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Smart farming technologies and changes to farm work: New insights into on-farm experiences

Ruth Nettle [a,*], Julie Ingram [b]

[a] Rural Innovation Research Group, University of Melbourne, Australia
[b] Countryside and Community Research Institute, University of Gloucestershire, UK

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ABSTRACT

The intersect between technologies and the future of work is a key topic for both practitioner and scholarly communities. In this paper, we explore this intersect within agriculture by examining the changes to work for farmers implementing smart farming technologies (SFTs) in the United Kingdom (UK) and Australia. We interviewed 17 farmers across the UK and Australia from horticulture, dairy and mixed farming (arable and livestock) enterprises who were implementing diverse SFTs. Interview questions explored farmers' experiences in implementing SFTs with respect to any changes to work for themselves and their employees. Based on an interdisciplinary conceptual framework we developed from the literature for analysing farm work, we applied qualitative data analysis methods to examine the changes to work. We found the benefits from reduced work-duration were commonly counteracted by time spent in computer set-up and data work, with subsequent negative effects for the cognitive and affective dimensions of workload. The organisation of farm work influenced the type of skills and knowledge required to implement SFTs, with larger and corporate farms outsourcing these requirements to advisers, while smaller-medium sized farms used SFTs to augment their existing knowledge and skills, enabling employers to do more with their own time and enhancing employee engagement in work. We found more similarities than differences in work changes between countries. The interrelationships and feedback loops we have identified between the different aspects of work bring a novel perspective to technological transitions in agriculture and represent an important orientation point for researchers and technology developers to better anticipate work effects from different types of SFTs.

1. Introduction

Smart Farming represents the application of autonomous systems and information and communication technologies (ICT) into agriculture, such as variable rate applicators, Internet of Things (IoT), geo-positioning systems, big data, unmanned aerial vehicles (UAVs, drones), automation and robotics (Balafoutis et al., 2020). Smart farming technologies (SFTs) and the accompanying digitalisation of agricultural practices are creating a highly automated and data-driven system, described as the Agriculture 4.0 era (Klerkx et al., 2019; Fielke et al., 2020). SFTs are suggested to have the potential to help address the many challenges and demands farmers face, including improving farm productivity (Rose and Bhattacharya, 2023) and sustainability (Lindblom et al., 2017; Godwin et al., 2003; Galaz et al., 2021; Hansen et al., 2023), augment labour in the context of farm workforce shortages (Nye and Lobley, 2021; Araújo et al., 2021) and improve decision making in increasingly unpredictable environments and heterogeneous contexts (Roy and George K, 2020; Balasundram et al., 2023). While farmers in regions such as North America, Europe and Australia are recognised as strong adopters of technologies like automated guidance of tractors (Barnes et al., 2019; Nowak, 2021), the uptake of SFTs is still considered relatively low compared to expectations (Kernecker et al., 2019; Giua et al., 2022). Suggested reasons for this have included the type of production system, farm size, level of farmer education, accessibility of technologies, and data management and governance issues (Groher et al., 2020; Higgins and Bryant, 2020; Kernecker et al., 2019; Nowak, 2021; Giua et al., 2022; Rose and Bhattacharya, 2023). However, labour and work have received limited attention from the scientific community (Malanski et al., 2019; Prause, 2021; Dedieu et al., 2022), yet it has begun to feature in studies of technology acceptance (Thomas et al., 2023).

While there has been increased attention paid to processes of

* Corresponding author at: School of Agriculture, Food and Ecosystems sciences, University of Melbourne, Building 142, Royal Pde, Parkville, VIC 3010, Australia.
E-mail addresses: ranettle@unimelb.edu.au (R. Nettle), jingram@glos.ac.uk (J. Ingram).

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responsible innovation (Rotz et al., 2019; Prause, 2021; Barrett and Rose, 2020; Fleming et al., 2021; Rose et al., 2021a, 2021b; Fielke et al., 2022), changes to work from the implementation of SFTs has not featured, even though they arguably relate strongly to these agendas. Understanding the work effects from implementing SFTs could guide research agendas, education and training policies and capacity building in farm advisory services (Klerkx et al., 2019) as well as help anticipate unintended consequences or adverse implications from technology implementation and digital transformation (Prause, 2021; Rose et al., 2021a, 2021b; Rijswijk et al., 2021). Recent studies have pointed to significant changes in work from the introduction of SFTs including: replacing tasks or augmenting jobs (McDonald et al., 2022; Martin et al., 2022); changes to knowledge and the managerial dimensions of farming such as information management and changes from experience-driven to data-driven modes of working (Ingram and Maye, 2020; Prause, 2021; van der Velden et al., 2023); changes in the employment relationship and employee experiences (Sam et al., 2022) and changes in working conditions, work organisation, labour management (Uztürk and Büyüközkan, 2024), relations between humans and animals, skills and training (Martin et al., 2022; Perrin et al., 2024).

There remains limited understanding of the day-to-day experiences of farmers and those working on farms and in advisory roles who are implementing SFTs (Ingram et al., 2022). While labour replacement and reduced working time are commonly mentioned as possible benefits from SFTs (Martin et al., 2022), other changes in work and working life are less explored and few studies have explored multi-sector and country level similarities and differences in the way agricultural work is changing. There is a call for more studies to examine how digital technologies are shaping labour and labour processes in agriculture (Prause, 2021) and thereby influencing how the Agricultural 4.0 revolution plays out (Rose et al., 2021a, 2021b; Sam et al., 2022).

In this paper, we identified key features of the change in work for farmers implementing SFTs in the UK and Australia and consider the implications for innovation policies and practices related to the development of SFTs. By examining the effects from SFTs on farmers' working life across different farming systems, we bring a novel perspective to how Agriculture 4.0 is unfolding.

The following research questions frame the scope of the paper:

1. How are SFTs changing the nature of work on-farm?
2. How can changes to work be better anticipated in policies and by research, technology and education stakeholders?

1.1. SFTs and changes to the work of farming

Different perspectives have been applied to the study of the intersection between work and technology in agriculture. From the perspective of the future of work and the socio-technical dynamics of agricultural technologies and digitalisation (Galaz et al., 2021; Spencer, 2023), some authors portray an unequal and unjust future where larger scale or corporately organised farms benefit most from SFTs. This could create a cultural 'lock-in' (Burton and Farstad, 2019) where farmers and farmworkers are 'molded' to machine requirements (Baur and Iles, 2022, p 136) and with greater control over the labour process by employers and the potential to entrench existing inequities and vulnerabilities, such as for seasonal workers (Nye, 2018; Prause, 2021). Others portray a less-bleak future where the work effects from SFTs assist with the effects of labour shortages and reduce drudgery (Rose and Bhattacharya, 2023; Morgan-Davies et al., 2017; Fielke et al., 2020; Stilgoe et al., 2013; Rose et al., 2021a, 2021b; Malanski et al., 2021; Ingram et al., 2022). Many authors describe a double-edged sword, with SFTs also being challenging to finance, taking time to learn (Eastwood et al., 2017; Lioutas and Charatsari, 2022; Mizik, 2023) and with challenges in dealing with the incompatibility between different hardware or software platforms or in retrofitting existing infrastructures (Higgins et al., 2023).

Beyond the perspectives that examine the socio-technical dimensions of SFTs and work, authors have also described change to the meaning and quality of work, including the farmer identity (McGuire et al.2015; Ogunyiola and Gardezi, 2022; Higgins et al., 2017), the relationship with animals (Martin et al., 2022) and the ways farmers accommodate technologies and modify their everyday lives (Carolan, 2017; Jakku et al., 2019). Modification of the farmers' management work is described by Hostiou et al. (2020) as a tradeoff, in which the time livestock farmers spend in data management, verification and interpretation reduced the time saved from remote animal monitoring. This additional workload has been described as creating 'techno-stress' (Martin et al., 2022, p9), negatively affecting the quality of working life for farmers. Such effects are also attributed to the overwhelming learning load brought about by the co-evolution between farmers' knowledge of machine control and data interpretation and the speed of SFTs' iteration (Eastwood et al., 2019).

The effects of SFTs on ways of knowing and the knowledge system of farmers are also affecting work (van der Velden et al., 2023; Ingram and Maye, 2020). The productive tension between data-driven smart farming and the embodied and intuitive understanding of the agro-ecological context led van der Velden et al. (2023) to examine farmers using precision technologies in an embodied way ('cyborg farmers' (p8), being those who maintain agency and resist the dominance of algorithmic rationality over other forms of knowledge. SFTs have also been distinguished by their different work demands for the farmer, including 'embodied knowledge technologies' (i.e. those that require no additional skills for their operation) and 'information intensive technologies' (i.e. those that require investment in terms of knowledge, skill and analytical service support (Barnes et al., 2019, p163–164). It is argued that information-intensive technologies present a greater hurdle to farmers' resources, capacity and knowledge (Weersink et al., 2018; Barnes et al., 2019) or that experiential knowledge could be increasingly marginalised (Prause, 2021). However, a recent study challenges the suggestion of de-skilling through digital technologies in the agricultural workforce (Prause, 2021).

The field of human-robot interaction and ergonomics is another perspective in which SFTs and work effects are examined (Douphrate et al., 2013). The physical, cognitive and social interaction between people and robots, the effects on working conditions and safety, and the extension and improvement of human capabilities and skills are the focus (Vasconez et al., 2019). Studies of robotics and work in agriculture closely focus on the nature of tasks (routine vs. non-routine and cognitive vs. manual tasks), the extent to which non-standardised tasks can be replaced and the extent to which complementarity and substitution occurs between labour and automation (Marinoudi et al., 2019).

While these perspectives draw out different aspects of work, few studies have examined the combined or cumulative effects of SFTs on work or compared effects across farm types or differences between countries. While there have been many studies related to the adoption of precision farming (e.g. Barnes et al., 2019; Giua et al., 2022; Kernecker et al., 2020), few examine post-adoption, or the lived experience of working with SFTs. Even then, most studies of work effects examine discrete technologies or sectors (e.g. dairy/robotic milking) (Eastwood et al., 2017; Martin et al., 2022) and not the combination or bundles of SFTs farmers may deploy within their farm operations (e.g. Lambert et al., 2015) and there are few cross-industry or cross-country studies to explore the commonalities or differences in work effects. There has also been a narrow focus on the type of work effects examined with limited emphasis on the effects on the work of farm employees or farm family members, the organisation of work, the quality of working life or changes in skill demands across the farm workforce. While some authors report employment changes with SFTs (e.g. robotics), the assumptions and realities of the positive and negative effects on employment, such as in increasing skilled jobs or triggering job losses (Rose et al., 2021a, 2021b, p307), have not been examined in detail.

In this study we aim to contribute to these gaps to bring together different disciplinary and theoretical perspectives on work to examine what happens to the work of farmers and their workforce, when they implement SFTs. Our approach expands the individual technology and sector focus to examine the real-world experience of farmers in different countries regarding the change to their work from the SFTs they have implemented. This research is an important and under-represented area of research and significant for understanding the implications of transformative technological developments in agriculture.

1.2. The context for farmers' use of SFTs in the UK and Australia

As with many countries in the global agricultural community, the UK and Australia are actively part of the Agriculture 4.0 movement, including in research (Moysiadis et al., 2021; Hansen et al., 2023; Pearson et al., 2022; Osrof et al., 2023), in the growing number of Agritech SMEs, and in the active encouragement of technological entrepreneurialism (e.g. Farmers to founders, 2024; Agritech UK, 2024; Australian Agritech Association, 2023). These countries were chosen for their commonalities in terms of similar timelines and strategies for fostering public and to private collaboration and investment in research and development across key sectors (Agritech UK, 2024; Department of Agriculture, Water and the Environment (DAWE), 2022). These countries also share the problem, broadly identified, of a lack of focus on the people dimensions of Agriculture 4.0 (Rose et al., 2021a, 2021b) with digital skills shortages in the wider farming community highlighted (Ayre et al., 2019; Ingram et al., 2022).

Farming systems differ in the two countries with respect to scale of operations (large paddocks in Australia vs smaller fields in the UK), with remoteness and unreliable rainfall characterising the Australian context making some SFTs more or less suitable. Furthermore socio-economic, historical, cultural and political backgrounds differ. However both are subject to the same drivers for efficiency on-farm (e.g. open markets, value chain demands) particularly since the exit of Britain from the European Union and the subsequent effects related to workforce shortages and reduced market supports (e.g. Azarias et al., 2020; Devlin, 2016; Lobley et al., 2018). Both countries are also navigating transitions toward more sustainable practices, often driven by government incentives, shifting consumer expectations, and environmental concerns. Examining the patterns of change to work from implementation of SFTs in the UK and Australia provided an opportunity to explore commonalities and differences at the farm level from an international perspective.

2. Conceptual framework

For this study we bring together theoretical perspectives related to the technology-work interface from farming systems and the sociology of work. Considering work at the level of the farm, farming systems scholars have generated frameworks for work assessment combining technical management and work organisation (Dedieu and Schiavi, 2019), considering the farmer as the driver of the system and the organiser of work (Cournut et al., 2018; Santhanam-Martin et al., 2021). These frameworks seek to incorporate the diversity of workers (family and non-family), working time and work organisation, including indicators of flexibility or room-to-manoeuvre in farm operations. More recently, working conditions and work-life balance have been incorporated (Cournut and Baley, 2021; Dumont and Baret, 2017; Duval et al., 2021a; Duval et al., 2021b) and with consideration of SFTs such as robotics (Hansen et al., 2020; Martin et al., 2022) as well as farm resilience more generally (Perrin et al., 2024). The quality of jobs or quality of working life are key areas of interest among scholars in the sociology of work (for example, Warhurst and Knox, 2022) and in agriculture (e.g. Nettle et al., 2018; Hansen et al., 2020). Table 1 provides a synthesis of different dimensions of work for assessing the effects of smart farming technologies used to develop our approach to data collection and analysis.

Table 1
Dimensions of work for assessing smart farming technology effects.

Dimension of work	Authors	Adaptations for this study
1. Work duration and the temporal distribution of work	Cournut and Baley, 2021; Perrin et al., 2024; Warhurst and Knox, 2022.	Perrin et al. (2024) include workload and work-life balance/taking holidays, as part of work duration. In our framework, we separate each of these dimensions, considering them to have the potential for discrete effects. For instance, physical workload may not relate to work life balance and work duration is not always related to work-life balance. Warhurst and Knox (2022) include job design and the nature of work as a key dimension of job quality, which spans both workload and work duration.
2. Workforce organisation	Cournut and Baley, 2021; Perrin et al., 2024; Martin et al., 2022; Santhanam-Martin et al., 2021. Uztürk and Büyüközkan, 2024	Cournut and Baley (2021) and Martin et al., 2022 describe workforce organisation as the spatial-temporal organisation of work at the farm level (i.e. who does what, and when). Perrin et al. (2024) includes the level of leeway and control in the definition including the capacity to innovate, marketing flexibility, diversity of production activities and number of workers in each activity and expands work organisation to include the nature of farm governance (e.g. collegial decision making); planning; worker versatility for a range of tasks; distribution of seasonal work over a year and attempts to level out work peaks. Uztürk and Büyüközkan (2024) describe 'tactical labour management'.
3. Workload (physical, cognitive and/or affective)	Martin et al., 2022; Warhurst and Knox, 2022; Hansen et al., 2020. Thomas et al., 2023	Martin et al. (2022) consider workload to involve time and flexibility. Our framework separates working time/work duration from workload. Workload, or the demands required to complete work tasks, include the physical, cognitive or affective aspects of work. We consider cognitive and affective demands discretely, given that 'techno-stress' (Martin et al., 2022, p9) and learning load (e.g. Eastwood et al., 2017) feature in studies of SFTs and such demands also relate to 'increased burden' (Thomas et al., 2023, p6).
4. Work-life balance	Cournut and Baley, 2021; Warhurst and Knox, 2022; Perrin et al., 2024.	As noted above, Perrin et al. (2024) combines work-life balance with the work duration dimension. Others have it as a separate consideration, which we also adopt.
5. Working conditions	Dumont and Baret, 2017; Duval et al., 2021a;	These authors include the dimensions of: income and social benefits (e.g. perceived

(continued on next page)

Table 1 (*continued*)

Dimension of work	Authors	Adaptations for this study
	Duval et al., 2021b Perrin et al., 2024; Cournut and Baley, 2021; Warhurst and Knox, 2022.	fairness of income); workers' health (e.g. exposure to accidents); workload (e.g. time at work and schedule flexibility); work organisation; professional norms and identity. Our framework separates these dimensions. Perrin et al. (2024) includes the availability of suitable infrastructure and equipment as a separate category to working conditions. Our framework notes working conditions as providing: flexibility in work; health and safety at work (including mental and physical health or psychosocial wellbeing (Warhurst and Knox, 2022); as well as availability and quality of equipment conducive to work.
6. Meaning of work	Cournut and Baley, 2021; Martin et al., 2022. Toshi	Including any form of subjectivity and emotions in work (stress, satisfaction, recognition, autonomy, feeling of coherence, identity). Our framework considers this dimension under workload (cognitive/affective).
7. Income and social benefits	Perrin et al., 2024; Warhurst and Knox, 2022	Perrin et al. (2024) includes benefits or discomforts of work (pleasure at work and in tasks; extent of stress at work; perception of income fairness). Warhurst and Knox (2022) include: income at or above minimum wage; terms of employment and extent of non-standard work; pay and benefits; social support and cohesion; and voice and representation. Our study focused on general work effects from SFTs at farm level rather than a comparison of effects before and after SFT implementation. We did not explicitly examine this dimension or collect income/pay information.
8. Skills	Cournut and Baley, 2021; Perrin et al., 2024 Gerli et al., 2022	Workforce qualifications and experience, quality of the relations between workers. Our framework focuses on changes to skills arising from SFTs and changing nature of skills at work such as in 'data work'. We consider 'data work' as a distinct category for examining work effects, given the reported challenges and issues experienced by farmers and advisers in data management and governance (Ayre et al., 2019; Jakku et al., 2019; Gerli et al., 2022).
9. Farm structure and the labour market	Martin et al., 2022	Farm size, social relationship of production, added value distribution, any variable related to organisation and interaction of production factors (land, labour and capital) and labour market. With our study focus on general work effects from SFTs, we report any effects of farm size or farm operations from SFTs, but do not seek to quantify such effects.
10. Technical-economic performance	Martin et al., 2022; Cournut and Baley, 2021	Farm profitability, productivity, income, metrics such as cows/worker. With our study focus on general work effects from SFTs, we report any technical or economic benefits noted by farmers, but do not seek to quantify or compare performance.

In describing our adaptations of the work categories for this study (Table 1), we have noted that different authors combine some of the dimensions of work categories. For instance, 'workload' sometimes includes dimensions of work-life balance and working conditions, and at other times not, making it difficult to differentiate different types of work effects. Therefore, to provide a more manageable approach and focus our data analysis, we combined some of the work categories in Table 1 to bring the number of work dimensions to 5, while retaining the key details of the source categories:

1. Work duration (time saved, time spent, timing, timeliness) (Item 1, Table 1):
2. Work organisation (people, jobs, tasks, workplaces) (who does what and when) (Item 2, Table 1)
3. Workload (physical and cognitive/affective dimensions of work) and including flexibility at work, meaning at work, work-life balance (Items 3, 4, 5, 6, Table 1)
4. Set-up and Data work: including the infrastructure and work in digitising and decision making associated with SFTs (Items 9,10, Table 1)
5. Skills and knowledge: in implementing and benefiting from SFTs (Item 8, Table 1)

We used this synthesised framework of farm work to structure our data collection and analysis of work effects from farmers implementing SFTs.

3. Methods

We chose a qualitative approach to examine the subjective experiences of farmers who had implemented any or multiple SFTs in their farming. Farmers were recruited through a combination of key informant networks of the authors, snowball sampling (Parker and Geddes, 2019) from primary respondents and a public call, through newsletters of organisations. The intention was to identify interviewees from the main farming sectors in the countries, with similar farming systems, and with experience of a range of SFTs. Among farmers, a diversity of enterprises and farm sizes were recruited, including farmers at different stages of adoption Semi-structured interviews were conducted with 17 respondents between 4 April and 18 August 2023. This included 10 farms in the UK and 7 in Australia (from the states of NSW and Victoria), involving arable (cropping) farms with or without beef and sheep (9), dairy farms (5) and horticulture farms (3). A range of solo-operators (4), family farms of different scales (10) and corporate farms (3) were involved in interviews. Such detailed interviews have proven useful for drawing out differences in farm work organisation in other studies

(Santhanam-Martin et al., 2021). The research received human ethics approval from the University of Melbourne, Australia [ID Number: 26115 and ID Number 21284].

Interview questions covered firstly the history and context for implementation of SFTs on the farm (i.e. *'What Smart farming technologies (SFT's) have you adopted on your farm?'; 'How did you decide that these were the highest priority for your farm?'; 'What results have you observed from adopting these technologies?'; 'Overall, how satisfied are you with the value that SFT's have provided to you and your farm?')*. Secondly, questions relating to the experience of SFT implementation were asked, focusing on changes to work, and covering the work dimensions reflected in the conceptual framework (Table 1) (i.e.*'What knowledge and skills were required and/or acquired in implementing SFTs?'* (work dimension 5); *'Were any changes to tasks, working time or the content of farm jobs (roles and identities) required (including for family members, employees, contractors)?'* (work dimensions 1, 2, 3, 4); *'Were advisory and other services required to select and implement the technologies?)* (work dimension 2); *'Have jobs been replaced or added as a result of implementing SFTs?'* (work dimension 2); *'Have the qualifications or experience of people to implement the technologies changed*?' (Work dimension 5). Finally, respondents were asked what, if any, SFT's they were considering for their farm in the next five years and what work changes they anticipated (work dimension 4).

In line with the hermeneutic tradition in social sciences, which *applies multiple qualitative methods to compare interpretations (*e.g. Hanson-DeFusco, 2023), our study included an on-line interactive forum with the research participants and additional stakeholders to provide a step to confirm and triangulate our findings from the farmer interviews. Farm advisers and industry representatives from both countries, identified through author and research participant networks, were invited to join the forum with the farmer participants which was held on 6 September 2023. In total, 30 participants from the UK and Australia were involved. Participants were presented with the main findings from the interview stage and were asked to qualify or validate and comment on the findings. The forum was audio recorded to contribute to our overall data analysis.

3.1. Data analysis

Interviews were transcribed and analysed with the assistance of qualitative data analysis software (nvivo12™). We applied an inductive approach to our analysis, adapting analytical techniques from grounded theory, including a constant comparison method, whereby each interview was open-coded and compared to the following interview text to test for fit (or deviation) between the data and the emerging codes (Charmaz, 2024; Charmaz and Thornberg, 2021) as well as to explore if each additional interview was generating new codes or alternative insights from earlier interviews. This first stage of analysis yielded 34 unique codes from across the 17 interviews with the final interviews not yielding new codes, meeting our criteria for saturation (Bryan and Charmaz, 2007). We then grouped these codes according to the dimension of work category to which the content was most closely aligned, generating themes: 'benefits from implementing SFTs'; 'data work'; 'future technology aspirations'; 'knowledge'; 'skills'; 'work duration'; 'work flexibility'; 'work organisation'; 'workload-physical'; 'workload-cognitive'. Text in each of these categories was then reviewed to examine the patterns and interrelationships within and between each category to create memos, representing the analysis of each coded category and the experiences of work changes within each code. Within each memo where relevant, the farmers' experience of the work effects were coded as being positive, negative or neutral. Adapting from sentiment analysis (DiMaggio, 2015), this step explored the positivity or negativity expressed in the text about farmers experiences. Negative experiences were recorded where the effects on work went against the aspirations or expectations farmers had for their lives and work (e.g. 'it's frustrating'). Positive experience was recorded where the effects on work were meeting or exceeding expectations, generating welcome effects (e.g. 'it's brilliant'). Neutral or mixed experiences were recorded where the work effects were neither positively nor negatively expressed or where both negative and positive effects were noted within the same category (e.g. 'working at night').

A final analytical step was to examine the audio-recording of comments and qualifications provided by the participants of the on-line forum with respect to our interview findings. These data either confirmed, supported minor adaptations or deepened the explanations for the work changes described in farmer interviews.

As the themes emerged through a systematic coding process applied across the full dataset, each theme is therefore grounded in multiple instances of work effects experienced across different interviews, technologies, and farmer contexts, ensuring that any one theme is not derived from a single case. In the results that follow, individual quotes are used for illustration of the work effects experienced.

4. Results

The characteristics of the farming systems and types of SFTs used by research participants are provided in Table 2. The results are then presented to reveal the patterns of effects related to work (positive, negative, neutral/mixed). Table 3 summarises all work effects noted. Interviewee quotes identify the location (Australia [Aus] or United Kingdom [UK]), the farm respondent number and the main enterprises on the farm (dairy, horticulture, livestock, arable [i.e. crop production]) as well as the date of interview.

4.1. Work duration (time saved, time spent, timing, timeliness)

Farmers reported a diversity of areas where time was saved by implementing SFTs, and this was viewed positively. However, areas where more time was spent were also reported, with negative effects. We report these in turn.

4.1.1. Time-saved

Any time saved from implementing SFTs was very important for those farmers operating on their own or with limited staff. These farmers described the effect of SFTs as: flexibility in the use of time, more family time, making life easier or being able to sleep in of a morning. Some reported this as the only way to keep farming, increasing their efficiency and their ability to run the operation on their own. For instance, one farmer described the importance of a solar-powered auto-gate opening device for dairy herd movement:

'… I just punch in what time I want the gate to open. I don't have to be here for it. Absolutely fantastic. I've built the whole farm infrastructure around that piece of kit.' (UK, Farm 5, dairy, 8/5/23).

This farmer mentioned numerous time-saving and automated operations on their farm, focused on getting the most from their time, including seeking multiple benefits from the one device. For instance, using machinery tracking devices to examine the extent of idle time, fuel costs and efficiency, as well as reduce risk of machinery theft. For them, every minute of saved time was of immense value.

Another farmer described the saved time from their implementation of satellite-assisted pasture growth and grazing decision software (with machine-learning features) that meant they did not have to make daily computer entries. Being a large farm with many employees, this system saved time in other ways, such as not having to physically sight paddocks to decide the next grazing or, if paddock checks were required, they could visit more specific paddocks rather than the whole farm. They also noted being able to quickly and easily generate weekly reports on grazing for external farm investors.

'… that system will know where the cows are eating. I don't have to enter the paddocks in … it will read the pre-grazing and post-grazing residuals as well … [you'll] look at your grass in the paddock as well, but it's just made everything so much more efficient … I do not have time to spend two hours walking around down the paddock.' (Aus, Farm

Table 2
The range of smart farming technologies being implemented by research participants.

Farm identifier/reference	SFTs in use or being trialled	Farm characteristics
UK, Farm 1, arable (organic), 15/5/2023	• sensors (grain quality) • weed control (e.g. electrophysical dock control), smart weeder (inter-row)/sowing • drones and accompanying software (crop surveillance, analysis of varieties, seeding rates, leaf area index, plant density) • trials of robotic planting, seeding, spraying • software – workforce data • contracting business	Arable/cropping farm, organic, 3–4 fulltime staff.
UK, Farm 2, dairy, 10/5/2023	• cow manager software system (cow heat /intake/health detection/camera) • electronic identification devices (EID) • pasture measuring/monitoring devices	Dairy farm, 2–3 staff
UK, Farm 3, sheep, 15/5/2023	• EID, hand-held scanner, • artificial breeding	Sheep farm, family farm
UK, Farm 4, arable, 16/5/2023	• EID, individual feeding • Yield monitoring, auto steer and controlled traffic farming, section control and crop green sensing, • tractor-based technologies (GPS, satellite imagery) • handheld or portable devices on motorbikes (ATV's)	Mixed farming (livestock, cropping)
UK, Farm 5, dairy, 8/5/23	• back switch gates (laneways) • tractor-based technologies (GPS, fertiliser, mowing) • auto weigh silos - filling/switch off • CCTV on farm buildings	Dairy farm, sole operator
UK, Farm 6, Mixed farming (arable, livestock), 11/5/23)	• tractor-based technologies/machinery operations monitoring • satellite imagery/data • variable rate: seeding, lime, P, K • precision /band spraying • software/analytics of farm efficiencies • trials of robotic planting and harvesting (sugar beet)	Arable/cropping farm (wheat, barley rape/canola, beans, peas, sugar beet), corporate farm management business, employed workforce across multiple farm enterprises.
UK, Farm 7, mixed farming (arable, sheep), 11/5/23	• variable rate: seeding, fertiliser • handheld or portable devices on motorbikes (ATV's)	Arable/cropping farm, farm manager
UK, Farm 8, dairy, 11/5/23	• tractor-based technologies (GPS, controlled traffic, maps for fertiliser, mowing) • cow collars (lameness and heat detection) • video camera monitoring (herd vision for body condition, lameness.	Mixed farming (dairy, beef and cropping), multi-generation farm, 1–2 employees.
UK, Farm 9, mixed farming (arable, livestock), 11/5/23	• GPS autosteer on tractors, precision application/automated shut-off systems for fertiliser • GPS soil sampling • Variable rate seeding, conductivity testing • EID tags on animals, software for animal record keeping • cow collars/rumination • walkover scales/recording • workplace software/communications apps • automated weather recording	Mixed farming (crops and suckler cows and sheep), 3 full-time employees
UK, Farm 10, mixed farming (sheep and cattle) and arable, 15/5/23	• EID on all livestock • Trials of livestock tracking collars (GPS positioning), • Weight monitoring • Auto-weighing stock, including walkover platforms at water troughs/ID readers/cloud systems. • Rumen sensors • Slurry scraping robots • Feed quality sensors (DM, nutrients)	Dairy and livestock farm
Aus, Farm 11, dairy, 4/4/23	• Robotic milking system • Livestock tracking/GPS collars • Milk meters • EIDs and scanners • CCTV on farm buildings	Dairy farm, mainly family workforce
Aus, Farm 12, mixed farming (arable, sheep), 7/6/23	• smart phone apps • soil sensors • tractor-based technologies auto steer, auto section control • EIDs and scanners for livestock • walk-over weigh scales • data analytics and software (e.g. N calculators) CCTV on farm buildings • drones, spatial maps	mixed farming (crops, cattle, sheep, feedlot)
Aus, Farm 13, horticulture/fruit, 18/8/23	• Irrigation sensors (changes in fruit tree trunk circumference and water pressure in the trunk) • Variable rate/auto-irrigation (phone control) • Hand-held tablets, phones and record keeping via chip, QR codes (data analytics via farm software) • Automated weather station information-decisions • Self-propelled harvest platforms • Packing shed robotics (vision systems for size/suction cups, precision packing, machine learning packing systems software, etc) • Fruit quality (vision systems)	Horticulture (fruit growing)
Aus, Farm 14, horticulture/fruit, 30/5/23	• Pre-harvest leaf blowers • Automatic (on-off) dendrometers (irrigation) • Overhead cooling/radiation trigger sensors • Packing shed robotics (vision systems for size/suction cups, etc) • Fruit quality (vision systems)	Horticulture (fruit growing)
Aus, Farm 15, dairy, 21/6/23	• satellite imagery/data (pastures and grazing systems machine learning/prediction)	Dairy farm, farm manager and 3–5 full time employees.

(*continued on next page*)

Table 2 (*continued*)

Farm identifier/ reference	SFTs in use or being trialled	Farm characteristics
	• tractor-based technologies (GPS, controlled traffic, fertiliser, mowing) • cow manager software system	
Aus, Farm 16, arable, 14/7/23	• tractor-based technologies (GPS, controlled traffic) • Satellite imagery/data • Drones • NDVI/crop scouting • Variable rate: seeding, P, K • Tractor company operations centre membership • Software: reporting, modelling (crop, rainfall, N calculators)	Arable/cropping farm, family members and 2–3 employees.
Aus, Farm 17, arable, 14/7/23	• tractor-based technologies (GPS, controlled traffic) • data analytics/software • Variable rate: seeding, P, K • Rate controller spraying	Arable/cropping farm, family members and 2–3 employees.

15, dairy, 21/6/23).

Time saved was also associated with other benefits. For example, the use of animal location/GPS devices provided an early warning if animals were in the wrong or risky locations and provided peace of mind without needing to personally check constantly. This also saved fuel and, in livestock systems, was noted to have additional animal health benefits including less herd lameness. Large-scale and horticultural farms with multiple employees and multiple cropping enterprises spoke of the time saving from their fleet of smart tractors in being able to monitor activities:

'… see who's doing what, where, when and why. So I haven't got to continually phone and ask people. We can then move machinery around … help us make ourselves a bit more efficient.' (UK, Farm 6, Mixed farming (arable, livestock), 11/5/23).

4.1.2. *Time spent*

Some experiences of SFT implementation involved extra time spent, causing frustration and concern. Many of these reported experiences related to data work, which we report separately below, including setting up systems, working with data or data interfaces (screens/ dashboards). However other issues and problems requiring more time than anticipated were reported, including: setting up screens (in tractors) and the systems and the infrastructure to collect and report data; time spent on computer work; and time spent sieving out less-useful information or integrating data with other data to make decisions. A further source of time spent related to fixing systems and screens/ glitches and in getting help from companies on these issues. Such effects were more prevalent in arable farming situations than in livestock and horticulture. The time spent related directly to farm decision making and ultimately farm performance, meaning the effect of this time was highly consequential for farmers.

While it was hoped SFTs would improve the use of time or make decisions easier or quicker, for some, the overall effect of this time spent was a perceived erosion in the value of SFTs, such as variable rate technologies. For instance, arable farmers spoke of the downsides of spending time on variable rate applications in different seasonal contexts, where the decisions were not guaranteed to succeed, or managing breakdowns and responding to alerts. The time spent on data interpretation was also noted:

'It's very quick and easy to source the information, [but] to …convert that into an actual decision … that's actually of commercial value … that's the bit that takes a long time.' (Aus, Farm 12, mixed farming (arable, sheep), 7/6/23).

Most farmers noted that they spend more of their time on the

Table 3
Summary of the work effects from Smart Farming Technologies reported by farmers, advisers companies and intermediaries.

Feature of Work	Negative work effects	Positive work effects	Neutral or mixed work effects (neither positive or negative OR sometimes noted as positive and sometimes noted as negative)
Time (spent/saved)	• Data cleaning and validating • Examining or analysing data/ computer work • Sieving out less useful information • Integrating data with other data to make decisions • Setting up screens systems and the infrastructure to collect and report data • Fixing systems and screens/glitches • Getting help from companies on these issues	• Quicker work scheduling (larger farms) • Less travelling to fix things (all farms) • Ability to generate reports quickly (larger farms/corporate) • Field robotics providing timely and responsive options • Less computer entry (e.g. satellite applications) • Quicker farm communications (farmers with employees) • Reduced paddock or animal observations (smaller/solo operator farms) • Movement of livestock without a physical presence positively whereby time was saved and reported positive. (smaller/solo operator farms) • Timeliness of operations to better suit people	• Working at night
Work organisation		• Communicating on the farm to organise work • Enable flexible deployment • Work scheduling and allocating tasks	• Matching people with technology • Routines of servicing • More back-office roles • Prioritising effort • Different people and roles
Work load – physical	• fitting cow collars	• Reduced effort in observing and moving animals such as for weighing.	
Work load – cognitive/affective	• Hyper-vigilance and switching off alerts (livestock farmers) • Frustration/giving up and dealing with problems	• Reduce mental fatigue • Peace of mind • Evidence • Improved quality of life	• Engaging with technology day to day
Set-up and data work		• Frustrations: 'system' integration limitations (sensors, telemetry, software, transmission, calibrating, synching damage)	• Finding data people • Wading through data (cognitive load)
Skills and knowledge in the workplace	• Maintaining relationships with technical companies • Can't rely on it	• Mutually reinforcing • Learning and understanding of system	• Checking data quality

technology aspects in farming:

'So we're going from a situation where we had zero time on technology. … to a time now ... I spend 15% of my time on technology.' (UK, Farm 4, arable, 16/5/2023).

Some of the farmers spoke of additional computer work at home at night, going over data outputs and discussing this with advisers or setting up systems for the following day. Some reported this as being productive, while for others it was a burden at the end of already long days. Work duration and the time spent in this way was a source of frustration. Some respondents described wanting to give up on it. The time spent on these issues was not providing the expected benefits to decision making and farm performance.

4.2. Work organisation

The effects related to work organisation from implementing SFTs differed as a result of the size and ownership status of the farm. Owner-operators with no or few staff reported limited changes in the organisation of work because technologies were prioritised to their own use of time.

'… there's only so many hours in the day and there's things we have to do, so we adopt technology to get what we can done.' (Aus, Farm 11, dairy, 4/4/23).

On larger farms with employees, SFTs were commonly used to communicate about farm operations and to organise work. One arable farmer described the use of visual reports in communicating with their farm team and deciding on work priorities:

'I do use NDVI[1] as a scouting tool … even today … my dad asked, "What's the area that's been impacted by slugs?" and a simple screen shot, draw on it with your phone, edit the picture, and show him that, and I go, "I think these are the potential areas of it" … I might fly the drone up … to show everyone … "Here's the range of the problem". (Aus, Farm 16, arable, 14/7/23).

Other farmers took a similar approach using other apps and platforms to share information and discuss work plans. One farmer described WhatsApp:

'… for even seeing a fence that needs to be fixed, you just send a photo and where it is, GPS tag it, and the whole team knows that needs to be fixed.' (UK, Farm 9, mixed farming (arable, livestock), 11/5/23).

Robotic technologies required farmers to organise their routines around servicing and liaison with technicians:

'Definitely liaising with the service technician a lot more. …you need to keep an eye on so you don't get a breakdown in the middle of the night.' (Aus, Farm 7, dairy, 4/4/23).

On family farms, SFTs were changing work roles, with grown-up children returning to the farm to work with technology and data to support the farm operations in some cases. For instance, the introduction of robotic milking was made easier for one farmer with a son keen to learn computing as part of the robotic system:

'He just taught himself … he made it his thing … the programming and setting up.' (Aus, Farm 11, dairy, 4/4/23).

For another, the son had the responsibility of using drones to monitor their farm trials:

'… [he] is modelling all those trials, … he's … come back to the farm and [has] something that he is engaged with.' (UK, Farm 1, arable (organic), 15/5/23).

Farmers described the change in jobs and work organisation as confronting for some employees:

'… we're going to need the same amount of people, but you just might not be doing the same job … it's got to be introduced into the workplace … with a huge amount of sensitivity.' (UK, Farm 1, arable (organic), 15/5/2023).

[1] NDVI (Normalized Difference Vegetation Index): a remote sensing method, using red and near infrared light to estimate the health and biomass of plants.

4.3. Workload (physical and cognitive/affective dimensions of work) (including flexibility at work, meaning at work, work-life balance)

4.3.1. Physical workload

Livestock farmers across countries spoke about monitoring tools that reduced the physical workload of interacting with, and moving, animals. Tools monitoring rumen function, lameness, calving and heat detection as well as in-paddock livestock weighing reduced the work of regularly moving beef or sheep into yards. While generally automated technologies in livestock were seen to lessen the physical workload, one livestock farmer mentioned the fitting (and removal) of animal collars as being physically hard. Further, much of the physical workload effects were interrelated with the cognitive and affective dimensions of work and with the timing of farming operations. This included the effects of reducing night work in use of automated irrigation:

'When we're getting up in the middle of the night, we're not nice to be around too. We've got to be able to cope with the day-to-day.' (Aus, Farm 15, dairy, 21/6/23).

In another case, auto-controlled fruit picking platforms were replacing manual ladders and bags, and this had flow-on effects to the working environment, work organisation, safety, timing of operations and fruit quality:

'Because of the [platforms]… people don't get as hot … you're not carrying that [apple] bag, you're standing in the shade … [there is less] bruising, we can also carry on picking in light rain… That's enabled us to better move our whole group of people around.' (Aus, Farm 13, horticulture/fruit, 18/8/23).

The increased maintenance work for robots and other farm infrastructure associated with the technologies, for instance laneway maintenance in robotic dairying with grazing, was also mentioned as a change to workload. Labour shortages featured in many accounts of the need to introduce technologies to reduce the total amount of work. Labour saving featured more strongly than labour replacement in the investment in SFTs:

'… things that can save jobs rather than increase productivity, because I can't find anybody to do the jobs, so I'm ending up doing so many of them myself.' (UK, Farm 3, mixed farming (arable, livestock, 12/5/23).

Reducing workload was also a priority for considering the attractiveness of the work to potential employees, with one employer describing investment in technologies for this reason:

'… so if I can … make the job easy enough, and there's air-conditioning and radio, because it's not the best job … it's not their great interest.' (UK, farm 7, mixed farming (arable, sheep), 11/5/23).

Overall, farmers reported being in the office more '*analysing the data' (UK, Farm 3, sheep, 15/5/2023)*.

4.3.2. Cognitive and affective workload and the meaning of work

Farmers mentioned the change in work to greater use of information and thinking (i.e. cognitive load) as a difficult change. However, there were also reported positive effects such as reducing fatigue with auto-steer and other features on tractors:

'… because you haven't had to have sat there for 12 to 14 h a day, concentrating on steering, finding the edge of the crop, the tractor does it all for you… you can concentrate on *[other] stuff.' (Aus, Farm 12, arable, 7/6/23)*.

The production of farm data and records through software systems was also reported as providing 'peace of mind' in farm compliance. This was particularly noted in the UK in providing evidence for their environmental reporting.

The engagement of employees in their work was also reported as a positive effect from SFTs. One farmer described the satellite pasture monitoring and use of this tool as being useful in engaging staff in what was happening on the farm and generating their interest in learning and using the system:

'… when you show the satellite images, it's like, wow, [the employees]

want to look at that … want to use it.' (Aus, Farm 15, dairy, 21/6/23).

This extended to assisting the confidence of both the employer and the employees that they are making the right decisions on the farm when the owners are absent. Another farmer described increasing employee interest in the farm because of their SFT use:

'… our employees have more interest rather than less interest, by having that information … they're very keen on the detail.' (UK, Farm 8, dairy, 11/5/23).

Some farmers attributed improvement in quality of life for themselves, their family and their employees from some technologies:

'You're not as tired … by using technologies, both me and my brother have more time to spend with our family on the weekends ….' (Aus, Farm 12, mixed farming (arable and sheep), 7/6/23).

However negative cognitive effects were reported from the continual flow of information from SFTs (e.g. sensors and monitoring systems) and not being able to 'switch off', leading to over-vigilance. One farmer with robotic milking system described this 'checking' work:

'There's a lot more monitoring the computer records … we're constantly checking for mastitis and heat detection ... and sick cows, because you don't see them all the time. … Just checking, double-checking that.' (Aus, Farm 11, dairy, 4/4/23).

To overcome this, some farmers disconnected the alerts or only switched on the system when they are with the animals so they can address any issue at the time:

'So, it's not connected - when I'm milking, I switch [it on] – I scroll through it and I look at what needs doing or what's coming up.' (UK, Farm 5, dairy, 8/5/23).

Despite their best efforts, some farmers described a frustration with their experience with SFTs that had an impact on their enjoyment of farming:

'Our hybrid system on our farm – lots of different tractors, lots of different bits and pieces … is costly, doesn't work, and you just end up giving up on it. You need to have lots of experience yourself to make it work, someone like me that likes being in the paddock and doing agronomy, if something goes wrong, you lose interest in it.' (Aus, Farm 16, arable, 14/7/23).

4.4. Set-up and data work: The infrastructure and work in digitising and decision making associated with SFTs

We use the label 'data work' to describe the work involved in the setting-up of new technologies and in the selection of software and the handling of data (such as collecting, collating, uploading, downloading and the cleaning, curating and interpretation of data). Farmers and advisers described this work as *'tricky'* and requiring farmers to *'wade through' (Aus, Farm 16, arable, 14/7/23)* the data themselves.

'It's very, very difficult to get the [grain quality] data off the actual hardware. … the first year we couldn't get any of the data off ... Second year, they took our boxes to get the data off and they lost it. The third year, we still haven't got the data off it ... the actual data retrieval is impossible.' (UK, Farm 1, arable (organic), 15/5/2023).

For some arable farmers and their advisers, dealing with software and programming problems and receiving poor levels of service support in the setting-up phase and at the start of the cropping season led to frustrations, including juggling software installation issues and running farm operations and focusing on problems rather than using data to make better decisions:

'… and this is myself dealing with it – just trying to deal with running a business as well … and I did everything I could to fix it [myself] … [no] breathing room to analyse … it's generally dealing with a problem rather than actually analysing the data … just loading, clearing.' (Aus, Farm 16, arable, 14/7/23).

'… when I've downloaded it, only half the job will come in. Half a dataset … I don't have time to be stuffing about.' (Aus, Farm 17, arable, 14/7/23).

All farmers spoke about the learning phase in setting up and using data. For some, this phase was a source of ongoing frustration, whereas others described the importance and value of accepting and persisting with this phase, because of the value in the use of accumulated farm data to inform decisions.

Farmers spoke of needing to work on learning the software and needing 'your hand held' during this phase. Others mentioned training staff and using training material of the suppliers. Some farmers spoke about being on the cusp of deriving benefits and could see the potential of data-informed farming, particularly better use of their own farm data:

'I would like to do a lot more analytics of the data. I think there's better decisions to be made based upon that…' (Aus, Farm 16, arable, 14/7/23).

The change to computer and technical/technological work was seen to largely be benefitting larger farms with dedicated people working on computers and in offices monitoring farm operations and generating and analysing reports. For the smaller farms, the amount of computer work was an issue with data workload in setting up systems, training staff, calibrating/verifying and testing new technologies.

4.5. Skills and knowledge

There were diverse effects from the implementation of SFTs on the skills and knowledge required in farm operations. In terms of their own skills, many of the farmers referred to a personal interest in computers and data as a motivation for embarking on the SFT journey:

'… it was a sort of hobby ... around building computers and things like that ...I've been able to… flourish in terms of the precision farming sector.' (UK, Farm 4, arable, 16/5/2023).

Farm owners described these SFTs as making better use of their own skills, for example, helping ensure they were not missing issues, such as in the early identification of sick cows or in focusing attention to the paddock or animal of most importance. Farmers emphasised that the technologies were not replacing their decision making:

'… it alerts us with which specific areas to go and look at. But then you've got to make a decision … which is usually down to me…the beauty of it is that …concentrates it to … the right case, ... it's making better use of the skill'. (UK, Farm 2, dairy, 10/5/2023).

The augmentation of employees' skills was also noted. Farmers described SFTs as helping increase employee skills and improving their confidence in their job. Younger employees were described as quick to learn and in some cases data-informed understanding gave them more agency in farm decision making. SFT use by employees was therefore an important consideration in the selection of technologies with some farmers identifying employees as the arbiters of whether technologies were going to work well for the farm or not, Many of the employers described teaching their current employees to take on new roles in data management:

'…[he] had just a truck licence … I taught him … how to make the maps, handle [shape] files... he can now handle all that …' (Aus, Farm 12, arable, 7/6/23).

Most farmers were uncertain about the extent to which the farm workforce would be replaced by automation, describing the augmentation of work and the changes in the skills people needed in roles, not replacement of people. There were some exceptions, notably in the post-farm gate horticulture sector (e.g. packing sheds), where automation was significantly changing jobs, for instance from packers and quality assurance staff to visual software and machinery engineers.

While the augmentation of decisions and skills were the predominant effect described, some farmers described new roles from their SFT investment, such as qualified electricians, mechatronics and other engineers, data scientists/analysts and business managers. For some farms, this was an exciting time, bringing in fresh ideas and perspectives to agriculture. However, it was acknowledged that the skills needed in this work co-evolves with the technologies on-farm, making the recruitment of new people into these roles difficult:

'… you've got to find people who understand spatial statistics … but also understand the agronomic drivers behind it to use it … we have to create them.' (Aus, Farm 12, arable, 7/6/23).

Maintaining relationships with companies and service technicians featured strongly in farmers' descriptions of their work in implementing SFTs. Farmers described a reliance on the availability and access to expertise, which meant a need for skills in relationship management:

'… you've definitely got to be able to maintain good working relationships with those people, which is definitely a skill that you need. Other farmers ended up - they've got no support.' (Aus, Farm 11, dairy, 4/4/23).

Some farmers described SFTs as helping compensate for less experience and skills, such as in assisting new farm owners or staff learn about a farmor providing extra confidence to employees in doing their jobs:

'… sometimes it takes away the thinking…' (Aus, Farm 15, dairy, 21/6/23).

However, it was also acknowledged that a level of technical knowledge was still required to be able to assess the accuracy of data inputs or outputs, with farmers noting that a level of discipline is required to work with data and skills were required to ensure the hardware and software system interface was working well.

There were divergent perspectives on the role of SFTs in knowledge of the farming system and the autonomy farmers had in decision making. Some farmers reported an enhancement to their knowledge and others reporting a need to have backups, seeing risks from over reliance on SFTs in case of system failure and lack of reliability in performance. In the former situation, SFTs enhanced farmers' knowledge of their system and improved their decisions and performance, while retaining full autonomy in their decision making. Data outputs were combined with observations and experiential knowledge to strengthen, prioritise or give confidence to decisions. For example, one farmer said SFT had "Not eroded [our knowledge]…but built on knowledge." *(UK, Farm 1, arable, 15/5/2023)*. On these farms, SFTs were not replacing physical observations, rather they complemented or provided a check to what was already known, or thought to be known:

'I use it as a backup. I wouldn't use it as my sole decision-making tool.' (UK, Farm 3, sheep, 15/5/2023).

'…it doesn't get away from the fact that we still need to ground truth the data that we're getting from remote sensing'. (UK, Farm 4, arable, 16/5/2023).

Other farmers described SFTs as adding to knowledge and providing a lot more insight and understanding of their systems, as well as enabling different ways of working and sharing knowledge across geographic regions:

'[to work on the nitrogen schedule] you can pull people from [anywhere] with a consultant who happens to be in [another location].' (UK, Farm 6, arable and mixed farming (sheep and cattle), 11/5/23).

Some described the additive effects of information derived from the technologies to help them learn about their systems. Some found the granularity of data valuable and "actually visually seeing the dataset" *(Aus, Farm 12, mixed farming, 7/6/23)* supported this learning. In contrast, some farmers described their main role as being the holder of knowledge, having experienced losing data or lacking confidence to rely on the data or systems:

'If I lost it tomorrow, it wouldn't be devastating ... going back to pen and paper ... because I can't rely on it.' (UK, Farm 3, sheep, 15/5/2023).

Others were concerned that their reliance on family members or technicians for the knowledge of the robotic system was a risk:

'If anything happened to both of us, we'd be in trouble. Our employee … has the basic understanding of the robot - but that's it … and my technician's phone number.' (Aus, Farm 11, dairy, 4/4/23).

With respect to education and training, all farmers described themselves as being self-taught. This is an experiential learning process where the early stages of using SFT can often require more time investment. They also trained their employees themselves, highlighting the lack of options for formal training.

'… we've just decided the technology that would be useful for us moving forward and we just learnt it ourselves.' (UK, Farm 10, mixed farming (sheep and cattle) and arable, 15/5/23).

Overall, we found common experiences in the UK and Australia with respect to the effects of SFTs on work. The differences between farms were related to the specific SFTs in use and the farm type. These effects on the work of farmers from the implementation of SFTs are summarised in Table 3. The interrelationships between these work effects is conceptualised in Fig. 1.

5. Discussion

Our research sought to answer the question: How are SFTs changing the nature of work on-farm? We found that SFTs are changing work duration in the time saved and in time spent, as well as in how work is organised. We also identified emerging characteristics of workload including farm data work, and different effects of SFTs with respect to the knowledge and skills of people working on farm including farm family members and employees. The sentiment of farmers toward work changes was also captured, bringing in their lived experience. These work changes were not straightforward for many of the farms involved in our study, as has been noted by Ohashi et al. (2024) in describing iterative processes of adoption. Many SFT farmers are in a continuous process of adoption, absorbing and adapting to new technologies and upgrades rather than adopting a one-off technology per se.

While SFTs saved time in some parts of the farm operation, this was often counteracted by the time spent in set-up or data work, including data interpretation. The time requirements in data handling have been previously identified as issues in precision farming and challenging farmers' capacity and knowledge (Lawson et al., 2011; Weersink et al., 2018; Eastwood et al., 2017, 2019), but our results suggest these changes to work do not only concern tactical labour management (Thomas et al., 2023), cognitive load or 'techno-stress' (Martin et al., 2022; Uztürk and Büyüközkan, 2024) but also increased relational workload (i.e. engaging with technicians and company support) as well as frustration from the farmers or employees in trying to master new systems, or being let down by them. For some farmers, this was affecting their satisfaction with farming and the meaning derived from their work, particularly as new tasks were largely shifting work from the paddock to the office. These un-resolved frustrations, labelled as 'burdens' in the review by (Thomas et al., 2023, p6), were making the set up and data work, including fixing routines (e.g. reloading, recoding software), like drudgery where time spent was becoming a grind, being necessary but disliked, which accords with the Kernecker et al. (2020) study reporting farmers as disillusioned about the SFTs they have experience with. This data work was central to the desired farm performance and productivity goals, yet this was being traded-off by the additional time spent. We agree with Martin et al. (2022) that any attention devoted to the reduction in working time from SFTs should not mask the diversity of the transformations of work.

We did not find substantial differences in work changes from SFTs between Australia and the UK, with striking similarities particularly related to data work. The largest differences were associated with farm ownership and work organisation (i.e. corporate, family farming or farms with employed workforces), as well as the sector (horticulture, arable or livestock farming). These differences influenced the prioritisation and selection of SFTs, which flowed on to the effects on work. Owner-operator and family farms tended to implement a range of technologies across many aspects of farm operations to reduce their physical workload or their own time spent and to better organise work, which was also noted in the review by Uztürk and Büyüközkan (2024). Solo operator farms reported significant improvements in efficiency from deploying a range of cost-effective SFTs (often described as 'kit'), like those reported by Mugnier et al. (2021), where technologies helped spread workload or saved time. Larger, multi-employee and corporate farms tended to implement technologies to generate efficiencies in costs

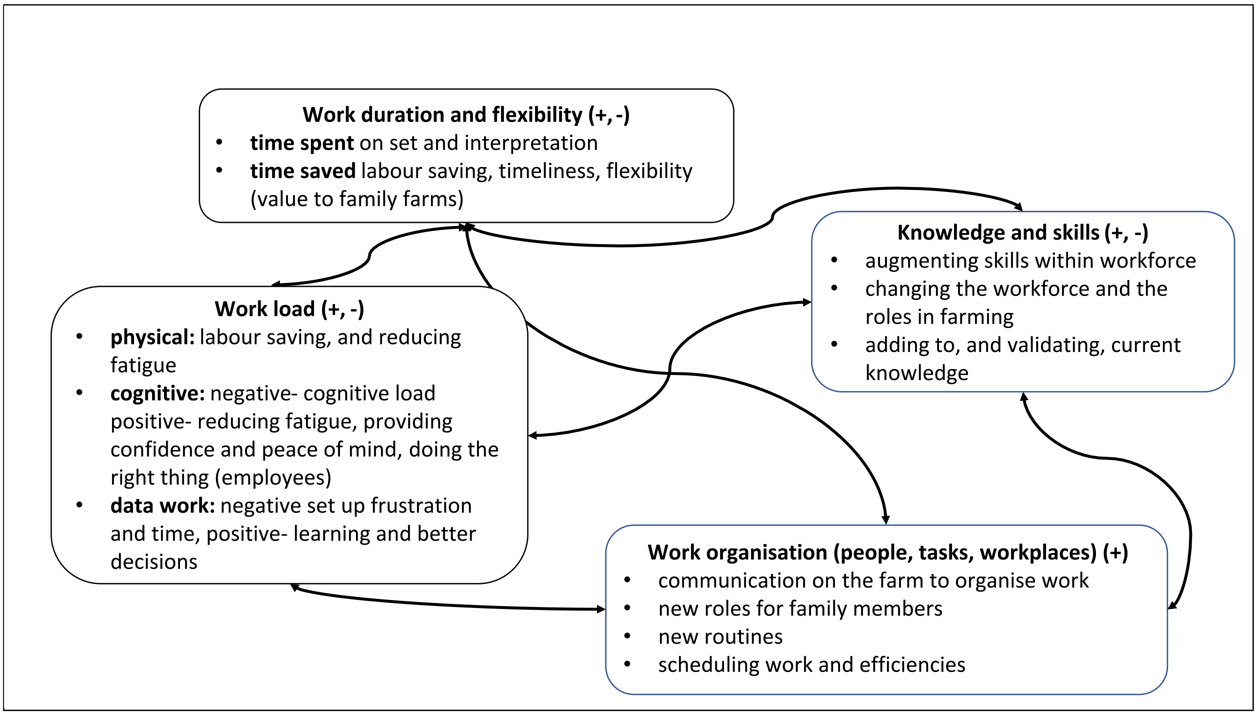

Fig. 1. The complex interrelationships between work effects (positive and negative) from implementing SFTs on UK and Australian farms in this study. Double headed arrows depict a two-way process.

and time, particularly related to reducing farm inputs use (e.g. fertiliser), while better directing the working time of employees. Consequently, the negative effects of time associated with data work and the learning challenge of technology implementation were mainly felt by the owner-operator farmers, where their own time was directed to these efforts, whereas larger or corporate farms had 'back-room' or advisory support to perform this work. While the implementation of information-intensive technologies is suggested to favour corporate farms (Carolan, 2020; Prause, 2021; Galaz et al., 2021), we did find that small and large owner-operated farms alike were seeking benefits from SFTs and were upskilling themselves or drawing on the skills and interests of family members to better work with data. The presence of a family workforce has previously been considered to reduce the need for labour-replacing technology (Barnes et al., 2019). Our study suggests otherwise, with returning children with computer skills enabling more effective use of SFTs.

We also found considerable nuance in the way skills are changing and the implications for the skills of farm owners, employers and employees in implementing SFTs. We found some similar patterns reported by others, being the presence of new professions (e.g. software engineers and data analysts) and a shift from physical or manual work to computer or data work (Delecourt et al., 2019; Eastwood et al., 2019; Ingram and Maye, 2020). However, our study revealed that changes in knowledge and skills were distributed unevenly and the changes were not only associated with the type of work being undertaken, but also with employee engagement in the workplace. Many of the farmers in our study described bringing their employees along in the implementation journey in a joint learning effort, reporting how SFTs were augmenting the skills of their farm workforce, including those employees with limited knowledge of farming. Overall, this contributed to retaining the current workforce by making the work more enjoyable or rewarding. This did not only relate to the embodied knowledge technologies such as machinery guidance, but also the information-intensive technologies, including variable rate applications (Barnes et al., 2019) with employees being assisted to interpret GIS maps and use satellite data for grazing management. The importance of *reskilling* existing workforces for SFT implementation contrasts with a common emphasis on the potential for de-skilling (Prause, 2021). That many of the farmers in our study were upskilling their existing staff or using technologies to complement and augment lower farming knowledge and skills reflects a complex picture of the effects of SFTs on knowledge and skills on the farm not currently captured in technology assessment (Gerli et al., 2022). While the farm workforce has been acknowledged as a contributor to farm innovation (Cofre-Bravo et al., 2019) their importance in the implementation of SFTs has not been acknowledged to any great extent prior to this study and is only now being highlighted as critical in technology acceptance in agriculture (Thomas et al., 2023).

Most farmers in our study also described SFTs as complementing and augmenting and not replacing their own knowledge or physical presence. SFT seem to provide new analytical capabilities, data is integrated with the farmer's own experiential knowledge and helps to target and to detect symptoms early, while data granularity and visualising data provides new insights for learning. These empirical insights counter to some extent concerns raised about farmer ability to utilise data (Ingram and Maye, 2020). Observation is still important with farmers describing their need for 'ground truthing' of data to confirm their own knowledge and observations, particularly when associated with their bonds with animals (as described by Fanchone et al., 2022). We conclude, as Baur and Iles (2023) have proposed, that farmers and farm workers are working to exert their own agency on technological futures for agriculture. This suggests that who is performing the work may be more important than the type of technologies implemented, blurring the lines of what counts as embodied knowledge or information-intensive technologies (Barnes et al., 2019).

This complex and dynamic picture of changes to work is captured in Fig. 1 which shows how the work dimensions are internally inconsistent (depicted with +,-), and are interconnected, with casual and feedback loops between them. There is also internal positive and negative effects within dimensions. Work duration involves continuous trade offs, SFTs can save time in some farms but this is often counteracted by the time spent in set-up or data work. This is closely linked to the many facets of workload (physical, cognitive, data, relational) where again there are internal tensions, for example cognitive load versus improved confidence in decisions. There are implications for organisational aspects, more positive for corporate farms as they are better supported to achieve improved performance and efficiencies compared to family farms. Finally, knowledge and skills acquired and required across the workforce has consequences for organisation of work (new roles and routines), as well as duration and workload. Thus, rather than a static framework with separate dimensions, it is a complex iterative system.

Our main contribution to understanding how SFT implementation changes the nature of work lies in revealing the interrelationships between the dimensions of work (Fig. 1) and the importance of interdisciplinary frameworks in the theorisation of the technology-work interface. This complexity reflects the resources (physical and human), resource flows and interactions that characterise a farming system. In considering how such changes to work could be better anticipated in research, education and technology development efforts, we suggest that the 'dimensions of work' framework and incorporating the dynamics and feedback loops between the dimensions, is an important starting point for researchers, technology developers and farm advisers to test assumptions and anticipate work effects from different types of SFTs and different types of users. Such application of our findings would also help shift current normative views and expectations that SFTs will broadly reduce work duration and workload. Overall, we suggest that data work is not being anticipated to the degree it is affecting the other dimensions of work. Given the interest in greater engagement of farmers with digital agriculture, more consideration of work effects is vital and arguably is a key element for a responsible innovation approach to SFT development (Fielke et al., 2020; Rose et al., 2021a, 2021b).

6. Conclusion

This paper set out to identify the key features of the change in work for farmers implementing SFTs in the UK and Australia to bring a novel perspective to how Agriculture 4.0 is unfolding. To date, there has been a lack of empirical evidence related to work changes from implementation of SFTs and our study has provided additional conceptualisation to understand the nuances of work effects within the farming system and between sectors. The importance of the outcomes for farmers from time saved in implementing SFTs, such as in the organisation of work and in the meaning they associate with their work, has not been acknowledged to any great extent in SFT development. The dimensions of work framework and their interrelationship provides an avenue for researchers, advisers and policy makers to consider these broader effects in the design of SFTs and to the focus for advisory services. These work effects, if acknowledged by AgTech developers, could support more responsible development of technologies, for example through user-centred design, as well as in post-sales support and training. This includes anticipating how technologies interrelate with these dimensions of work and what services are most valued to minimise negative effects on work.

Our findings give weight to the key issue of inadequate levels of after-sale or implementation support generally experienced by farmers and for which advisory services have not been sufficiently developed. While there is an emphasis on technology development and entrepreneurialism through innovation funding for start-ups in the UK and Australia, service design remains technology focused rather than farming system focused. While farmers are involved in technology testing and experimentation, overall it is up to farmers and their advisers to navigate the implementation in the farm system on their own. There is a need for research and innovation policy to factor-in the implications for work, beyond time use, raising questions about the governance of SFT development and implementation. In anticipating work effects, our study has shown that it is important to not only consider the work itself but who is doing the work and their agency, as well as the interaction between data work, work organisation, work duration and skills within the farming system. Although providing insights from Australia and the UK, commonalities in experiences suggest that the study findings are transferable to other farming contexts that share similar levels of SFT development, support and uptake.

We suggest future research be directed to understanding change to employment patterns, farm workforce skills and knowledge, the nature of data work and how challenges are overcome, including the new forms of drudgery that may be emerging from data work. Such research should include farm experiences from developing countries and patterns associated with demographic shifts including for new generation farmers and change in gender roles. The role of SFT tools in enhancing on-farm learning, both family and employees, emerged as an unexpected positive effect and merits further study. More comparative studies are also needed to examine the extent to which institutional arrangements may support the factoring in of work effects and further studies to examine how the negative effects on work found in this study can be overcome and positive effects optimised.

CRediT authorship contribution statement

Ruth Nettle: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Julie Ingram:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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Data availability

Data will be made available on request.

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Ruth Nettle is a social scientist and leads the Rural Innovation Research Group in the School of agriculture, food and ecosystem sciences (Faculty of Science) at the University of Melbourne, Australia. Her research focuses on people and change, work and employment and agricultural innovation and bringing interdisciplinary methods to examine critical issues for sustainable agriculture.

Julie Ingram is a scientist with the Countryside and Community Research Institute (CCRI) at the University of Gloucestershire in the UK. Her research focuses on Agricultural Knowledge and Innovation Systems (AKIS) and innovation processes. She is a specialist concerning knowledge exchange within the agricultural community and knowledge processes within the context of sustainable agriculture. At the European level Julie has led Work Packages in EU Horizon 2020 and FP7 projects in agricultural sustainability.