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Digital technology and on-farm responses to climate shocks: exploring the relations between producer agency and the security of food production

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Abstract

Recent research into climate shocks and what this means for the on-farm production of food revealed mixed and unanticipated results. Whilst the research was triggered by a series of catastrophic, climate related disruptions, Australian beef producers interviewed for the study downplayed the immediate and direct impacts of climate shocks. When considering the changing nature of production under shifting climatic conditions, producers offered a commentary on the digital technology and data which interconnected with climate solutions deriving from both on and off the farm. Perceptions of digital technologies were mixed. Some viewpoints outlined how data driven climate solutions supported on farm planning and decision making, helping to manage climate risks and shocks. However, alongside these narratives, concerns were raised about satellite-based sustainability surveillance and their implications for producer agency. These concerns include the data-informed actions of non-farming third parties, such as bank loan call-ins for properties perceived to be a climate risk, remote surveillance of ground cover, and the commercial re-appraisal of pastoral lands as carbon sinks. Digital solutions to climate shocks thus emerge as inherently ambivalent, a response to shocks and a potential catalyst for renewed crisis. Drawing upon the theoretical lens of relationality, we argue that digital data are increasingly entangled with other material and non-material elements that may disrupt and/or reconfigure the management of farming and with that, the future security of food production. In some instances, data-based solutions to climate risks and shocks present even greater risks to producer agency than climate risks and shocks themselves.

Keywords Climate shocks · Secondary shocks · Digital technologies · Food security · Beef production · Sustainability surveillance

Introduction

With its extensive land holdings across 43% of Australia's landmass used for cattle grazing on native and modified pastures (WWF, 2024), the beef industry has been on the front line of climate shocks. Climatic shocks are sudden and unanticipated events such as droughts, floods and fires which cause significant disruptions to human health, livelihoods, ecosystems, livestock, infrastructure and assets (see O'Neill et al. 2017; Hamilton et al. 2020). Climate shocks, risks and vulnerabilities are important considerations for long term food security. However, research has primarily focussed on Majority World regions (aka the Global South) whose populations are deemed already vulnerable to food insecurity (see for example, Kogo et al. 2021; Nébié et al. 2021). Whilst that work is essential, there has been less

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attention on the nexus of climate shocks and the security of food production in Minority World contexts, such as Australia, the site of this study. Based on data collected through face-to-face interviews with pastoral beef producers in Central Queensland, this paper provides insights into the ways in which frontline actors prepare for climate shocks and aim to maintain the production of food, indirectly contributing to food security.

Extensive cattle grazing properties are increasingly becoming the focus of exogeneous climate mitigation and adaption strategies – or solutions to climate change. A key mechanism entangled in the complexities of managing natural systems is data, which is proliferating alongside digital technologies and attention to rural connectivity and connectivity literacy (Marshall et al. 2024). Whilst digital technologies have been far more common in extensive cropping systems, they have recently started to filter into extensive livestock systems. As argued in this paper, the interface between climate shocks and digital technologies are central elements in decision making relating to production. Given the claimed potential of these technologies to revolutionise food production in ways that enhance sustainability and improve food security (e.g., Basso and Antle 2020; Lindblom et al. 2017; Maffezoli et al. 2022; Shepherd et al. 2020), this is an issue that warrants further research. However, to date there has been little scrutiny of how livestock producers perceive, experience, and utilise digital technologies to manage, mitigate, or prepare for climate shocks at the property level. This paper aims to contribute knowledge in this area by focusing on how producers navigate the material and non-material elements at the intersection of natural systems, digital technologies and climate change solutions.

As well as addressing producer perspectives of the complex ways in which technology, data and climate matters intersect – this paper explores the implications for future food security. Whilst food security has garnered public attention following the impacts of Covid19, labour shortages, wars in Ukraine and the Middle East – scholarly attention has disproportionally focussed upon the consumption end of the supply chain, or the accessibility of food. In the Minority World context such as the United States, United Kingdom and Australia, the accessibility argument recognises that food is plentiful if households have the financial means to purchase it (Lambie-Mumford 2019; Leroy et al. 2015; Richards et al. 2016). However, more recently, major catastrophic events have highlighted the vulnerability of supply, and the lack of availability of foods even when customer purchasing power is strong. In Australia, for instance, major flood events have destroyed crops and disrupted the distribution of food into major supermarket chains (MacMahon et al. 2015; Smith et al. 2016) with media footage of empty shelves reminding people that food supply should not be taken for granted. Hence, it is timely to refocus food security to the site of production and better understand how climate shocks are experienced and navigated by producers, aligning with a recent call to include *sustainability* and *agency* into policy frameworks (Clapp et al. 2022; HLPE 2020). This broadened conceptualisation of food security scholarship encompasses climate and ecological crises and the "…capacity for individuals and communities to make meaningful decisions about and participate in food systems on their terms…" (Clapp et al. 2022:4).

In this paper, we aim to contribute to knowledge on how producers manage climate shocks by addressing two research questions: (1) How do producers engage with digital technology and data to prepare for climate shocks? and (2) What are the implications for the security of food production at the property level? To address these questions, we engage with a relational approach to agri-food technology that is interested in the social and material relations through which producers assemble technology to address broader goals in the context of their existing practices and priorities, and what these socio-technical forms engender for producer agency and food futures more broadly (e.g., Carolan 2017; Comi 2023; Higgins et al. 2023; Legun and Burch 2021; Van der Velden et al. 2023). This paper is structured as follows; the next section provides background information relating to the climate shocks, producers' responses, and the emerging digital intensification of the pastoral grazing sector. It then introduces a relational approach as an analytical lens to dissect how producers engage with digital technology to prepare for climate shocks, and the effects of such engagements for on-farm food production. This is followed by the research methodology governing the empirical study in the Australian grazing industry. The findings give voice to producers who describe their experiences of shocks and their engagement with digital tools to build preparedness for shocks, before discussing and presenting conclusions from this research.

Climate shocks, data-driven sustainability, and producer engagement with digital technology

This section examines work published on climate shocks and the risks they pose, the shift toward data-driven sustainability solutions, and the ways in which an emphasis on producers' engagement with digital technologies contributes to scholarly understanding of how producers prepare for and respond to shocks.

Climate shocks

Shocks, as sudden and unpredictable events, are of interest in the scholarship of food and agriculture due to their far-reaching effects. It is well established that climate shocks are on the increase. Writing in *Nature Sustainability*, Cottrell et al. (2019) note that climate and geopolitical shocks to food production pose cumulative threats, affecting crops, livestock, aquaculture, and fisheries. Documenting 226 shocks across 134 nations, they observe that the frequency of shocks has increased in all sectors. Extreme weather events are responsible for over 50% of shocks to cropping systems and 23% to livestock. For both agriculture and pastoralism, extreme weather events present a risk for the loss of productivity, diminished farm income and rural livelihoods – particularly for producers in semi-arid regions of the world (O'Neill et al. 2017). In relation to Australia's cattle herd, climate change affects animal growth, feed intake, reproduction and vulnerability to heat stress (Godde et al. 2021). Inevitably climate shocks have a direct impact on the production on food. In 2023, the United Nations Food and Agriculture Organisation estimated that disasters over the previous 30 years had resulted in a loss of around USD 3.8 trillion worth of crops and livestock production – or around 5% of global agricultural gross domestic product per year (p10). In 2019, the IPCC reported that "Climate change has already affected food security due to warming, changing precipitation patterns, and greater frequency of some extreme events (high confidence)" (p8).

In Australia, the site of this study and a major food exporting nation, events that can be described as climate shocks include heavy rain leading to floods, extended droughts, and bushfires. Although Australia's identity as a land of drought and flooding rains is captured in Dorothea Mackellar's (1911) century-old poem, *My Country*, recent climatic events are unprecedented. Major floods devastated vast areas of rural Queensland, as well as its State capital Brisbane in 2010-11, resulting in the loss of life and major damage to homes, businesses, and infrastructure. The town of Theodore in Central Queensland, a major beef producing area and one of the sites of this study, saw the largest evacuation in Queensland's history with 300 residents airlifted as flood waters from the Dawson River peaked at 14.7 m (Channel 9 News 2020). These events were repeated in early 2022, when New South Wales and Queensland were again subject to extensive and catastrophic flooding. In 2019/20, the hottest and driest years were recorded, and mega-fires burned uncontrolled for months. The fires affected 24 million hectares of forest (or 23% of temperate forests in South-Eastern Australia) (Abram et al. 2021:1) and wreaked havoc on human and animal populations, with 33 people and over one billion animals killed.

Climate change and climatic shocks such as drought, floods and fires have already had a direct impact on food production and with that, rural livelihoods. Australia's Department of Agriculture, Fisheries and Food modelling for the year 2021 showed a 23% reduction in farm profits due to changes in seasonal conditions (when compared to 1950–2000) with future climate change expected to see even tougher conditions (Hughes and Gooday 2021). Whilst local occurrences, shocks have impacts beyond Australia's shores. Qureshi et al. (2013) note how drought in Australia is significant enough to cause global food price spikes in wheat, meat and dairy (Qureshi et al. 2013). Yet Kchouk et al. (2022), writing almost a decade later, observe that Australia-Oceania is the only region in the world where farm-based food security studies are rare compared to water security studies – a gap this research addresses.

Data-driven climate solutions

There is a growing body of work on climate solutions and how these intersect with primary production. Central to solutions is measurement, significantly enhanced through advances in digital technology that have resulted in the proliferation of data. The Australian pastoral industry has become one of the most recent industries to be subject to what Archer (2021:284) terms "data driven sustainability". He describes a "socio-technical imaginary of neoliberal sustainability" (Archer 2021:282) whereby sustainability reporting is now dependent upon data from intense and invasive regimes of monitoring and surveillance. Gale et al., (2017:77) refer to this as "ICT-induced disintermediation", as remote surveillance enables new flows and arrangements of information, by-passing key stakeholders such as producers and enabling timely verification without the need for onsite audits. Whilst earlier forms of sustainability governance relied on analogue data, Archer (2021) cautions that digitised forms of surveillance differ in that they are automated. With automation comes the acceleration of datafication and the exponential distribution of traceability (Archer 2021:284) and estimates that farms will generate over 4 million data points per day by 2050 (Klauser 2018).

Arguably, one of the most significant digital tools available for grazing sector monitoring are remote sensing technologies such as drones or aircraft which monitor the earth's surface using Lidar (Light Detection and Ranging) or satellite systems (Horn and Isselstein 2022). Australia is one of the world's largest users of Earth Observation data, with the European Space Agency's Sentinel satellites equipped to provide a complete data set to assess climate hazards in Australia (Parker et al. 2021; Rapach et al. 2024). Big data deriving from that mission provide information on flood, fire, earthquakes and groundwater and geomorphological changes. These data can be combined with long term climate monitoring using machine learning algorithms, providing ground cover reports, soil quality and pasture information (Parker et al. 2021).

Australia is amongst a small number of countries that have adopted these technologies to monitor pastoral lands – with Government-owned websites such as *MyForage* (Queensland Government 2024a) (customised reports at the property level) and *AussieGRASS* (Queensland Government 2024b) (rainfall and pasture growth maps) or *VegMachine* (Beutel et al. 2019) freely available online. *MyForage* combines multiple data sources relating to soil phosphorous, long-term carrying capacity, rainfall and pasture by land type, fire scarring and climate projections to assist with stocking rate decisions (Queensland Government 2024a). Importantly, the granularity of the data means these technologies can support decisions at the paddock level as banks and investors have shown keen interest in remote sensing data, particularly in the service of sustainability credentialing, risk management and carbon markets. For instance, an article in Australia's *Financial Review* (Eyers 2023) details how spatial finance can support banks and insurers to assess the resilience of a property to fire and flood. Such data can be combined with information from open data collections and artificial intelligence (see Caldecott et al. 2022). Aggregated data on extensive livestock systems in Australia are available from numerous entities including the Australian Bureau of Agriculture and Resource Economics, Research Data Australia and Meat and Livestock Australia – bringing together big data as a tool for intelligent support systems which can be retrieved through automated scripts (Bahlo and Dahlhaus 2021:10).

The claimed potential of these digital solutions to sustainability monitoring is consistent with the perspectives of scholars who argue that digital technology is key to enabling farmers to produce more food for a growing world population whilst at the same time reducing the adverse environmental impacts and risks associated with agricultural production (Basso and Antle 2020; Hatfield and Kitchen 2013; Maffezoli et al. 2022; Talebpour et al. 2015). However, claims that digital technologies are overwhelmingly positive for farm productivity, food security, and management of environmental risks have been subject to critique. Digital technologies arguably reinforce "neoliberal industrialized agricultural production systems and food systems" (Klerkx et al. 2019:11), and in doing so "advance the interests of nonfarm [corporate] agribusiness within a rapidly restructuring agriculture" (Wolf and Buttel 1996:1271). Indeed, Levidow (2015:87) claims that digital technologies are integral to the emergence of a corporate-environmental food regime, which "reinforce corporate power to extract more market value from agro-food value chains". This has contributed to ecological degradation, which ultimately undermines food security (Tzachor et al. 2022). Thus, while bringing considerable gains to agri-food conglomerates, digital technologies have also resulted in harms to ecological systems, local economies, and health without alleviating hunger (Bronson and Knezevic 2016:3). Similarly, scholars have criticised the potential of digital agriculture to enhance food security. Stock and Gardezi (2021:193), for instance, observe that digital agriculture is "…discursively articulated as a clever gambit against climate-induced food insecurity".

These critiques are important in highlighting the limitations of digital agriculture in addressing food security and environmental degradation. Nevertheless, they privilege "broader, deterministic power structures" (Van der Velden et al. 2023:3) and in doing so provide limited insight into the "micro-politics and small interactions on the farm" (Van der Velden et al. 2023:3) that shape how producers work with digital technologies in practice, especially in the context of managing climate shocks – the key focus of this paper. In the next section, we discuss an emerging body of work that attends to the diverse and nuanced ways in which technology is utilised and experienced by producers, and what this engenders for how on-farm climate shocks and the broader security of food production are managed.

On-farm engagements with digital technology: a relational approach

A relational approach to digital agriculture provides an important alternative to dominant macro-structural accounts in critical agri-food studies that emphasise the constraints of social structures – such as the power of supermarkets, corporate agribusiness, and financial institutions – on farming practices (Darnhofer 2020:506). It does so by aiming to "account for multiple understandings" of how digital technology is performed in practice, "which include both positive and negative interpretations and outcomes" (Carolan 2018:747), and highlighting diverse ways in which producers variously accommodate, re-work, or resist technology to accord with their own priorities, knowledge, and experiences. From this perspective, there is no recourse to underlying mechanisms or hidden social forces that impose limitations on producers' agency. Instead, farming is reconceptualised as a "dynamic socio-material process" (Darnhofer 2020:513) that is continually being done or enacted, and which brings into being, or closes off, various options, effects, and identities (Mol 1999). We tease this out in more detail below with specific reference to the social science literature that applies a relational approach to digital technology in an agricultural context.

First, in contrast to conceptualisations that focus on how on-farm implementation of digital technology is driven by structures and actors beyond the farm, a relational approach examines the diverse ways in which technology is assembled and made workable in the context of existing farming priorities, knowledge, and practices. From this perspective, digital technology does not solely act upon producers and farming practices in pre-determined or totalising ways that align predominantly with the interests of technology companies, corporate agribusiness, or financial institutions. Instead, emphasis is placed on how producers engage with digital technology as part of their "efforts to exercise 'good care' for their farming enterprise as an economic and social unit" (Higgins et al. 2017:200). This involves recognition of producers' situated expertise (Legun et al. 2022), embodied knowledge (Van der Velden et al. 2023), and practical judgement (Higgins et al. 2023) in shaping the ways in which technology is interpreted and integrated on-farm. It also involves acknowledgement of *tinkering* – the "improvisational, local, specific and often small" (Comi 2023:2) socio-material practices that enable producers to make technology useable and thereby effective in achieving on-farm priorities. In doing so, producers are recognised as "active agents in assembling their farming worlds" rather than passive subjects to wider structures and actors (Higgins et al. 2023:8). However, this does not mean that producers have unlimited options and choices in how they interpret and integrate digital technology. While producers are key agents in on-farm decision-making, agency is distributed among a range of human and material actors. How agency is distributed, and the power asymmetries associated with those distributions, is an empirical question to be investigated, rather than something that is determined by macro-structural actors and processes. Studying how agency is enacted through diverse practices and across different contexts, provides crucial insights into the options and choices that digital technologies engender for producers as well as the farming and food futures they make possible (Carolan 2018), an issue we tease out in greater detail below.

A second area of focus for a relational approach are what digital technologies engender for producer identity and agency. In contrast to what Carolan (2017:136) refers to as "totalising narratives" that view technology as having uniformly negative consequences for producers due to being driven by the commercial interests of off-farm (usually corporate) actors, a relational approach explores the multiple effects and affectivities of technology. The broader aim of this body of work is to "identify the practices of agro-digital governance that afford sovereignty" for producers and to nurture "an understanding about the worlds they may make possible" (Carolan 2018:760). This emphasis is particularly relevant to the aims of this paper in identifying which sets of practices might enhance, or detract from and impose limits on, the capacity of producers to prepare for climate shocks.

The distributed nature of producer agency (Comi 2020) means that digital technologies have mixed effects for on-farm decision-making and thus the capacity of producers to prepare for climate-related shocks. For example, Legun and Burch (2021) in their study of Aotearoa New Zealand apple producers' perceptions of AI robotic technology, observed considerable variation in how producers assembled their orchards in anticipation of this technology. Such variation was due to "the particular landscape, work, and institutional assemblages" orchardists were entangled within (Legun and Burch 2021:389). They identify three sets of practices through which producers assemble their orchards in anticipation of robotic technology – technocratic, deliberative, and isolated. As Legun and Burch (2021:388) argue, these influence in different ways "how orchardists viewed their own agency within their own complex landscape… and, as a result, whether or not they viewed themselves as active agents able to shape a robotic future". A further example is provided in the work of Ogunyiola and Gardezi (2022), who argue that the transition to digital agriculture changes what it means to be a 'good' farmer by reconfiguring farmers' social identities in multiple and sometimes competing ways. Thus, while digital technologies transform "farmers from a 'traditional' cultivator into a farm manager and collector or gatherer of data" (Ogunyiola and Gardezi 2022:7), this can create tensions with other identities such as the importance of lived experience and experiential knowledge in interpreting and validating data. However, as Van der Velden et al. (2023) observe, farming knowledge and experience does not always create tensions. Producers' embodied knowledge is integrated with a data-driven knowledge culture "in different ways and with different intensities" giving rise to a "scale of possibilities" for producer decision-making and agency (Van der Velden et al. 2023:13). A final example is research by Higgins et al. (2023) who draw attention to the 'deliberative assembling' work performed by producers aimed at holding together what they value – such as farming knowledge, trust, and farmer autonomy – with non-local practices and priorities such as data-driven knowledge and growing dependence on commercial sources of advice. This work relies in different ways on support networks that include agronomists, advisors, and machinery dealers. Yet, these networks also pose challenges in making digital technologies workable for producers in the context of their existing farming priorities, knowledge, and experiences. In navigating such challenges, producers engage in three types of tinkering practices – disconnecting, experimentation, and trade-offs and compromises (Higgins et al. 2023). These practices engender different distributions of agency that variously open or foreclose options for producers in making digital technologies useful and useable in their farm planning and decision-making.

A relational approach to digital technology has two important implications for the study of how producers prepare for climate shocks. First, it shows that producers are active agents in making digital technology workable in ways that align with their existing priorities, knowledge, and experiences. This highlights the importance of understanding how producers assemble technology to "maximise benefits for the farm and farmer themselves" (Comi 2023:16) and in doing so contribute to "more resilient farms" (Comi 2023:17) that support preparedness for climate-related shocks. At the same time, a relational approach recognises agency as distributed, and it emphasises the importance of studying empirically the relations between human and non-human actants in shaping the capacity of producers to build more resilient farming worlds. Second, recognition of agency as distributed brings to the foreground the affects and effects that technologies engender, both positive and negative. This is particularly valuable in identifying how producer efforts to integrate technology into their existing knowledge and practices can produce tensions, trade-offs, and unanticipated consequences, as well as afford new possibilities and options, that may impact in diverse and non-uniform ways on producers' capacities to prepare for climate shocks. However, while a relational approach provides insights into what digital technologies engender for producer agency and identity, research using this approach to date has paid limited attention to what producer engagement with such technology engenders for the security of on-farm agri-food production – the focus of our second research question. This is an area of inquiry that we contribute to in this paper. The next section reports on the methodological approach adopted in this study, before delving into the key interpretations from the empirical study.

Methodology

This research is informed by a qualitative program of inquiry in Central Queensland, Australia and surrounding regions. The area predominantly supports cattle grazing and is interspersed with cropping and horticulture properties (key products include wheat, cotton, citrus, and grapes). Central Queensland incorporates the regional city of Rockhampton, which is marketed as Australia's 'Beef Capital', with the region reportedly carrying over three million head of cattle (Rockhampton Regional Council 2024).

Conceptually, the research design was informed by recent advances in food security scholarship (HLPE,2020), which highlight the importance of sustainability (defined as the long-term regeneration of natural, social, and economic systems), and agency (defined as the capability to participate in food systems and institutions to ensure equitable food access and livelihoods) (Clapp et al. 2022:4). The starting position for sampling and data collection was to privilege producer perspectives and tap into everyday lived realities in navigating and preparing for shocks and ensuring the continuous production of food into the future. Researchers adopted the purposive approach of selecting research participants based on their ability to contribute to explaining and understanding social research problems, which has been termed 'problem sampling' (Layder 2018). Aligning with the relational focus of this study, face to face, semi-structured interviews were determined as the most appropriate method to gain insight into how producers are "involved in a diverse and changing set of dynamic relationships with a host of human and non-human entities" (Darnhofer 2020:514).

The criteria for identifying and selecting interviewees for the study was twofold; (a) targeting geographical areas within the catchment where beef producers have been exposed to the climate shocks of flood and drought[1] in recent memory, and (b) to target graziers across a range of land and cattle management practices, including set stocking, rotational, time-controlled grazing and regenerative practices. With the research being focussed broadly on producers' preparation for climate shocks, sampling did not specifically seek producers that were engaging with digital technologies, rather, digital insights in this paper were interpreted from the data inductively. Just over half of the properties visited were engaged in some aspect of digital data usage, mostly related to pasture monitoring, feed budgeting and trading cattle. As shown later in the paper, not all producers commented on the interface of digital technology and beef production were actively engaged with on-farm digital technologies, but nevertheless found themselves involuntarily entangled in them.

A partial snowballing sampling approach was employed – graziers were also found via internet searches. In total, researchers interviewed 31 people across 19 properties during 2022–2023. Many of the properties were represented by a male and female grazier couple with some joined by adult offspring resulting in a final sample of 20 male and 11 female graziers across management styles of varying intensity, including continuous, rotational and holistic and regenerative grazing[2]. Three of the 19 properties represented also engaged in cropping alongside beef production, and for two of those three properties, beef production was the dominant business. Deriving from a history of colonialisation that saw

[1] Major fire events have not affected this area.

[2] We refer to three distinct types of grazing management in the Australian beef industry. Continuous grazing is characterised by "unrestricted and uninterrupted access to pastures" (Allen et al. 2011), rotational grazing applies principles of rotation and resting of pasture, and intensive rotational grazing practices, which we term "holistic and regenerative grazing", that focus on smaller paddock, higher rotation frequency and higher stocking density adapted to the needs of plant growth and soil health (Hall et al. 2014).

vast interior native grasslands claimed for pastoral grazing, an important feature of the Australian grazing industry is the large size of land managed by grazier families. In this geographic sample the properties ranged from around 5,000 ha to 27,000 ha under management. All producers interviewed could point to recent periods of drought across the two decades 2000/2010s with the most recent recognised as the 2019 drought. Around a third of properties had experienced floods that resulted in the loss of livestock, infrastructure and in some cases where crops were grown, topsoil.

The formal interview phase lasted around one hour, with open ended questions addressing the background of the property, change over time, management and decision-making practices, experience and responses to disruptions and shocks, the environment and natural assets and perceived business viability. All interviews were digitally recorded and transcribed. Data were analysed by two researchers using NVIVO14 software and a thematic coding, re-coding, inter-coder reliability regime. Initial rounds of coding were inductive and theoretically open, and later considered with an analytical lens drawing upon a relational approach to digital agriculture.

Research findings

This analysis commences with new developments in the pastoral landscape that form its background and context including recent events of climate disruption, sudden changes on climate policy, and the emerging digital intensification of the traditionally extensive pastoral grazing industry. The following section outlines key relational elements through the voices of producers as they evaluate ways in which digital technologies, data and climate change intersect.

The digitalisation of on-farm efficiency and resilience

Australia has some of the largest pastoral properties in the world whose management has been the domain of low intensity continuous grazing practices (‘set stocking’, see Bartley et al. 2023; McDonald et al. 2023). The research revealed how disasters and disruptions have precipitated changes in land management, especially a turn to practices of sustainable intensification in livestock grazing to build nature-based disaster resilience and preparedness. Interviewees gave evidence on how digital tools and apps facilitate and accelerate the shift of practice by providing direction and structure for producers’ management decisions and planning. For example, some producers, particularly those engaged in holistic or regenerative practices, reported using the satellite data provided by data analytics companies such as CiboLabs and Maia Grazing to monitor feed, estimate pasture biomass and adjust cattle numbers accordingly. With a shifting emphasis toward pasture management, some reported rethinking their identity as “grass rather than cattle farmers” (Interview 06). As such, the growing intensification of management driven by systems that generate data augments the ability of land managers to monitor and continuously optimise *multiple* key characteristics across a large size property, including ground cover, erosion control, contour banking, vegetation management and the condition of the animals.

This research revealed how meaning and objectives of management have evolved as frequent climate events have come to represent a new normal. Management used to be understood as a set regime disrupted by drought or floods on occasions, while more recently, disruption has become integral to land management. “Drought is simply part of it, all management is just getting ready for the next dry”, explained one grazier about the investments made to improve the property and keep up with external pressures. He continued, “we have put this infrastructure together over 20 years – it cost a lot of money. This is preparedness!” (Interview 09). Another grazier reflected on resilience as a management objective: “We do some resilience, for the next flood, financially as well as land management” (Interview 16). The important role of the land, as part of grazing management in times of increasing shocks, was summed up by a producer from a flood prone area, “Higher levels of natural capital can measure when people are doing a good job. High level of natural capital means that you can get through droughts, floods, shocks” (Interview 14). The attention to management aided by digital efficiency tools and monitoring technology ultimately results not only in overall increased productivity, delivering, as one grazier put it, “more beef from less cattle and less land” (Interview 18), but critically, as the producer insights show, also improved financial resilience and resilience of the land.

In this context a producer reflected on how the extensive grazing industry, in terms of adoption of digital technologies, lags other sectors such as broad acre cropping, and needs to start exploiting efficiencies from integrating digital technology into practices (Interview 07). One grazier described a walk-on weighing system called Opti-weigh that can be operated on pasture rather than in the cattle yards. “This has been an absolute breakthrough, just to be able to get the weight of those cattle in the paddock without upsetting the cattle by bringing them back to the yard” (Interview 08). An experienced user of Opti-weigh marvelled, “it weighs our cattle in the paddock all the time and we can see the condition of country changing through the cattle before you can actually see it visibly by the eye” (Interview 11). This illustrates how an additional overlay of information and data streams across very large size properties can augment practice and are subtly incorporated into decision making to advance the outcomes of productivity and resilience of the land.

Another example of digital intensification that is linked to climate preparedness is cattle trading as an approach of drought management aimed at rapid, flexible de-stocking and re-stocking based on pasture feed availability data to prevent overgrazing. Traditionally, the grazing business was centrally focused on raising cattle, on creating genetic composite herds adapted to the local land, which allows animals to thrive on local conditions and be most efficient in converting grass to meat. Accordingly, in times of drought, beef producers would hold on to the valuable composite herd and purchase supplementary feed at high cost to keep animals alive. Participants described how the refocus of grazing management on grass cover and sustainability of the land de-emphasizes breed preferencing in favour of trading cattle: “Every animal on farm is for sale at all times” (Interview 03), irrespective of weight or genetic composition. Producers rely on apps or stock agents’ online trading systems, which provide “a stream of updates on which animals are overvalued or which are not” and make it easy, as a producer explained, “to be in and out of cattle” (Interview 02). Critically, when facing drought, the ability and the established channels to make a fast trade enable early responses. “We are on the front foot, we always move early, because we measure everything” said one producer (Interview 11) and another added, “We can handle the worst seasons, we sell early, we sell them off before the market can tank” (Interview 06).

Using digital technology to manage the mind space

Data from the study also reveals ways in which digital technologies are harnessed by producers to manage the complexities of production during times when climate, politics and market prices present challenges. Those adopting these technologies (over half of the sample) framed their digital management practices distinctively in terms of supporting ‘mind space’ and mental wellbeing. A producer on a grazing and cropping property spoke about the nexus of mental wellbeing and enterprise management: “When it is a tough time or there are shocks, mentally this can be challenging. Because you’ve got to rise above the mental strain” (Interview 12). Participants spoke of “anxieties and trauma” (Interview 13) on rural properties and in rural communities, that heavily impact the “headspace” and can be especially challenging during “long periods of dry” (Interview 02). Making a living off the land requires independence and self-reliance, as producers face major decisions over capital, livestock and people while feeling “isolated” and “secluded” (Interview 01). In the past, mental strain was managed by acting within traditions, paradigms and observing generational experience and knowledge to the challenges. Producers of a new generation realise that relying on the experience of familial management legacies may not be sufficient to securing a livelihood in a changing outside world. Previous generations have based their sense of wellbeing on “circumstances beyond one’s control”, such as good weather and rainfall (Interview 03). This mentality has given way to a new sense of “managing change” and “focusing what can be controlled” (Interview 05), a confidence inspired by past failures of the land or business, and by education and knowledge allowing the younger generation, or those changing to more holistic or regenerative practices, to see the benefits of change.

Producers explained the key role of digital tools in supporting the reset of farm practice through their specific ways of providing flexibility, capability, and consistency, which “support a sense of control” (Interview 14). Digital apps and systems can also create openness to new ideas as they “bring down restrictive barriers of thought” (Interview 02) shaped by tradition and generational paradigms, and they offer direction through a structured, methodical workflow, which relies on “measurements and data rather than experience and tradition” (Interview 12) and allows producers “to forecast all the time so we are more confident and we know what’s happening” (Interview 03). Internet and telecommunication technology also offers resources that support a departure from traditional practice, allowing rural producers to expand beyond their geographical communities to broader virtual communities of what several participants called “like-minded people” (Interview 04). For instance, some of the participants subscribed to communities with a specific philosophy of beef production and pasture management known as ‘cell grazing’ or time-controlled management (see Richards and Lawrence 2009) or other regenerative practices that depart from more traditional forms of land and cattle management.

New ideas and the consultation with peers lead to action plans which are set “when the brain is right” (Interview 02), not in moments of pressure – such as in the middle of drought. Participants emphasised how digital tools are crucial in giving them confidence and control to execute decisions under pressure by eliminating interference from human emotions. “100% no emotion” said one producer (Interview 11). Another one added, “you can never really totally separate emotion from the business, but you try to set up a system to take a lot of that out of it for you” (Interview 13). Digital tools and systems have evolved to provide a sense of connection in an insular and isolated environment, and, as a young landowner remarked “vital control of the headspace” (Interview 02) that leaves you, as another one said, “to only to worry about what you haven’t planned for" (Interview 05). Digital management of the mind space clearly emerges as a crucial factor in aligning technology with farming priorities. It also enables producers to make decisions that afford sovereignty (Carolan 2018) in securing their livelihoods during challenging times, and in planning for the future.

Sustainability compliance and distributed agency: the production of 'secondary shocks'

Producers are aware that sustainability in farming has evolved from intrinsic values of good land stewardship into a marketable commodity. Sustainability, in this conception, is important for reasons of compliance with market and government regulation or to generate additional farm income (Higgins et al. 2014). Sustainability as a commodity requires evidence to prove sustainable management has been performed, particularly in relation to climate credentials. Producers recounted how previously, proof of compliance was provided through written reports, audits, and farm inspections, which have been onerous, time consuming and responsible for a large share of administrative work on farming properties. Digital technology adoption and data generation through digital tools have fundamentally changed how sustainability proof is provided and obtained.

During research fieldwork, participants described "pasture ground cover" as the epitome of sustainable management (Interview 01), reducing soil erosion and addressing the harmful effects of nutrient run off into the Great Barrier Reef Marine Park. Sustainable grazing management aims to minimise patches of bare soil and maximise ground cover which is associated with high water infiltration and retention, prevention of erosion and run-off, and soil biodiversity. Ground cover was broadly accepted as making land "rain ready" (Interview 04, 10) to respond with life after long periods of dry. Ground cover emerged as the touchstone of successful or even acceptable land management. Producers sometimes compare ground cover with neighbouring properties and offered comments on run-down or overgrazed land on other farms. "I would never take my country that short", remarked one producer (Interview 11), while another talked of recently purchased land "that had been conventionally grazed to the floorboards forever" (Interview 04). Beyond neighbourly competition, ground cover appeared as a form of hard currency of sustainability assessment, describing not only the amount of grass cover on a particular block of land, but more profoundly, representing the health of the land and the soundness of the landowner's management style, ability, and integrity.

Unsurprisingly, ground cover also provides a tangible proxy for sustainability assessment by sophisticated technology including satellite based remote sensing and other supplementary data collection on the ground. Pre-digital approaches relied on visual grass checks, recalled one grazier, including monitoring and self-reporting of pasture cover, diversity and health by landowners themselves, a practice at the time promoted through the Queensland Department of Primary Industries (DPI) (e.g. Partridge, 1996). Subsequently, satellite-based systems provide more accurate and widely accessible ground cover assessments, including via web-based services such as *MyForage* (Queensland Government 2024a) and *AussieGRASS* (Queensland Government 2024b), and private digital technology services such as those provided by Maia Grazing (2024) or CiboLabs (2024), as mentioned above.

As opposed to traditional processes of auditing, disclosure, and reporting, farm data can be generated through remote sensing *in absentia* of the producer. One grazier explained how researchers recognised their change of management style long before it was even visible on farm itself. "They saw the change before we did, they could see when the change happened, from the data that they were seeing from the satellite" (Interview 04). The availability of pasture data could ultimately be highly consequential in decisions that concern the property value and the producers' livelihoods as in the case of a Central Queensland producer's loan application: "We had all the [environmental and financial] data they needed at our fingertips, and I think that gave them the confidence to back us. Yeah. I don't know whether they would have if we didn't have that information" (Interview 04).

As surveillance data provide proof of sustainability and compliance on rural properties, external organisations are increasingly interested in deploying a mix of premiums, incentives, and penalties to get producers not only to accept satellite compliance data, but also to embed digital data collection more deeply as a standard practice. There was a lingering awareness and discomfort about data and information leaving the spatial territory of the farm to inform decision makers from external entities such as banks and supply chain actors. The research data shows that satellites attract landowner suspicion as sinister vectors of farm data conveying a sense of being spied upon but also a lack of knowledge how data is being used, interpreted, by whom and for what purposes. A participant explained the terms of compliance under the Standard for Agricultural Environmentally Relevant Activity (ERA) within the Great Barrier Reef (GBR) catchment, that legally require properties within the Fitzroy Basin catchment of Central Queensland not only to keep record of "relevant primary documents related to agricultural ERA activities" but also to maintain ground cover of no less that 50% (Queensland Government 2022, p.3). Some graziers described how compliance is based on the monitoring of satellite data and dispatching

GBR compliance officers to properties for ground-proofing and visual assessments, with non-compliance constituting an offense under the *Environment Protection Act 1994* and potentially attracting a penalty. Unsurprisingly, several participants referred to "zealous climate policy" (Interview 16) and "the political landscape" (Interview 14) as the greatest threats to the beef producing industry.

Graziers perceive that also some market actors derive competitive benefits from data availability to support compliance with their own private industry standards and marketing campaigns. A producer described how,

> Meatworks now have the ability to prove what part of the property this beast has been on, what grass it's been eating, what quality of life it's had, and that's important to the consumers. So you need to start managing for that because, you know, you will get penalised. (Interview 18)

While this perception may be overstated in relation to how buyers check compliance, other participants described that publicly available data sources reveal evidence on where beef cattle was raised and the sustainability attributes of the land it has grazed (e.g. ground cover). Such data adds to the power of buyers in determining commercial terms including quality grades, pricing, and premiums, and can affect producers' ability to access markets, such as the EU, where compliance with climate policies have been gaining significance since the beginning of the transitional phase of the "carbon border adjustment mechanism" (CBAM) (European Commission 2023).

Monitoring by unknown third parties de-stabilises previously taken for granted and shared understandings of farm boundaries and private property and was perceived by some producers to represent more of a shock to the farm enterprise than climate related disasters, a concept we refer to as 'secondary shocks'. These secondary shocks result from what Archer (2021) terms 'sustainability surveillance', deriving from decisions made by off-farm actors in the service of solutions to climate change. Producers in one fieldwork area in Central Queensland still felt the repercussions from the secondary shocks associated with the 2011/2012 floods. They spoke of disaster not primarily in terms of the floods themselves, but of the response of the banks since that time. Producers described the aftermath of the floods and the sudden move by banks to start calling in rural loans, which illustrated a significant vulnerability of affected grazing properties not only to disruptions of the natural landscape but also to sudden ruptures in the financial landscape. Grazing properties and rural landowners described how they, as an asset heavy industry, rely significantly on bank loans to manage, maintain, and safeguard their land and business operation. It also highlighted a significant change in landowner-bank relationships as the loan call-ins were apparently not negotiated, as would have been the customary practice in the past, but simply served upon producers by written notice, seemingly based on algorithmic decisions made remotely. A landowner recalled, "Someone woke up in the morning scratched themselves and said I don't want to do Ag anymore, too much debt, get rid of some customers" (Interview 16).

Multiple participants confirmed that banks have great interest in farm generated data, and within the stories of data driven improvements of business and productivity, a few voices of concern became audible, "we used to assess pasture visually, but now satellites are recording it – talk about paranoia – so you can actually go to the internet and find out how overgrazed your place is" (Interview 17). Another producer was even more explicit, saying that

> …banks want to look at existing property information to see how it is managed before approving finance for a new one, they are always looking for data. We've spoken to a satellite monitoring company doing pasture monitoring, and they have said that the banks have approached them and asked for access to their data. They refused, thank god. (Interview 18)

Moreover, especially after disasters, satellite data will readily reveal the extent of damage from floods, fires, or drought the property has sustained, which is critical information for banks and insurance companies in assessing value, viability, and future risk profile. The prospect of publicly available management data raises many doubts, especially considering how bank algorithms may result in decisions deeply affecting rural producer livelihoods, including interest rates access to finance, and even the value of the land, without any knowledge or direct involvement of producers themselves.

Farming food or carbon? The food security tensions that digital technology engenders

As we have seen, the turn to climate adapted production, enabled and accelerated by digital technology and the seamless flows of data, creates secondary shocks for producers. However, in doing so, it also draws grazing properties into the emerging carbon economy. Carbon farming epitomises a sustainability economy that is entirely driven by data generation. Due to the very recent passing of the *Climate Change Act*2022 (Australian Commonwealth) and the subsequent emission compliance reforms, there is now burgeoning demand for carbon offsets across Australian industries. These offer significant income streams for farms in exchange for commitments to regenerate land and sequester carbon (Australian Government, Clean Energy Regulator, 2024). One grazier remarked, "I am not sure if they are serious about climate change, but whatever, it is a nice income stream for us" (Interview 13).

Producers identified many uncertainties of current carbon farming schemes. There is a lack of policy clarity, measurements and carbon baselining requires significant up-front investment from producers, times to achieve financial returns are long and so are contractual commitments to carbon farming that must be locked in for a minimum of 25 years. Yet carbon farming offers financial and potential policy benefits, which, besides the revenue from selling carbon offsets, include improved nature capital, potential price premiums for carbon neutral certified beef, higher land-values compared to ordinary grazing blocks and potential interest from big corporations to purchase carbon offsets or entire properties. A grazier with a carbon project on his property enthused, "carbon in your soil is the single best idea to support farmers in the history of farming" (Interview 12).

At the heart of the carbon farming economy, lies the generation and sharing of data streams as key evidence of actual and permanent carbon sequestration. Evidence of ground cover can be provided through satellite imagery, photographs, drone footage or even a visual assessment of the pastures. Carbon sequestration, in contrast, is ultimately indistinguishable from its underlying data. Producers tell a story of how production on their land has changed over time. Clearing land for pastures to graze beef cattle was the origin of the industry's contribution to food security. Over time sustainable grazing management evolved to encompass land, grass, water, and soil management. With carbon farming, livestock grazing has now arrived at producing carbon sequestration services, which is essentially reducible to data. One grazier summed up, "The whole carbon thing is a story. You can tell the story and you'll get it through!" (Interview 17).

Due to its vast landholding and potential carbon sinks of soil and vegetation, some producers believe that pastoralism may become an offsetting rather than a food producing industry. A producer reflected:

> People aren't going to stop driving cars and watching video games, they are not going to reduce consumption. So, we have got to find offsets, and that is land, agriculture to a large degree. People can make a lot of money out of it, but the risk is that we end up totally unproductive, in other words, people buying it have no compunction to farm it. That's not just an environmental disaster, but a social disaster. (Interview 14)

Beyond carbon offsets, corporations have also been investing in strategic purchases of agricultural land for the specific purpose of procuring carbon offsets (ABC 2021). Some participants expressed concern that land will be removed from food production as producers make more from selling carbon offsets rather than beef, or from speculating on land investments, which poses a threat to food security and rural livelihoods.

Discussion

The intersection of climate shocks, digital technology and data, and food security are complex. A relational approach drawn upon in this paper is valuable in highlighting this complexity and in problematising structural narratives which view digital technologies as vehicles that intensify the penetration of corporate capital into agri-food production at the expense of producer control. In this section of the paper, we re-engage with the research questions introduced at the start of the paper to tease out in what ways a relational approach contributes to scholarly understanding of how producers use digital technologies to prepare for and manage climate shocks, and the effects these technologies, and the data they produce, engender for on-farm food production.

In response to Research Question 1: 'How do producers engage with digital technology and data to prepare for climate shocks?', we have found that producer engagement occurs largely because of experiences with previous disasters and disruptions. Experience of drought was universal amongst producers. Some experienced the effects of floods and the downgrading of land investments that followed. Consistent with current research on digital agriculture using a relational lens, producers engaged with technology in ways that built on this experiential knowledge and situated expertise (Higgins et al. 2023; Van der Velden et al. 2023). However, producers also used such technology to provide a sense of direction and structure for future decision-making. This is evident in the use of apps and data that enabled producers to rapidly de-stock and re-stock in response to changing climatic and market conditions. It is also evident in how producers used technology to manage the mind space, providing a greater sense of confidence and control over decisions they make, and supporting tinkering with new practices (Comi 2023; Higgins et al. 2023) that enhanced producer capacity to cope with or manage change. This finding aligns broadly with Van der Velden et al.'s (2023:1) conceptualisation of the "cyborg farmer" in which "emotions and materiality of the body are taken seriously" in how producers interpret and use digital technology. Our analysis provides a slight twist, highlighting how such technology is used to invoke *less* emotion in farm decision-making, thereby contributing to improved capacity to make decisions under pressure. At the same time, this finding highlights the practical, situated, and embodied ways in which producers engage with technology to guide future decision-making, a process that is not fully captured by existing relational concepts such as 'preparatory assembling' (Legun and Burch 2021) and 'anticipatory imaginaries' (Carolan 2020).

Our research also shows that the data produced through digital technologies – such as satellite imagery or drone footage – provides an important foundation for producer participation in the carbon economy. Producer engagement with digital technology to prepare for climate shocks affords access to opportunities that may not have been otherwise envisaged. Such participation affords, and indeed encourages, investments in nature capital that help to support on-farm resilience in a changing climate. New climate change legislation in Australia has placed pastoral lands in a new position as carbon stores, particularly since land-use and land-use change, and forestry (LULUCF) play important roles in climate strategies of the agricultural sector (e.g. DAFF 2024; Ward 2023), and the vast expanses of Australian pastoral land have untapped potential to sequester carbon. Pastoralism, agriculture, forestry, and fisheries are the only industries capable of genuinely achieving net zero emissions within the boundary of their own operation, whereas other industries such as mining and fossil fuels or residential development and government are inherently unable to do so without accessing large amounts of offsets from the carbon markets. However, while enhancing *current* producer capacity to prepare for climate shocks, carbon farming may also diminish their *future* ability to produce food, a point that we elaborate on further below. Therefore, producer engagement with digital technology can mean simultaneously inhabiting different and sometimes contradictory worlds "with varying political ontologies and assumptions about what is and what ought to be" (Carolan 2018:761).

In response to Research Question 2: 'What are the implications for the security of food production at the property level?', our analysis reveals how the use of digital technologies to prepare for climatic stresses create what we term 'secondary shocks'. An important insight from our interviews with beef producers is that off-farm, data-driven sustainability accounting practices linked to solutions to climate change can be experienced as shocks – often more so than direct climate shocks such as floods and droughts. As noted above, data from digital technologies were reported as an asset to some producers in taking the stress out of decision making, and an indispensable tool in monitoring, planning, and tinkering with decision making in challenging geographic and climatic conditions, such as extended dry periods on large size pastoral land. Yet, at the same time, the distribution of agency engendered by such technology meant that actors off-farm were reported as being empowered to exercise increased property surveillance via remote sensing technologies. At face value, this aligns with the literature which highlights how digital data accelerates the availability of information to non-farm actors whose interests may not intersect with those of primary producers (Archer 2021; Gales et al., 2017). The shift in sustainability governance from analogue/on-site audit regimes to remote, discrete systems of surveillance has accelerated the availability of data at the paddock scale. Not only has information via data points increased in volume, flows of information can be collected without the knowledge or consent of the producer. This 'disintermediation' (Gales et al., 2017) fragments the control over the farm, as demonstrated by graziers receiving loan call-in letters from banks without a prior visit, inspection of accounts or land assets, or a conversation with landholders. For graziers, this represented a new vulnerability as markets and governments gear up their sustainability expectations. Attempts by financial institutions to use the data produced by digital technologies also generate uncertainty for producers and undermine the contribution of those technologies to the interests of producers (see Forney and Epiney 2022). In doing so, such uncertainty may lead to reluctance on the part of producers to utilise digital technologies further in preparing for shocks and stresses, with possible indirect consequences for the security of food production.

Nevertheless, consistent with a relational approach, we argue that secondary shocks are not an inevitable or predetermined consequence of producer engagement with digital technology. Our findings reveal nuance as well as contrast in what these technologies engender for producers and on-farm food security. The data produced through digital technology make possible relations with other off-farm actors that can produce "more flexible, responsive and adaptive outcomes" (see Comi 2023:17) and which enhances the capacity of producers to prepare for shocks. This is evident in how data that contributes to secondary shocks can also enable producer participation in the emerging carbon economy, and the new income streams this makes possible. At the same time, a key finding of our paper is that while carbon farming affords producers new market opportunities, and enhances their capacity to prepare for climate shocks, this has potentially detrimental consequences for food production. This is particularly evident in producer narratives about land being locked up as carbon market investments. Whilst the data afforded by digital technologies can enable producers to access new income streams (such as carbon farming) that act as a buffer against shocks and stresses, the privileging of carbon markets may have unfavourable outcomes for food production.

Conclusion

This paper has examined how climate shocks and farm-level food security are mediated by digital technology and data in a Minority World context. It contributes to scholarly understanding of how the evolving relations between climate shocks and digital technology shape producer agency on farm, an understudied aspect of food security. Our emphasis on the relations between digital technology and climate shocks in an extensive grazing context represents a further contribution to the dominant emphasis of critical digital agriculture research on intensive and/or crop-based farming systems. Drawing upon a relational approach to digital agricultural technologies, the paper has shown that engagement by producers with such technology has mixed consequences for producers in preparing for climate shocks and contributing to future food production. On the one hand, digital technologies enhance producer resilience and planning for future shocks. The data generated by digital technology also enacts new opportunities for producers to contribute to the carbon economy, providing them with an income stream that improves their financial capacity to prepare for future climate shocks. On the other, data produced from technologies used on and off-farm distributes agency to external actors and organisations, such as banks. This distribution of agency gives rise to power asymmetries that produce 'secondary shocks' for producers. Significantly, we argue that regardless of the effects digital technologies engender for producers, the data they produce has potential to undermine the contributions producers make to food production. Thus, the distribution of agency to actors external to the farm potentially undermines producer capacity to prepare for future shocks, with associated negative impacts on food production. Yet, those opportunities afforded by data – such as enabling participation by producers in the carbon economy – *also* represent a possible future threat to the security of on-farm food production as productive land is set aside for carbon farming. In concluding, the paper contributes to scholarly knowledge on the relationship between climate shocks and data-driven climate solutions by demonstrating that digital technology does not necessarily have uniformly negative consequences for how producers prepare for and manage climate shocks. At the same time, any positive effects on producer planning and decision-making need to be considered in the context of tensions and trade-offs for the security of future on-farm food production. These tensions and trade-offs require further research by agri-food scholars.

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