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Tracking the diverse pathways to value for digital agriculture

Simon Cook[A] and Davide Cammarano[B,*]

For full list of author affiliations and declarations see end of paper

*Correspondence to:
Davide Cammarano
Department of Agroecology, iClimate, CBIO, Aarhus University, Tjele 8800, Denmark
Email: davide.cammarano@agro.au.dk

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Lowenberg de Boer and others reviewed the adoption of precision agriculture – a subset of digital agriculture – and concluded that, while adoption was patchy, it has approached saturation for some technologies that are easy for farmers to use. If we also consider the use of field machinery that contains significant digital technology as adoption, or of inputs such as germplasm or agrochemicals that rely heavily on digital technologies for their formation and use, the rate of technology adoption increases substantially, since these components are used on the majority of large farms throughout the world. In effect, digital technology is entering food systems in a variety of forms, only some of which measurable as adoption by farmers. If we look beyond the direct use of technology by farmers and include the range of products or processes that embed digital technology, we expect the level of digitisation to exceed the low level indicated some years ago by analysis of processes (Manyika *et al.* 2015).

Shepherd *et al.* (2020) defines digital agriculture as 'the use of detailed digital information to guide decisions along the agricultural value chain'. Excellent as this definition is, we suggest to expand its scope for two reasons. Firstly, digital agriculture does more than guide decisions. It is also used, for example, to develop new insights, to facilitate control, or to support innovation processes that create the many applications now emerging globally. Secondly, digital agriculture is active beyond the domain of value chains. For example, to help observe the environment in which they operate, to help quantify complex processes, regulate or value it (Cook *et al.* 2022). We observe applications for digital agriculture throughout and around food systems; from production, through processing to marketing and resource management.

The scope and diversity of digital agriculture development can create difficulties for scientists trying to understand the nature of change and the likely opportunities for them to contribute. What is the common purpose that links and organises such a wide range of digital agriculture applications? All digital agriculture applications are driven by value creation. In general, we know that they create value by reducing costs, increasing productivity and efficiency, increasing product value and by enabling innovation. Further, we know that they do so through the agency of four classes of technology by using: (1) new, cheap and actionable data; (2) complex models to combine data to generate valuable insight for users; (3) digital technology to control processes; and (4) new and extensive communication networks through which to innovate.

In this Special Issue, we bring together accounts of digital agriculture development from Australia, Brazil, Argentina, Uruguay, Chile, India, France and the EU. Each account provides independent insight of digital agriculture development. Together, they provide a spectrum of experience that illustrate the pathways that developers of digital agriculture follow. We organise these experiences using the classification of Pavitt (1984), with four types of technology adoption.

The first adoption type is called supplier dominated. In this class, farmers are customers of suppliers of digital technology. They purchase the technology in anticipation of benefits, predominantly from gains in efficiency. Examples of successes and failures are observed in this special issue from India (Goswami), Australia (Lawes) and Latin America (Puntel). Other studies observe mixed successes in reference to precision agriculture in the US, EU and elsewhere (Lowenberg-DeBoer and Erickson 2019).

The second adoption type is the scale intensive adopter. In food systems, organisations such as bulk handlers or fertiliser producers derive value from scale. These organisations are strongly vertically integrated and adopt digital technologies to improve processes up and down the value chain to support gains of efficiency, purchasing or marketing power.

As Pavitt (1984) observes, these changes are often internally sourced and IP protected behind organisational walls. Digital agriculture in such organisations may develop out of public sight, but may develop wherever the organisations are integrated vertically. For example, Goswami *et al.* (2023) reports adoption by tech giants in Indian agriculture. Lawes *et al.* (2023) reports the enabling effects of a vertically integrated data supply chain in Australian grains. Hansen *et al.* (2023) identifies the need for a digital curriculum to achieve broader adoption by these adopters.

The third adoption type of digital agriculture development is the specialist supplier. Such firms acquire value from digital technology by embedding it within agricultural machinery or within other specialist inputs such as agrochemical or germplasm, which they then sell to farmers or others within the food system. The digitally-enhanced product or service commands a higher price by virtue of superior performance enabled by the technology embedded within it. Users thereby share the value of digital technology with suppliers. In such cases, the IP is often developed in-house by the supplier and stays there, perhaps protected by patent or specialist know-how. Examples of this class are cited in India (Goswami *et al.* 2023), Australia (Hansen *et al.* 2023) and Latin America (Puntel *et al.* 2023). However, start-ups also face many difficulties.

The fourth adoption type is called the science-based adopter. These develop technology applications based on a strong public science base, fostered through a strong concentric integration between actors within the agricultural system. This is the intended outcome of research policy in France and the EU to support digital agriculture (Bellon-Maurel *et al.* 2023). The process is also implicit in the public-private partnerships reported for Australia (Hansen *et al.* 2023; Lawes *et al.* 2023) and in the digital agriculture start-ups observed in India (Goswami *et al.* 2023). The openness of the public research process is seen as vital for the development of next-generation phenotyping (Tripodi *et al.* 2023). It is also required for the development of advanced weed or insect recognition cited in Australia (Amrani *et al.* 2023; Mahmudul Hasan *et al.* 2023), although in all such cases, the investment needed to scale these applications up will almost inevitably move the IP into the domains of the third class – specialist supplier – before digital agriculture applications can be offered to farmers. Jackson and Cook (2023) illustrate the opportunities and challenges of pulling digital technologies into the livestock industry in Australia.

In summary, the assembly of papers in this Special Issue explain the diverse pathways to the development of digital agriculture that are occurring globally. Individual accounts reflect the prevailing needs, capabilities and obstacles within their country or region. Together, they show a growth of adoption at different loci throughout the food system, ultimately rewarded by better productivity, product quality or resource valuation.

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Author affiliations

[A]Centre for Crop and Food Innovation, Murdoch University, Murdoch, WA 6150, Australia.

[B]Department of Agroecology, iClimate, CBIO, Aarhus University, Tjele 8800, Denmark.