., Fanzo, J., Godde, C. M., Jarvis, A., … Rockström, J. (2021). Articulating the effect of food systems innovation on the Sustainable Development Goals. *The Lancet Planetary Health*, *5*(1), e50–e62. https://doi.org/10.1016/S2542-5196(20)30277-1

Hingley, M. K. (2005). Power imbalanced relationships: Cases from UK fresh food supply. *International Journal of Retail & Distribution Management*, *33*(8), 551–569. https://doi.org/10.1108/09590550510608368

International Society of Precision Agriculture. (2019). *Precision Ag Definition*. https://ispag.org/about/definition

IP Australia. (2020). *Australian Intellectual Property Report 2020*. https://www.ipaustralia.gov.au/sites/default/files/2020_ip_report.pdf

Janssen, S. J. C., Porter, C. H., Moore, A. D., Athanasiadis, I. N., Foster, I., Jones, J. W., & Antle, J. M. (2017). Towards a new generation of agricultural system data, models and knowledge products: Information and communication technology. *Agricultural Systems*, *155*, 200–212. https://doi.org/10.1016/j.agsy.2016.09.017

Jones, J. W., Antle, J. M., Basso, B., Boote, K. J., Conant, R. T., Foster, I., Godfray, H. C. J., Herrero, M., Howitt, R. E., Janssen, S., Keating, B. A., Munoz-Carpena, R., Porter, C. H., Rosenzweig, C., & Wheeler, T. R. (2017). Toward a new generation of agricultural system data, models, and knowledge products: State of agricultural systems science. *Agricultural Systems*, *155*, 269–288. https://doi.org/10.1016/j.agsy.2016.09.021

Kane, G. C., Nguyen Phillips, A., Copulsky, J. R., & Andrus, G. R. (2019). *The Technology Fallacy: How people are the real key to digital transformation*. MIT Press.

Keogh, M. (2019). *A national vision for digital agriculture*. ACCC. https://www.accc.gov.au/speech/a-national-vision-for-digital-agriculture

Keogh, M., & Henry, M. (2016). *The implications of digital agriculture and big data for Australian agriculture*. Australian Farm Institute.

King, B., Fielke, S., Bayne, K., Klerkx, L., & Nettle, R. (2019). Navigating shades of social capital and trust to leverage opportunities for rural innovation. *Journal of Rural Studies*, *68*, 123–134. https://doi.org/10.1016/j.jrurstud.2019.02.003

Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. *NJAS - Wageningen Journal of Life Sciences*, *90–91*, 100315. https://doi.org/10.1016/j.njas.2019.100315

Kobayashi, M., Ohyanagi, H., & Yano, K. (2015). Omics Analysis and Databases for Plant Science. In *Genomics, Proteomics and Metabolomics in Nutraceuticals and Functional Foods: Second Edition* (pp. 150–159). Scopus. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84976871379&partnerID=40&md5=e618138e18ba371d35b76e1fd1656059

KPMG, & Skills Impact. (2019). *Agricultural workforce digital capability framework*. CRDC and others.

Kramer, M. P., Bitsch, L., & Hanf, J. (2021). Blockchain and Its Impacts on Agri-Food Supply Chain Network Management. *Sustainability*, *13*(4), 2168. https://doi.org/10.3390/su13042168

Kretser, A., Murphy, D., Finley, J., & Brenner, R. (2015). A Partnership for Public Health: Branded Food Products Database. *Procedia Food Science*, *4*, 18–26. https://doi.org/10.1016/j.profoo.2015.06.005

Kühne, B., Gellynck, X., & Weaver, R. D. (2015). Enhancing Innovation Capacity Through Vertical, Horizontal, and Third-Party Networks for Traditional Foods. *Agribusiness*, *31*(3), 294–313. https://doi.org/10.1002/agr.21408

Kumar, A., Singh, R. K., & Modgil, S. (2020). Exploring the relationship between ICT, SCM practices and organizational performance in agri-food supply chain. *Benchmarking: An International Journal*, *27*(3), 1003–1041. https://doi.org/10.1108/BIJ-11-2019-0500

Lamb, D. (2017). Telecommunications and Australian Agriculture: Will Top-Down Meet Bottom-Up? *Farm Policy Journal*, *14*(3), 17.

Lammers, T., Tomidei, L., & Regattieri, A. (2018). What Causes Companies to Transform Digitally? An Overview of Drivers for Australian Key Industries. *2018 Portland International Conference on Management of Engineering and Technology (PICMET)*, 1–8. https://doi.org/10.23919/PICMET.2018.8481810

Lawes, R., Chan, C., & van Rees, H. (2018). *The National Paddock Survey—What causes the yield gap across Australian paddocks* [Update Papers]. GRDC. https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/02/the-national-paddock-survey-what-causes-the-yield-gap-across-australian-paddocks

Leonard, E., Rainbow, R., Trindall, J., Baker, I., Barry, S., Darragh, L., Darnell, R., George, A., Heath, R., Jakku, E., Laurie, A., Lamb, D., Llewellyn, R., Perrett, E., Sanderson, J., Skinner, A., Stollery, T., Wiseman, L., Wood, G., … Cotton Research & Development Corporation (Australia). (2017). *Accelerating precision agriculture to decision agriculture: Enabling digital agriculture in Australia : summary report*.

Lev, L., & Stevenson, G. (2011). Acting Collectively to Develop Mid-Scale Food Value Chains. *Journal of Agriculture, Food Systems, and Community Development*, 119–128. https://doi.org/10.5304/jafscd.2011.014.014

Llewellyn, R., & Ouzman, J. (2015). *Adoption of precision agriculture-related practices: Status, opportunities and the role of farm advisers* (p. 76). CSIRO.

Lowenberg-DeBoer, J., & Erickson, B. (2019). Setting the Record Straight on Precision Agriculture Adoption. *Agronomy Journal*, *111*(4), 1552–1569. https://doi.org/10.2134/agronj2018.12.0779

Mackenzie, J. S., & Jeggo, M. (2019). The One Health Approach—Why Is It So Important? *Tropical Medicine and Infectious Disease*, *4*(2), 88. https://doi.org/10.3390/tropicalmed4020088

Maglaras, G., Bourlakis, M., & Fotopoulos, C. (2015). Power-imbalanced relationships in the dyadic food chain: An empirical investigation of retailers' commercial practices with suppliers. *Industrial Marketing Management*, *48*, 187–201. https://doi.org/10.1016/j.indmarman.2015.03.014

Malerba, F. (2006). *Sectoral Systems: How and Why Innovation Differs across Sectors*. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199286805.003.0014

Manyika, J., Ramaswamy, S., Khanna, S., Sarrazin, H., Pinkus, ., Sethupathy, G., & Yaffe, A. (2015). *Digital America: A Tale of the Haves and Have-Mores*. McKinsey Global Institute.

Mearian, L. (2018). Walmart's Frank Yiannas on the use of blockchain for food safety. *Computerworld*. https://www.computerworld.com/article/3309656/qa-walmarts-frank-yiannas-on-the-use-of-blockchain-for-food-safety.html

Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: Synthesis*. Island Press.

Molden, D., de Fraiture, C., & Rijsberman, F. (2007). Water Scarcity: The Food Factor. *Issues in Science and Technology*, *23*(4), 39–48. Science Database.

Montealegre, F., Thompson, S., & Eales, J. (2007). An Empirical Analysis of the Determinants of Success of Food and Agribusiness E-Commerce Firms. *International Food and Agribusiness Management Review*, *10*(1), 21.

National Farmers Federation. (2020). *Farm Data Code. Edition 1.* NFF. https://nff.org.au/wp-content/uploads/2020/02/Farm_Data_Code_Edition_1_WEB_FINAL.pdf

National Farmers Federation, & KPMG. (2018). *Talking 2030—Growing agriculture into a $100 billion industry*.

National Research Council. (1997). *Precision Agriculture in the 21st Century: Geospatial and Information Technologies in Crop Management*. National Academies Press. https://doi.org/10.17226/5491

Nguyen, N. C., Wegener, M., Russell, I., Cameron, D., Coventry, D., & Cooper, I. (2007). Risk management strategies by Australian farmers: Two case studies. *Austraqlian Farm Business Management Journal*, *4*(1 & 2), 23–30.

Nirmalathas, T. A. (2016). Regional Australia is crying out for equitable access to broadband. *The Conversation*. https://theconversation.com/regional-australia-is-crying-out-for-equitable-access-to-broadband-69711

OECD. (2015). *Innovation, Agricultural Productivity and Sustainability in Australia*. OECD. https://doi.org/10.1787/9789264238367-en

Oreszczyn, S., Lane, A., & Carr, S. (2010). The role of networks of practice and webs of influencers on farmers' engagement with and learning about agricultural innovations. *Journal of Rural Studies*, *26*(4), 404–417. https://doi.org/10.1016/j.jrurstud.2010.03.003

Pachauri, R. K., Mayer, L., & Intergovernmental Panel on Climate Change (Eds.). (2015). *Climate change 2014: Synthesis report*. Intergovernmental Panel on Climate Change.

Pavitt, K. (1984). Sectoral patterns of technical change: Towards a taxonomy and a theory. *Research Policy*, *13*(6), 343–373. https://doi.org/10.1016/0048-7333(84)90018-0

Perrett, E., Heath, R., Laurie, A., & Darragh, L. (2017). *Accelerating precision to decision agriculture. Analysis of the economic benefits and strategies for delivery of digital agriuclture in Australia* (p. 331). Australian Farm Institute.

Pigford, A.-A. E., Hickey, G. M., & Klerkx, L. (2018). Beyond agricultural innovation systems? Exploring an agricultural innovation ecosystems approach for niche design and development in sustainability transitions. *Agricultural Systems*, *164*, 116–121. https://doi.org/10.1016/j.agsy.2018.04.007

Polk, M. (2015). Transdisciplinary co-production: Designing and testing a transdisciplinary research framework for societal problem solving. *Futures*, *65*, 110–122. https://doi.org/10.1016/j.futures.2014.11.001

Pretty, J., Benton, T. G., Bharucha, Z. P., Dicks, L. V., Flora, C. B., Godfray, H. C. J., Goulson, D., Hartley, S., Lampkin, N., Morris, C., Pierzynski, G., Prasad, P. V. V., Reganold, J., Rockström, J., Smith, P., Thorne, P., & Wratten, S. (2018). Global assessment of agricultural system redesign for sustainable intensification. *Nature Sustainability*, *1*(8), 441–446. https://doi.org/10.1038/s41893-018-0114-0

Pretty, J. N. (1997). The sustainable intensification of agriculture. *Natural Resources Forum*, *21*(4), 247–256. https://doi.org/10.1111/j.1477-8947.1997.tb00699.x

QGIS Development Team. (2021). *QGIS Geographic Information System. Open Source Geospatial Foundation Project*. http://qgis.org

R Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing,. https://www.R-project.org/

Ramasubramanian, L. (2010). The Digital Revolution. In L. Ramasubramanian, *Geographic Information Science and Public Participation* (pp. 19–32). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-75401-5_2

Rejeb, A., Keogh, J. G., Zailani, S., Treiblmaier, H., & Rejeb, K. (2020). Blockchain Technology in the Food Industry: A Review of Potentials, Challenges and Future Research Directions. *Logistics*, *4*(4), 27. https://doi.org/10.3390/logistics4040027

Rocchi, B., Romano, D., Sadiddin, A., & Stefani, G. (2020). Assessing the economy-wide impact of food fraud: A SAM-based counterfactual approach. *Agribusiness*, *36*(2), 167–191. https://doi.org/10.1002/agr.21633

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., … Foley, J. A. (2009). A safe operating space for humanity. *Nature*, *461*(7263), 472–475. https://doi.org/10.1038/461472a

Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., Wetterstrand, H., DeClerck, F., Shah, M., Steduto, P., de Fraiture, C., Hatibu, N., Unver, O., Bird, J., Sibanda, L., & Smith, J. (2017). Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio*, *46*(1), 4–17. https://doi.org/10.1007/s13280-016-0793-6

Rojo-Gimeno, C., van der Voort, M., Niemi, J. K., Lauwers, L., Kristensen, A. R., & Wauters, E. (2019). Assessment of the value of information of precision livestock farming: A conceptual framework. *NJAS - Wageningen Journal of Life Sciences*, *90–91*, 100311. https://doi.org/10.1016/j.njas.2019.100311

Ruiz-Garcia, L., Lunadei, L., Barreiro, P., & Robla, J. I. (2009). A review of wireless sensor technologies and applications in agriculture and food industry: State of the art and current trends. *Sensors (Switzerland)*, *9*(6), 4728–4750. Scopus. https://doi.org/10.3390/s90604728

Sanderson, T., Reeson, A., & Box, P. (2017). *Cultivating Trust: Towards an Australian Agricultural Data Market* (p. 30). CSIRO Australia.

Satell, G. (2019). Why “Move Fast and Break Things” Doesn’t Work Anymore. *Harvard Business Review*, 5.

Schiller, R. J. (2017). *Narrative Economics* (NBER WORKING PAPER SERIES No. 23075). NBER. http://www.nber.org/papers/w23075

Sedex Australia. (2018). https://www.sedex.com/sedex-australia/

Shafiee-Jood, M., & Cai, X. (2016). Reducing Food Loss and Waste to Enhance Food Security and Environmental Sustainability. *Environmental Science & Technology*, *50*(16), 8432–8443. https://doi.org/10.1021/acs.est.6b01993

Shepherd, M., Turner, J. A., Small, B., & Wheeler, D. (2020). Priorities for science to overcome hurdles thwarting the full promise of the ‘digital agriculture’ revolution. *Journal of the Science of Food and Agriculture*, *100*(14), 5083–5092. https://doi.org/10.1002/jsfa.9346

Skog, D. A., Wimelius, H., & Sandberg, J. (2018). Digital Disruption. *Business & Information Systems Engineering*, *60*(5), 431–437. https://doi.org/10.1007/s12599-018-0550-4

Sligo, F. X., & Massey, C. (2007). Risk, trust and knowledge networks in farmers’ learning. *Journal of Rural Studies*, *23*(2), 170–182. https://doi.org/10.1016/j.jrurstud.2006.06.001

Solow, R. M. (1991). *Sustainability: An Economists Perspective*. 18th J Seward Johnson Lecture, Woods Hole Oceanographic Institution.

Spence, M. (2002). Signaling in Retrospect and the Informational Structure of Markets. *The American Economic Review*, *92*(3), 434–459. JSTOR.

Staples, M., Chen, S., Falamaki, S., Ponomarev, A., Rimba, P., Tran, A. B., Weber, I., Xhu, X., & Zhu, J. (2017). *Risks and opportunities for systems using blockchain and smart contracts*. CSIRO Data 61. https://linkinghub.elsevier.com/retrieve/pii/S096098229770976X

Sykuta, M. E. (2016). *Big Data in Agriculture: Property Rights, Privacy and Competition in Ag Data Services*. http://www.ifama.org/resources/Documents/v19ia/320150137.pdf

Tabrizi, B., Lam, E., Girard, K., & Irvin, V. (2019). Digital Transformation is Not About Technology. *Harvard Business Review*, 7.

Taylor, D. H., & Fearne, A. (2006). Towards a framework for improvement in the management of demand in agri-food supply chains. *Supply Chain Management: An International Journal*, *11*(5), 379–384. https://doi.org/10.1108/13598540610682381

Taylor, D. H., & Fearne, A. (2009). Demand management in fresh food value chains: A framework for analysis and improvement. *Supply Chain Management: An International Journal*, *14*(5), 379–392. https://doi.org/10.1108/13598540910980297

Theuvsen, L., Plumeyer, C.-H., & Gawron, J.-C. (2007). *Certification Systems in the Meat Industry: Overview and Consequences for Chain-wide Communicaton*. *57*(4), 563–569.

Thomas, C. (2018). *2030 Industry Roadmap. Australian Agriculture's Plan for a $100 Billion Industry* (p. 48). National Farmers Federation.

Trendov, N. K., Varas, S., & Zeng, M. (2019a). *Digital technologies in agriculture and rural areas—Briefing paper* (p. 26). FAO.

Trendov, N. K., Varas, S., & Zeng, M. (2019b). *Digital technologies in agriculture and rural areas—Status report* (p. 152). FAO.

Tripoli, M., & Schmidhuber, J. (2018). *Emerging Opportunities for the Application of Blockchain in the Agri-food Industry* (p. 40). FAO and ICTSD.

UNEP. (2014). *Assessing Global Land Use: Balancing Consumption with Sustainable Supply. A Report of the Working Group on Land and Soils of the International Resource Pane*.

UNI-IHDP, & UNEP. (2012). Inclusive Wealth Report 2012 – Measuring Progress Toward Sustainability. *International Journal of Sustainability in Higher Education*, *13*(4), ijshe.2012.24913daa.006. https://doi.org/10.1108/ijshe.2012.24913daa.006

United Nations, Department of Economic and Social Affairs, & Population Division. (2019). *World population prospects Highlights, 2019 revision Highlights, 2019 revision*.

United Soybean Board. (2019). *Rural Broadband and the American Farmer*. United Soybean Board. https://api.unitedsoybean.org/uploads/documents/58546-1-ruralbroadband-whitepages-final.pdf

US FDA. (2019). Deputy Commissioner Champions More Digital, Transparent Food Safety System. *Conversations with Experts on Food Topics*. https://www.fda.gov/food/conversations-experts-food-topics/deputy-commissioner-champions-more-digital-transparent-food-safety-system

van der Burg, S., Bogaardt, M.-J., & Wolfert, S. (2019). Ethics of smart farming: Current questions and directions for responsible innovation towards the future. *NJAS - Wageningen Journal of Life Sciences*, *90–91*, 100289. https://doi.org/10.1016/j.njas.2019.01.001

Verbeke, W. (2005). Agriculture and the food industry in the information age. *European Review of Agricultural Economics*, *32*(3), 347–368. https://doi.org/10.1093/eurrag/jbi017

Wathes, C. M., Kristensen, H. H., Aerts, J.-M., & Berckmans, D. (2008). Is precision livestock farming an engineer's daydream or nightmare, an animal's friend or foe, and a farmer's panacea or pitfall? *Computers and Electronics in Agriculture*, *64*(1), 2–10. https://doi.org/10.1016/j.compag.2008.05.005

Wei, Y. D., Lin, J., & Zhang, L. (2020). E-Commerce, Taobao Villages and Regional Development in China. *Geographical Review*, *110*(3), 380–405. https://doi.org/10.1111/gere.12367

Weiss, M., Jacob, F., & Duveiller, G. (2020). Remote sensing for agricultural applications: A meta-review. *Remote Sensing of Environment*, *236*, 111402. https://doi.org/10.1016/j.rse.2019.111402

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L. J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., De Vries, W., Majele Sibanda, L., … Murray, C. J. L. (2019). Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet*. https://doi.org/10.1016/S0140-6736(18)31788-4

Wiseman, L., & Sanderson, J. (2018a). *Agricultural Data Rules. Best management practice*. CRDC and others.

Wiseman, L., & Sanderson, J. (2018b). *The Legal Dimensions of Digital Agriculture in Australia: An examination of the current and future state of data rules dealing with ownership, access, privacy and trust*. CRDC. https://www.crdc.com.au/sites/default/files/P2D%20Legal%20Dimensions%20-%20Griffith%20USC%20Final%20Report.pdf

Wojnowski, W., Majchrzak, T., Dymerski, T., Gębicki, J., & Namieśnik, J. (2017). Electronic noses: Powerful tools in meat quality assessment. *Meat Science*, *131*, 119–131. https://doi.org/10.1016/j.meatsci.2017.04.240

Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M.-J. (2017). Big Data in Smart Farming – A review. *Agricultural Systems*, *153*, 69–80. https://doi.org/10.1016/j.agsy.2017.01.023

Wolfert, S., Goense, D., & Sorensen, C. A. G. (2014). A future internet collaboration platform for safe and healthy food from farm to fork. *Annu. SRII Global Conf., SRII*, 266–273. Scopus. https://doi.org/10.1109/SRII.2014.47

World Bank (Ed.). (2021). *World Development Report 2021: Data for better lives*. World Bank.

World Economic Forum. (2019). *Why the agtech boom isn't your typical tech disruption*. https://www.weforum.org/agenda/2019/02/why-the-agtech-boom-isn-t-your-typical-tech-disruption/

Yiannis, F. (2019). A day to remember all year. *Food Safety News*. https://www.foodsafetynews.com/2019/06/a-day-to-remember-all-year/

Zhang, Y., Baker, D., & Griffith, G. (2020). Product quality information in supply chains: A performance-linked conceptual framework applied to the Australian red meat industry. *The International Journal of Logistics Management*, *31*(3), 697–723. https://doi.org/10.1108/IJLM-06-2019-0157