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Adoption of autonomous robots in the soft fruit sector: Grower perspectives in the UK

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ABSTRACT

The effects of changing geopolitics, demographic change, and COVID-19 have caused significant disruption to labour in the agricultural sector around the world. In the UK, the challenges to free movement of labour and safe working conditions caused by COVID-19 have exacerbated the labour shortage caused by Brexit. In these circumstances, the use of autonomous robots in those sectors hardest hit by labour shortages, such as soft fruit, is being considered as a potential solution. Autonomous robots for use in the high value crop sector, including soft fruit, are at varying stages of technology readiness with robots for disease treatment, packhouse, and logistic support already commercially used and robots for picking approaching a demonstration phase. However, the pathway to implementation is not determined by technology readiness alone, but rather by the intention and ability of growers to adopt. To date, there has been limited investigation of the views of soft fruit growers towards the introduction of autonomous robots in the sector. We used a mixed methods approach, utilising a grower survey and qualitative interviews conducted in the UK, to explore the factors affecting adoption of autonomous robots on soft fruit farms. In general, the survey shows that growers are optimistic about the prospects of autonomous robots on soft fruit farms, although not necessarily in the short-term and there are several factors affecting uptake, particularly cost and infrastructure, as well as issues such as data ownership, cybersecurity, skills, and trust. We reflect on our findings in the context of existing research on technology adoption by growers and make a series of industry and policy recommendations which have global relevance.

1. Introduction

In many places around the world, the agricultural sector is struggling from a lack of labour. This includes the European Union, which has seen a loss of 2.5 million agricultural workers in the last decade [1]. There are a several reasons for labour shortages, which vary in different places, but commonly cited drivers include a negative perception of careers in agriculture, geopolitical or demographic changes affecting labour flows, and COVID-19. The pandemic led to lockdowns and travel restrictions which -'kept seasonal temporary workers, which [agriculture] has grown reliant on, from reaching their workplace curbing the productivity of this essential sector' ([2], 1). This led to agricultural labour shortages in the hundreds of thousands in parts of the European Union [3].

In the UK, the decision to leave the European Union, and the subsequent impact on free movement of labour, has manifested into labour shortages before and during the COVID-19 pandemic [4]. As well as the end to free movement, the labour shortage has been attributed in part to the speculation of so-called 'unskilled' workers being unwelcome in Britain, as well as the economic impact of the fall in value of the pound [5]. UK horticulture is reliant on a large seasonal labour force with 98% of workers coming from the EU [6]. Schemes to encourage farmers and growers to hire home citizens have widely proved unsuccessful [4]. Barbulescu et al. [4] found that 69% of UK growers experienced labour shortages in 2021 and 70% of these respondents faced a labour shortage of over 10%.

The UK soft fruit sector is worth around £244 million and employs 35,000 workers [7]. The sector is particularly reliant on seasonal human labour. British Summer Fruits, the trade body representing 95% of commercial fresh berry growers in the UK, identified the need for 29,000 seasonal staff in the berry industry.[1] The workforce depends on EU seasonal workers returning each year with past figures suggesting that

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[1] Evidence submitted to the EFRA Committee in Parliament. https://www.committees.parliament.uk/writtenevidence/39912/pdf/

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75% of pickers on average return to pick in the next season. With restrictions on migration after leaving the European Union, this return rate fell to 45–50% with a prediction of a further fall to 30% in 2022[1]. The impact of labour shortages in this sector has been failing businesses, reduced planting of crops, and high-value produce rotting.

Technological solutions, including autonomous robots, could help to address shortfalls in labour [8,9,10] and there is a feeling that the COVID-19 pandemic has accelerated efforts towards agricultural automation throughout the world [8,11], speeding up an assumed transition towards the so-called fourth agricultural technology revolution [12]. The British Summer Fruits evidence submission to Parliament highlights that autonomous solutions are being increasingly used in the packhouse, but other key farm operations, such as picking, packing, and disease treatment still require human labour.

The benefits of autonomous farm robots have been discussed by Rose et al. [13] and could provide gains for productivity and the environment, as well as offering social benefits to health, employment, and grower lifestyles. It is speculated that the advent of agricultural robots to perform tasks such as packing and picking would raise the quality of fresh produce, lower production costs, reduce the drudgery of manual labour, reduce chemical inputs, and, in some parts of the world, compensate for the lack of farm workers [14,13,15]. The Robot Highways project[2] is demonstrating autonomous robotic solutions for picking, packing, forecasting, logistic support, and disease treatment. It plans to eliminate fossil fuel use across all farm logistic operations (robots run on renewables), cut fungicide use by 90% (via a UVC disease treatment robot), reduce packhouse labour by 30% and farm labour by 40% (logistic support robots alone could save 20% labour cost and 10% land usage, [7]), increase productivity by 15%, and reduce fruit waste by 20% through accurate forecasting. Others have argued that the agricultural workforce of the future using robots will be smaller but more highly skilled, which in turn may transform the public image of the agricultural profession, thereby making a career more attractive [16, 17].

In the soft fruit sector in the UK at the moment, most fully autonomous robotic solutions are in the development or testing phases. There is some automation in packhouses and low-cost platforms for logistic support, as well as potential near-term scaling of autonomous UVC disease treatment in strawberry crops, but further research and demonstration is needed before commercial scaling of picking and other operations [9]. As robotic solutions become available, there is a need to recognise that the implementation of autonomous robots to farms around the world is not without challenge nor controversy.

Adoption challenges of all kinds – technical, regulatory, social, political, ethical, scalability – could mediate the pace and extent to which autonomous robots can solve environmental and labour challenges. To date, there has been limited research exploring farmer/grower perspectives of the use of autonomous crop robots on-farm, particularly in the soft fruit sector; for example, highlighting potential adoption challenges, identifying ethical issues, or allowing stakeholders to be involved in the co-development of technological solutions to the immediate and long-term challenge of labour shortages. Such research is important as Baur and Iles [18] remind us that robots form part of a socio-technical network. They write (page 4) that ‘a robot is not simply a tool moving through a farm field in isolation’, but rather something that is continually interacting with end users, shaping the farm environment, as well as being shaped by farmers/growers.

We use a UK case study in the soft fruit sector, which has been heavily impacted by labour shortages, to investigate what soft fruit growers think about the implementation of robots on their farms. We conduct this study to cut through media, industry, and policy headlines which extol ‘new robotic advances that promise to transform agriculture’ ([18], 1), focusing on adoption challenges which may temper the grand, rapid promises of progress [12,19]. After a short literature review, we focus on four main areas:

1 The extent of **labour challenges** in the soft fruit sector and the promises of robots
2 Potential **roles** for autonomous robots and the timescale of implementation
3 **User readiness** and **adoption challenges** for autonomous robots
4 **Solutions** and **alternatives**

We provide recommendations for technologists, farming stakeholders, and policy-makers about the likely contribution of autonomous robots to the soft fruit sector, as well as the key barriers and solutions to adoption. Whilst these lessons are learned from a UK case study of soft fruit, we identify those broader lessons that can inform the development of robotic and non-robotic solutions in other regions and in other high-value crop sectors which are also struggling with lack of labour.

2. Previous studies on user views of autonomous farming robots

We restrict our discussion here to the application of non-static autonomous robots in farming. The implementation of static robots in dairying is more widespread [20,21], whilst part automation for example in the form of autosteer or variable rate technology has also experienced wide uptake in some places [22]. We focus particularly on the soft fruit sector, where autonomous robotic solutions are not commercially scaled, and on comparable sectors that have already adopted forms of robotic solutions (e.g. viticulture, top fruit [e.g. apples]). In the soft fruit example used in this study, autonomous robots could be applied in different types of controlled or non-controlled environments, such as polytunnels, glasshouses, or open field systems. There is little information on adoption rates for technologies, including robotics, in fruit farming. Groher et al. [23] conducted a survey with 105 fruit farmers and 69 strawberry growers in Switzerland, finding that 16% and 7%, respectively used automated steering and 2% and 3% used automatic data collection.

Fully autonomous non-static vehicles present a number of adoption challenges. In reviews and thought pieces, these are discussed extensively by Sparrow and Howard [15], Rose et al. [13] Ryan et al. [24] and Daum [25]. The assumed transformation towards more digitalisation on farms around the world is part of a switch to socio-cyber-physical systems [26] and growers, alongside other farming stakeholders, are key actors within them. Reviews have shown that autonomous robots potentially pose a number of ethical risks to health and safety, data ownership, and displacement of labour [13,24,27,15]. Vasconez et al. [28] note the challenge of human-robot interaction in farming in an environment for which few standards or up-to-date regulation exists, a subject which Basu et al. [29] and Lowenberg-DeBoer et al. [30] also discuss. Adoption challenges such as high costs, lack of digital skills and infrastructure, lack of trust, and limited reliability also challenge speedy adoption on-farm [13]. Based on adoption of other precision farming technologies, the pace of change is likely to be different for farms of varying size, scale, workforce age, and access to digital infrastructure [31,32,13]. Herein, Rose et al. [13] mention four principles of ‘responsible innovation’ that are to be considered in the design and development of autonomous robots. These principles are (i) anticipating the impacts of innovation, (ii) reflecting on one’s work and adapting accordingly (reflexivity), (iii) including a wide range of stakeholders in the design process and, (iv) responding to stakeholders’ concerns, ideas and knowledge by constructing appropriate institutional structures such as policies, laws and regulatory frameworks for safeguarding growers’ concerns.

A key part of this framework is the inclusion of technology users. Research shows that various factors need to be in place before a technology is ‘ready’ to be adopted [33]. These factors are (i) the technology needs to be able to function effectively in the use environment, (ii) the

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[2] https://gtr.ukri.org/projects?ref=51367.

technology must be scaled effectively within the marketplace, (iii) it must be able to operate effectively within existing or updated laws and regulations, (iv) it must be accepted by the user and, (v) those users have to be able to domesticate the technology by making it work on their farm (skills, infrastructure, cost etc. play a role here). Thus, whilst technology readiness is important, views of users and their ability to adopt and use autonomous robots within a particular regulatory environment are vital.

As autonomous crop robots in farming are not in widespread use, empirical research exploring user perceptions of autonomous robots and adoption factors is limited.[3] Some research has been undertaken, however, to understand what farmers, growers, and workers think about the introduction of autonomous robots to their farms. Much of this research has focused on collecting user views to assist with the design of robotic technologies, rather than necessarily to challenge fundamentally the direction of travel towards automation [13].

Some viticultural and tree fruit growers are utilising robotic solutions for harvesting, pruning, fruit transportation, spraying, thinning, and forecasting, although many are still not widely scaled [34,35]. However, Zhang et al. [[35], 21–16] report that ‘robotic technologies for tree fruit production have never been so close to being practically applicable’, but identify skills, safety, cost, and technical challenges as barriers to implementation. To assist with the development of a semi-autonomous vineyard sprayer, Adamides et al. [36] sought the views of growers in the spirit of participatory design. Farmers and agriculturalists were involved in two field experiments to test the design of the sprayer. In one experiment, thirty users were given the chance to operate robots in the vineyard environment without running into obstacles. In the second, five users were asked to perform spraying on set targets. Feedback was received on design suitability via surveys which enabled the team to develop the user interface further. The team found this process useful as a means of setting up two-way dialogue and building trust in the technology. Reflecting on the progress of a five-year project in New Zealand to develop AI and robotics for apples, blueberries, and viticulture, Legun and Burch [37] interviewed 22 apple orchard managers and found that each was assembling their orchard in different ways in anticipation of robotic futures. This project is seeking to co-design robotic solutions in these farming sectors with growers and workers [38].

In a soft fruit example, Baxter et al. [39] ran a two-day demonstration event involving autonomous robots working alongside human fruit pickers, assisting with in-field transportation of the fruit. Following this trial, a questionnaire was distributed to the workers and a verbal debriefing was held. From the debriefing after the work trial, the human pickers generally viewed robots positively and their behaviour appropriate, despite having a few reservations with the concept of roles being conducted by autonomous machines.

More general studies have been undertaken to gather farmer views of autonomous field robots. Three papers explore the perception of German farmers towards their implementation. One study by Spykman et al. [40] explored the views of 174 German farmers and their preferences towards the size of robots. Opinions differed by the scale of farming, with larger farmers wanting larger robots and highlighting economic benefits, and smaller farmers preferring smaller robots and focusing on environmental benefits. More farmers generally imagined owning small robots as opposed to an autonomous tractor in ten years, but at the same time viewed autonomous tractors as more suitable for most specified agronomic tasks. Two further studies by von Veltheim and Heise [41] and von Veltheim et al. [42] used the Unified Theory of Acceptance and Use of Technology (UTAUT) to explore the views of 490 and 500 German farmers towards autonomous field robots. In the former study, an overall neutral-positive stance with three distinct sub-groups of opinions were identified – open-minded (willing to consider robots), convinced (in favour of robots) and reserved (sceptical about robots). The second study identified similar UTAUT-related factors affecting attitude, including performance, trust, and safety concerns.

Adoption challenges for autonomous robots in general have also been noted in other studies. Devitt [43] provides a useful overview of the cognitive factors affecting a farmers’ intention to adopt autonomous robots, including technology performance, effort expectancy, social influence, facilitating conditions, and trust as being key factors. In a survey on future farm automation in Germany, Kester et al. [44] noted that lack of trust would likely be a barrier to uptake, as well as the challenge of using robots in pedestrian environments. The possibility to reduce workload, increase productivity, and reduce costs such as labour appeared to be the most pressing drivers for the intention to adopt. Based on interviews with farmers in Queensland, Redhead et al. [45] discussed robotic adoption factors such as system complexity, rural communication infrastructure, and data storage. Barbulescu et al. [4] spoke to 50 growers and 73 seasonal workers in the UK about the suitability of robotic solutions. Initial data suggested that growers felt that the technology showed promise, but may be too expensive, may not be ready for 5–10 years, and more suited to certain tasks such as packing.

In short, however, despite the existence of a few small studies on adoption factors and user views towards autonomous robots in farming, farmers’ and growers’ attitudes toward crop robots have hardly been studied. This is also true in the soft fruit sector and in the UK which has seen a dearth of studies investigating grower views thus far. Our study fills this gap by exploring the views of UK soft fruit growers towards the adoption and implementation of autonomous farm robots and aims to draw lessons for the development of the technology in the UK and elsewhere.

3. Materials and methods

The objective of this study is to document the perspectives of soft fruit growers about autonomous robots in soft fruit cultivation. The perceptions of soft fruit growers in the UK were gauged through a growers’ survey and grower interviews. We focused on the following key themes in both:

1 Labour challenges and the promises of robots
2 Roles/timescales/future
3 User readiness and adoption challenges
4 Solutions and alternatives

We focused our attention on commercial-scale soft fruit businesses who paid a levy to the Agriculture and Horticulture Development Board. To pay a levy, a business must turnover (or have an adjusted sales figure of) more than £60,000. These are the businesses most likely to benefit from autonomous robots since they are large-scale and have sizeable labour requirements. Robotic manufacturers are focusing on these type of businesses. Based on publicly available data, there are approximately 125 levy-paying soft fruit businesses in the UK.[4]

An online survey was developed using Qualtrics software (Appendix 1) and distributed between 15 February 2021 and 25 March 2021 by deliberately targeting larger, retail soft fruit growers or grower

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[3] In the soft fruit sector, autonomous robotics for use on-farm are generally in the demonstration phase around the world, including the disease treatment, packing, and picking robots involved in the Robot Highways project https://www.robothighways.co.uk/.

[4] 86 soft fruit levy papers voted in a 2021 ballot on the future of the Agriculture and Horticulture Development Board. Turnout of eligible voters (businesses paying a levy) across all horticultural sectors was 69%. If this turnout was the same in soft fruit specifically, there would be approximately 125 soft fruit levy payers in the UK. The AHDB were asked for the exact number, but this was not available https://consult.defra.gov.uk/ahdb-relationship-team/ahdb-order/supporting_documents/Annex 1 Breakdown of Horticulture and Potato Sector Ballots.pdf.

representatives (e.g. representatives of purchasing organisations, which are made up of individual grower members, run as a single enterprise). We identified grower businesses from the British Summer Fruits website whose members grow 95% of the berries purchased by UK supermarkets. We telephoned or emailed these businesses, with one-follow up contact, asked the British Summer Fruits to send the survey around to members, as well as utilising known contacts (e.g. Berry Garden Growers which have 28 growers are part of the project consortium) and social media. We did not ask specifically whether respondents were levy payers,[5] and responses were anonymous, but we took a number of steps to ensure that our 41 final respondents were levy-paying scale businesses. Firstly, 20 of the 41 final respondents confirmed to us by email or verbally that they had filled in the survey. Following-up with these growers, 100% either confirmed that they represented levy-paying businesses or publicly available accounting through Companies House[6] showed that they were of the scale required to pay the statutory levy. A second layer of confirmation that our respondents were levy payers came from the size of businesses which responded. The average full-time workforce was 53.5 and the average seasonal workforce was 488. The ranges were 1–500 for full-time staff and 30–4000 for seasonal staff. These statistics provide strong evidence that our respondents were levy-paying sized businesses. For the five growers who did not list employment details, four stated in the survey that they had often struggled from a lack of seasonal labour (suggesting a commercial-scale business), whilst the other had a 25 ha strawberry operation, again a levy-paying scale. We did receive a 42nd response from a grower who employed just three members of staff and this response was removed because this was not strong evidence that it was a levy-paying business.

Although the final response of 41 growers may appear small, the best available evidence suggests that this represented a third or more of soft fruit levy paying businesses in the UK. We state 'a third or more' because some growers represented more than one business. The breakdown of respondents to this survey is shown in Appendix 2, showing that growers from across England and Scotland (major soft fruit growing regions) responded with several different soft fruits covered.

Furthermore, online interviews were also conducted for ten growers to explore further some of the themes raised in the survey responses. We conducted a purposeful sample, contacting those businesses who we had spoken to previously on the phone and who had expressed interest in filling in the online survey. At least eight of these businesses could recall filling in the online survey and represented levy paying businesses. The interview schedule, shown in Appendix 3, was developed to give greater depth to the questions asked in the survey, also drawing on concepts from the academic literature on 'user readiness' [33] and barriers/solutions to the adoption of technology [46]. Interviews were conducted by Teams or Zoom, recorded, transcribed, and analysed with NVivo software. Given the busyness of growers during season, the interviews lasted up to 20 min. Interviews were coded thematically following the open and merged coding methodology of Bryman [47] and a coding map can be found in Appendix 4. The survey and interviews were also subject to ethical review and approved by the Ethics Committee of the University of Reading (Application 1495D and 1694D). Both the survey and interview were piloted and questions refined based on feedback. These were piloted on grower representatives on the Robot Highways consortium. Comments related to the complexity of questions and the length of the survey and interview guide for busy growers. Adjustments were made to ensure lengthy questions (e.g. labour use figures) were not compulsory and the number of questions was reduced.

4. Results and discussion

We explore each objective outlined in the introduction in separate sub-sections below using both survey and interview data in all sections. Interview quotes are used to provide evidence for the themes identified. Individual quotes do not imply that the view was necessarily widely held by all growers interviewed.

4.1. Labour shortages and the promises of autonomous robots

Growers were asked in the survey about the impact on various farm operations of a shortage of seasonal labour. Fig. 1 shows that a shortage of labour is a major problem for picking in particular, but also in other areas. This is unsurprising because the operations requiring manual tasks to be undertaken necessarily need (currently) human labour to perform those tasks.

In the interview, for those growers who were excited to embrace robotic technologies, solving the labour shortage was the major driver for adoption, but they also mentioned the potential ability of robots to work 24/7 as a key benefit:

"I bet every single grower will answer the same way. It's about reducing the labour shortage issues because we're facing that every year and it gets worse and worse. And…also the quality of the labour we've seen changes over time…it's not what it used to be." (G10)

"If a robot can pick continuously all the time, that is the key really to the whole system and that's where we'll see the wins. But if they can't pick 24 hours a day, then I think that's just not going to happen." (G2)

Autonomous robots were seen as giving the potential to increase productivity and profitability. One grower thought that if labour could be substituted and robots could work longer, *"hopefully it would work out cheaper" as the "return on investment would work out more efficient than employing people" (G4).* Another said:

"Hopefully we could have some savings on the people because at the moment there is a shortage. If you've got a robot, you just tell the robot. They are not temperamental and have no emotions and personal problems, and they are not going to get sick or are not arriving." (G5)

These results echo the concerns raised both in the UK and globally about the immediate impact of labour shortages in horticulture [4,3,48]. Yet, it may not be a simple case of autonomous robots replacing labour. A recent study showed that regulatory requirements in most places around the world demand human supervision of autonomous robots for safety [30], which means human recruitment is still required and the financial savings of reduced labour may not transpire immediately. Our study has shown that the impacts of labour shortages are felt more strongly in specific farming operations, particularly those that involve manual tasks.

4.2. Roles for autonomous robots, timelines, and the future

In the survey, growers were asked about the farm operations to which autonomous robots could make an important contribution

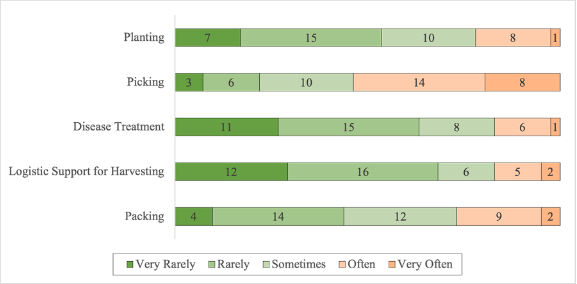

Fig. 1. Number of growers reporting a negative effect of lack of labor on various farm operations ($n = 41$).

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[5] With hindsight, this was a misjudgement, but we took steps to gain further information to check our targeting strategy.

[6] https://www.gov.uk/government/organisations/companies-house.

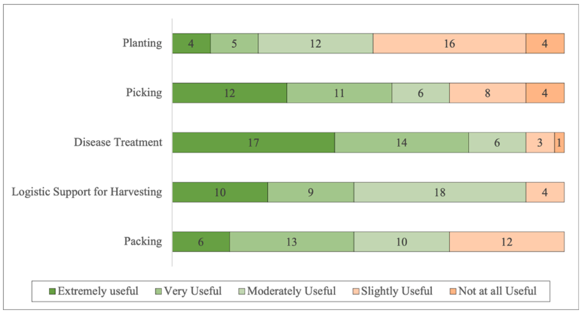

Fig. 2. Perceived grower usefulness of autonomous robots for different farm operations ($n = 41$).

(Fig. 2). Partially linked to those areas in which lack of seasonal labour had caused problems, growers felt that autonomous robots could play a useful role in disease treatment, picking, and logistic support for harvesting. Opinions were more polarised on their usefulness in the packhouse, although 19 growers thought they could be extremely or very useful here. The growers' opinions of robots as useful in the packhouse may reflect the fact that automation is already being utilised in packhouses in the soft fruit sector. There was less enthusiasm about the role they could play in planting.

Interviews further probed grower perceptions of robotic applications and we explore these views in themed sub-sections.

4.2.1. *How do growers find out about robotic solutions?*

Firstly, we were interested in the information sources growers were using to make judgements about the areas in which autonomous robots could be valuable. Most growers were forming their views and opinions on autonomous robots through media and the internet, rather than through face-to-face demonstrations, which is unsurprising given the technology readiness level of some applications. One grower said:

"I've seen some of the robots already, not like in live, but I've seen the videos and at the moment it doesn't seem flexible enough. It's not very advanced enough to be able to perform the tasks now." (G5)

Some growers based their knowledge on attending conferences and following academic research. One said:

"Only yesterday I was at the FPC Futures conference. The whole day was dedicated to robotics, automation, vertical farming, so there was a lot of information to be had there and we made lot of connections."(G8)

Some big growers are already working with robotic companies and so they have *"got inside track into their development of autonomous robots"* (G6). Some growers reported their source of information to be *"demonstration shows like Fruit Focus 2021"* (G1).

One grower noted, however, the difficulty of knowing how the technology development was progressing:

"I wouldn't say the press has been particularly informative because an awful lot of these companies have been in sort of stealth mode and not really revealing very much for a while." (G6)

4.2.2. *Which farm operations can robots help with?*

Amongst the various roles of autonomous robots that growers anticipated, picking and packing roles were mostly discussed followed by disease treatment and data collection. Amongst the different roles that robots could play one grower said:

"I'd suppose that the temptation is to go for the largest, most manual tasks because that is the biggest addressable market, so I suppose it's likely to be harvesting and packing, and…repetitive manual tasks." (G6)

For picking, however, there was some scepticism about the performance of robots, which could be worse for some fruits than for others. Talking of robots being slower in picking than humans, a grower explained:

"Picking is the most tricky job, because a human being when they look at strawberry has to make 50 decisions. Now the robot needs the cameras to make these decisions and the problem with that is that it will probably take another millisecond to do that. And by the time you've done that, the pickers have already picked it." (G2)

On the subject of robots being better suited for some fruits than others, a grower argued:

"I do think we probably need them for harvesting blueberries. I don't really see how we're going to be able to use robots on raspberries or strawberries. This is because blueberry picking is a little bit different and the bush looks different. I'm not convinced about the same for strawberries and raspberries. I just can't see how that's going to work." (G5)

On packing operations, a grower said:

"It will be interesting how much we can robotize our packing line in the pack house as well. So currently that is semi-autonomous and we still rely on quite a bit of workers for us around the line. But we are talking to companies which got solutions for end of the line where punnets are picked up by robots and placed into crates and even stacked…endless opportunities there." (G10)

On disease treatment and pest management a grower said:

"I think we could use the robots to help with…disease protection because I've seen already some robots, and I think that's going to be quite easy." (G5)

Data collection and fruit prediction was also considered an important task for robots and this was explained by a grower:

'I think the most important one that we could get up and running straight away is gathering data and what I mean by that is if it would predict the flowers and fruits and then we get a more accurate determination of when these flowers and fruits will come into production. That is one of the biggest things." (G2)

4.2.3. *Expected timescales for robots*

As for the timescales of robotic implementation, answers were mixed. For most robotic applications, growers put a timeframe of 5–10 years, which suggests that autonomous robots are not an immediate solution to labour shortages. Most growers put the delay down to adoption challenges, which are further developed in the following section. There was a sense from growers that some applications may be quicker to market than others. For example, one grower gave an anticipated timescale of 4–5 years for picking (G10), whilst another thought that robotic data collection would be available next year (in 2022) and may be a '*quick win*' (G2). For UVC disease treatment growers mentioned that it was approaching technology readiness and one said, *"we are looking into that next year"* (G10).

On asking how their farms would look like in 2030 in terms of technology, some growers spoke about using autonomous robots, others spoke about using differently powered machines, better plant varieties, upskilling their existing workforce and lastly having predictable growing environments with advanced data technologies.

Some predicted robotic futures, others did not, as the two quotes below illustrate:

"I would like to believe by 2030 we will have a robotic picking inside which will be dealing with majority of the fruit…I think it's going to be before 2030 anyway, but by 2030 definitely we have more robotic solutions in terms of applying biological chemicals and UV light to replace chemicals…Basically we'll have an autonomous system in place in transporting fruit from out of the field to the packing area, which is again hopefully is in the very near future." (G10)

"I personally am not sure that we will have [robots]. I'm not really keen on this idea…they could be a sledgehammer to crack a nut… Sometimes the solution might be just mechanization, you might not need an autonomous robot." (G6)

4.2.4. *Summarising grower views of robots*

From the results above, there are three interesting areas for further reflection. The first involves a discussion of the specific farm operations to which autonomous robots can make an important contribution. Barbulescu et al. [4] reported scepticism amongst UK growers on whether autonomy could cope with the diversity of tasks required on the farm. The literature on farmer technology adoption shows that innovations are most widely adopted where they are relevant and solve pressing user problems [46]. By listening to grower views in the soft fruit sector, and elsewhere, robotic solutions can be targeted towards those farm operations that are both suffering the most from labour shortages and for which the nature of the work suits autonomous robots. This will require two-way dialogue between grower and technology developer, both to elucidate user needs, but also to help users understand the technical possibilities and limits of solutions.

Secondly, the views of growers imply that there is a disconnect between growers and technology developers in the UK, which makes establishing two-way dialogue more difficult. Growers in our study used various methods to gather information on robotic solutions, but struggled to keep up with the latest developments. Previous studies have highlighted the challenge of open innovation within agricultural innovation systems that are comprised of private companies and research institutions who are in competition with one another [49]. Turner et al. [49] explored the 'competition silos' that are created within competitive agricultural innovation systems, finding that this can block co-innovation from occurring. Such competition can limit the appetite of technology companies to involve stakeholders in the co-development of products.

Thirdly, the future of autonomous robots in the UK soft fruit sector is uncertain and hard to predict, a finding that is likely to be true for other crop sectors and places around the world. Research on the uneven pace and scale of technology uptake in farming has illustrated that many different visions of future farming are possible and are likely to co-exist [50,51]. Our interviewees spoke about larger farms being better placed to invest in robotic technologies, as a result of larger cashflows, a more diversely skilled workforce, and more social connections, than smaller ones. Such an uneven engagement with new farming technologies has also been noted in other studies [31,52]. Our interviewees also had different visions of what their farms might look like in 2030; most predicting a wide adoption of autonomous robots, but others articulating different visions. This supports the survey work on robots carried out by Spykman et al. [40] in Germany.

4.3. User readiness, adoption challenges

Based on Rose et al. [13], the survey asked growers to respond to a series of statements centred around adoption challenges, including cybersecurity, data ownership, and infrastructure (Fig. 3).

Headline findings from Fig. 3 are that 76% of growers strongly agreed or agreed that autonomous robots are the future of the soft fruit industry. 78% of growers expected employers to factor in costs for maintenance and repair of the robots, whilst 66% believed that employers should be responsible for autonomous robots working safely alongside their workers. The survey also specifically asked about infrastructure available for robots on the farm. Fig. 4 shows that 27% of growers felt all of their production sites were close to charging points and 36% felt that most of their production sites were close to sources of charging. In contrast, 37% thought that their farms were isolated from, or most production sites were a long way away, from charging infrastructure. These results imply the need for infrastructure changes for charging (for robots running on certain sources e.g. solar or electricity) and secure storage (all robots). The more isolated the field, the more likely autonomous transport to the production site is not possible (e.g. illegal to drive autonomously on public highways). For access to all fields, well maintained farm tracks will be needed, as well as risk assessments and modifications for the people that may be encountered on the route (e.g. residents, workers).

Table 1 shows nine factors that were discussed in the interviews as playing a key role in adoption decisions: cost/benefit; infrastructure; robot performance; repair and maintenance; skills; trust; safety; security; and technology readiness. These factors are interlinked.

The adoption factors for autonomous robots raised by growers in our study echo the findings of a burgeoning literature on farmer/grower

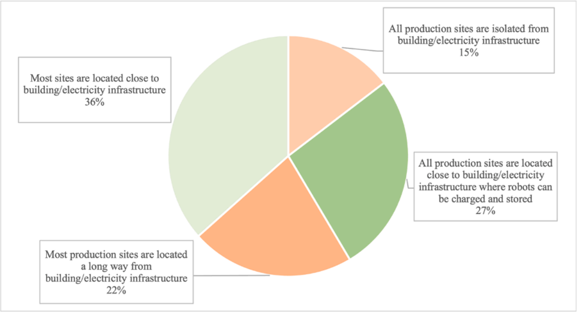

Fig. 4. Grower responses on the location of their production sites in relation to sources of electricity for charging robots ($n = 41$).

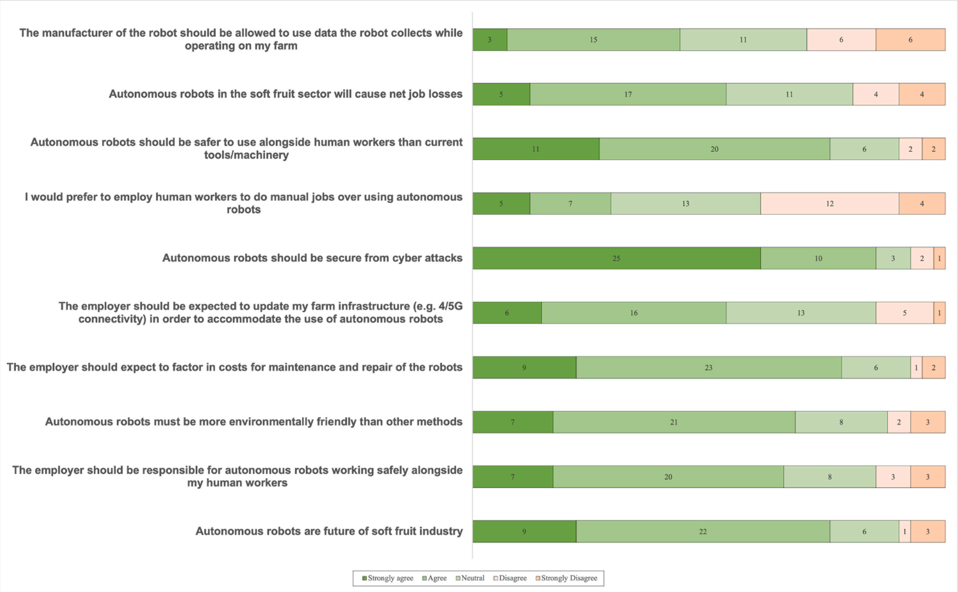

Fig. 3. Graph showing grower responses to statements about autonomous robots ($n = 41$).

Table 1
Adoption factors for autonomous robots given by UK soft fruit growers in interview.

Adoption factor	Sample quote/s
Cost/benefit	*"For 90% of the growers out there in the country, the finance side today are the costs and not everyone is capable of investing so much money into it."* (G10) *"These things aren't being produced in numbers that would reduce the cost enormously, so that's going to be at a hefty cost. I appreciate that it can be challenging but at present that would definitely be the biggest barrier."* (G8)
Infrastructure (digital connectivity, power or electricity, topography, space in the packhouse, field containment or other solutions if footpaths cross the land)	*"We need dispersed electricity availability. How do you get power to these robots in field systems? So that's either using solar power or a connection to the grid, and you obviously need good Wi-Fi connections."* (G6)
Performance of robot for some operations	*"It is going to be slow. We need seasonal workers because they pick better than robots."* (G9) *"Unless a robot can get up to speed, but I don't see how they can do that without us changing the way we grow, we'd have to almost place every strawberry. Make it visible."* (G2)
Repair and maintenance	*"We have 10 at the moment and only 4 or 5 of them are working. So there is a challenge there and keeping every single one running. So, I think that is the scary part, because then you're employing people that are probably on huge salaries to look after these things."*(G2).
Skills	*"I think that the one of things will be to make sure that they have skilled enough labour to operate autonomous robots. There is a lack of understanding at the moment about what level of skill will be required for that."* (G8)
Trust	*"The growers need to have trust in the technology, does it work, would it continue to work, can we rely on it, it's a big step."* (G8)
Safety	*"Obviously, if you have a lot of autonomous robots whizzing around, they've got to be completely reliable. You know, we've all read about the Ocado robots starting a fire. So we need to be sure that everyone is comfortable with them from the health and safety aspect."* (G6)
Security/crime	*"And then there's a third challenge which is security. How are we going keep them secure and not stolen?"* (G6)
Technology readiness	*"We're ready but the technology is not ready yet."* (G10)

technology adoption in general. These studies have tended not to focus on autonomous robots, but it is unsurprising that the factors affecting adoption of robots are not dissimilar to those identified for precision farming technologies (see e.g. [53,46,33]). Non-static autonomous crop robots present more adoption challenges in the areas of health and safety, responsibility, and regulation, but there is much to learn from existing literature on overcoming barriers to adoption. Despite the myriad of studies identifying constraining factors such as cost, trust, poor infrastructure, and lack of digital skills (see e.g. [54,55]), growers continue to report the same issues. This implies that the progress towards adoption of autonomous robots in horticulture is unlikely to be rapid, even if technical readiness comes quickly. Relatively slower progress towards adoption than the language of the so-called fourth agricultural revolution implies, even in the midst of an immediate labour crisis, would correlate with the historical pace of technology adoption in agriculture, which is often, if not always, slow [12,56].

4.4. Solutions and alternatives

Growers suggested solutions to some of the barriers above, particularly on cost, trust, and technology readiness. These included the need for further investment into the development of robotic solutions so that readiness could be sped up and support more readily available for growers to invest. On grants and investments, a grower said:

"I think it needs a little bit more money in it. The solution probably will be to invest more. So for us if we don't because we haven't got enough money, we would need probably some funds, some government funds, maybe schemes which would help us to invest in that. Whatever that may be, like pay less tax etc. But I think a grant would be nice." (G4)

High manufacturing costs for the first generation of autonomous farm robots may mean that purchasing costs for the end users are high. Cost reduction strategies suggested by growers includes competitive pricing or leasing arrangements; such a service model is being actively considered by developers of autonomous robots across all farming sectors. One grower said:

"I think that rather than purchasing if there is some form or lease agreement so that growers may not have to stump up an enormous amount of cash." (G8)

Scaling was a concern for one grower:

"Electric cars are high cost now, but we know they'll come down when they are made in the millions. Similarly if robots are made in the millions it will get costs down, but we know that these robots will not be produced in millions and I think that inevitably what's happening in any nascent industry is that you have a whole lot of people developing similar, wanting the same solutions and developing ways and competing against each other and that may bring the price down and it may sell more but it may also stifle innovation and that might not be desirable so I am worried about it." (G5)

Constructive engagement with growers, and co-development of robots, was considered important for adoption. Growers wanted robot manufacturers to talk to them and also to be invited to field demonstrations:

"I would just urge them to keep close to the growers. For example, if you're talking about security you need to go and talk to practical farmers about how you would keep valuable bits of kit secure. How can we work with you to make this easy? They need to talk to us to actually work out how to implement this on the ground." (G6)

"I think field demonstrations is something which we would like to see. We would like to see their results and know how easy or difficult it is to use a robot in our fields." (G5)

Co-development could help address products being developed that would be too expensive:

"I think they've just got to think from the very start how much the end product is going to cost a grower and whether that fits in with the overall supply chain costs. I think too many of these projects start out as a really good idea. Maybe a university project and then they progress and then a bit too late in the day they start thinking, "Oh, how are we going to manufacture this cheaply enough?" It's better to start at the very beginning thinking I want to make a robot which costs this much and then you value engineer it from the start." (G6)

Collaboration between industry, government, and growers would also be needed because many of the challenges holding back implementation, such as poor digital connectivity and other infrastructure, cannot be addressed by one set of stakeholders alone. It could also build trust according to growers. Barriers to co-development may be difficult to overcome, but there may be a role for government and other funders to provide incentives for open collaboration and data sharing whilst recognising commercial realities [57]. Paschen et al. [57] argue that governments have a 'pivotal' role in creating non-competitive opportunities for industry co-innovation and to providing financial incentives to businesses to work in a more collaborative manner. Support for co-innovation is equally important in the development and implementation of autonomous agriculture.

Notwithstanding the promise of autonomous robots in the soft fruit sector, in the survey, six respondents to the open-ended final question (28 responses) mentioned that robots are a long way off. All growers in the interviews felt that some of the applications were not yet ready, whilst some were not keen on adopting robots on their farm. Both positions mean that alternative solutions are required, at least in the short-term, to address labour shortages. Growers widely talked about the need for more seasonal workers to be allowed to work in the UK as it was not considered viable to fill the gap with British labour:

"For us, it's really being able to source the workers. Now we've got a pilot scheme which is reviewed on an annual basis and it really would help us if we could have the ability to source the workers as we need them and in the numbers we need them. But that's how I see it, but for sure we don't get much help from the British people. Most are not interested." (G5)

This view reflects the evidence provided to the UK Parliament by British Summer Fruits, who called for an uplift in the amount of seasonal worker permits.

One grower spoke about bringing British labour into the industry and felt that collaboration with robotic technologies could make the industry more attractive:

"Robotics, autonomous farming and vertical farming are sexier than mud and dirt, so I think we need to be working hard to get British people and young people understanding that farming has a bright future and it is not as they think." (G8)

When mentioning alternative solutions in the survey, most respondents suggested a mixed approach of labour along with automation. Growers wanted a sustained revival of the seasonal workers scheme and licensing of growers to recruit foreign workers directly instead of agencies. Some also proposed moving production abroad. Technology alternatives mentioned in the survey and interviews included:

1 Developing plant varieties that required less husbandry control and offered easier picking
2 Gene editing (linked to point one)
3 Technological glasses to help growers pick fruit quicker
4 Improved data science and fruit prediction
5 Improved crop protection methods
6 Semi-autonomous equipment to aid workers

These results again show the value of learning lessons from existing case studies of farmer technology adoption. Financial support in the form of tax breaks or grants can help growers to adopt new technologies [46], as long as prices do not increase in line with the support on offer (displacement effect). Our results also give a clear message that we should not be seduced by so-called 'game-changing' technologies [58]. Research on the so-called fourth agricultural technology revolution has found that Artificial Intelligence, robotics, drones (etc.) are hyped in popular and policy discourse around the world [12,18,19,21,59]. Yet, these technologies may not be ready to solve immediate challenges, and thus optimising the use of existing solutions may prove more effective [60]. It seems clear that autonomous robots are not going to solve the labour shortage across the high value crop sector on a short timescale, especially for more complex operations; not just as a result of lack of technology readiness, but due to complex adoption challenges, regulation, and scaling. Policy-makers and the farming industry should, therefore, be open to pursuing other solutions, instead of focusing too heavily on autonomous robots as the game-changer. This was a key message in a recent report by Nye and Lobley [48] who presented a number of ideas for attracting old and new labour to agriculture, whilst presenting autonomous robots as just one part of the solution to labour shortages.

Our study focused on larger scale soft fruit growers, where the labour shortage is more of an acute problem. Bronson and Sengers [61] argue that new digital farming technology is often targeted towards larger farms as a more attractive market for developers. This can lock-in design and implementation models which are not accessible to all farmers/growers. Therefore, if we are to consider making autonomous solutions viable for a wide range of farming sectors, including different scales and niche sectors, further incentives will be needed to encourage roboticists to manufacture solutions for all.

In developing solutions for the soft fruit and other crop enterprises, whether autonomous or not, the grower should be placed at the heart of development. Growers in our study reported feeling disconnected from the development of robotic technologies. Literature on technology co-design or co-innovation in farming stresses the value of farmer-centric [62], user-centred [63], design thinking [64] or participatory design [65]. By involving the users throughout development, robotic solutions can be designed that meet the needs of growers, as well as being easy to use on-farm. Whilst more participation does not guarantee success, it improves the chances for smooth adoption. It is acknowledged that participatory design can take time, be expensive, and lead to a plethora of conflicting opinions from stakeholders, but in the long-term, it can build trust in the final product [66]. A good example of collaboration in the development of robotic crop solutions is the co-design of a code of practice for use of autonomous robots in Australia [67]. This brought policy-makers, industry, and farmers together to develop a set of standards for use of robotic solutions, which is key to giving farmers/growers confidence to use them safely.

Participation can be undertaken in various forms, at an early stage of development by inviting growers to workshops or running consultations to brainstorm a list of problems and solutions, to the relatively later stage of inviting growers to demonstration events where technologies are tested on trial sites, or allowing them to test them on their own farms, in order to provide feedback. There should be transparency in how grower feedback has been taken on board in the development of the final product. More innovative forms of participation [68] can also be undertaken to find out what stakeholders think about autonomous robots, including through deliberative workshops, or by exploring what growers are saying about robots on social media or online farming forums, or through in-depth surveys, interviews, or focus groups.

5. Concluding remarks

Autonomous robots are generally viewed optimistically by major, retail-orientated soft fruit growers in the UK as offering benefits to productivity and the environment, not least as a result of immediate short-term labour shortages. The main limitations of this study are that we surveyed grower views of autonomous solutions that are not widely scaled in the UK and focused only on large-scale soft fruit growers. Grower opinions are, therefore, based on perceptions of likely usefulness. Further research is required to explore how robots, growers, and workers interact in demonstrations of robots and during scaling. Worker views are particularly important since they will come into regular contact with robots during an initial phase of human-robot collaboration [38]. Though there are always structural and cultural differences between farming sectors in different places around the world, our findings on technology readiness are likely to be widely applicable. The adoption challenges identified in our study will be more or less applicable depending on a number of contextual factors: including socio-economic drivers of demand, strength of connectivity, level of farmer skills, levels of financial and gender inequality, the state of regulations, and advisory support available to farmers.

Our findings on early grower views towards robots, however, illustrate a similar set of challenges to those identified for the implementation of other precision farming technologies. User readiness, in combination with technology, market, and regulatory readiness [33], are key determinants for the implementation of autonomous crop robots in the soft fruit and other sectors. Growers require skills, cashflow, trust, and security solutions in order to adopt autonomous solutions. They also need to be sure that the technology can perform, which may be easier and more desirable for some farm operations, such as disease treatment, picking and packing, than others, such as planting. Regulations and safety standards are needed to provide confidence to the grower that autonomous robots can be utilised effectively, whilst infrastructural improvements, such as improved rural connectivity, field containment or safety features for human-robot interaction, charging and storage facilities, must accompany rollout.

It is clear that lack of technology, market, regulatory, and user readiness could threaten the viability of autonomous crop robots as both a short- and longer-term solution to the challenges currently being faced by farmers/growers. When assessing grower solutions to these barriers, the emphasis on financial support and co-operation illustrates the need for collaboration between industry, government, and growers in co-development and scaling. Growers may need financial assistance to make infrastructural changes to farms and to invest in robots. They will certainly need external support and incentives for enhanced rural connectivity and open innovation where roboticists and growers work together on developing solutions. The robotics industry will also require enhanced private and public investment to design and manufacture products that can be sold to growers at a competitive price.

Mechanisms to accelerate the adoption of autonomous robots, however, should not come at the cost of developing other solutions to problems faced in the high-value crop sector. Some growers indicated a desire to employ and upskill a human workforce, to extend seasonal worker schemes, and to explore non-autonomous solutions to enhance productivity, profitability and environmental sustainability. These solutions can be developed alongside autonomous robots within a pluralistic strategy for future farming. The development of these other solutions demands a similar approach of collaboration between all stakeholders involved in agricultural innovation systems.

Data availability

Interview and survey questions are contained within the supplementary material as are respondent characteristics and interview codes. The data from the interviews and survey are not available due to commercial sensitivity (low sample population [possibility to identify] and commercially sensitive data given). No permission was given to archive the data.

CRediT authorship contribution statement

David Christian Rose: Conceptualization, Methodology, Visualization, Data curation, Writing – original draft, Supervision, Validation, Writing – review & editing. **Mondira Bhattacharya:** Visualization, Methodology, Data curation, Software, Writing – original draft.

Declarations of Competing Interest

None.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.atech.2022.100118.

References

[1] B. Schuh, et al., Research For AGRI Committee – The EU Farming Employment: Current Challenges and Future Prospects, European Parliament, Policy Department for Structural and Cohesion Policies, Brussels, 2019. https://www.europarl.europa.eu/RegData/etudes/STUD/2019/629209/IPOL_STU(2019)629209_EN.pdf.

[2] S. Kalantaryan, J. Mazza, M. Scipioni, Meeting Labour Demand in Agriculture in Times of COVID 19 Pandemic, Publications Office of the European Union, Luxembourg, 2020, JRC120800, https://doi.org/10.2760/686549, 2020, EUR 30235 EN, ISBN 978-92-76-19174-2.

[3] FAO. 2020. Migrant workers and the COVID-19 pandemic. Rome. 10.4060/ca8559en.

[4] Barbulescu, R., Vargas-Silva, C., Robertson, B. (2021). Written Evidence submitted by Dr Roxana Barbulescu, Prof.Carlos Vargas-Silva and Dr Bethany Robertson (LS0035). EFRA Select Committee. https://committees.parliament.uk/writtenevidence/40060/pdf/.

[5] Grant, W. (2017). Who will pick fruit and harvest vegetables after Brexit? Reviving SAWS could be a solution. LSE Blog. https://blogs.lse.ac.uk/brexit/2017/11/17/who-will-pick-fruit-and-harvest-vegetables-after-brexit-reviving-saws-could-be-a-solution/.

[6] House of Commons Library. (2017). Migrant workers in agriculture. Briefing paper, Number 7987. https://commonslibrary.parliament.uk/research-briefings/cbp-7987/.

[7] P. From, L. Grimstad, M. Hanheide, S. Pearson, G. Cielniak, RASberry - robotic and autonomous systems for berry production, Mech. Eng. Mag. Select Artic. 140 (6) (2018) S14–S18.

[8] D. Bochtis, L. Benos, M. Lampridi, V. Marinoudi, S. Pearson, C.G. Sørensen, Agricultural workforce crisis in light of the COVID-19 pandemic, Sustainability 12 (2020) 8212.

[9] T. Duckett, S. Pearson, S. Blackmore, B. Grieve, Agricultural Robotics. The Future of Robotic Agriculture, EPSRC UK-RAS Network, 2018, https://doi.org/10.31256/WP2018.2.

[10] V. Marinoudi, C.G. Sørensen, S. Pearson, D. Bochtis, Robotics and labour in agriculture. A context consideration, Biosyst. Eng. 184 (2019) 111–121.

[11] M. Fairbairn, J. Guthman, Agri-food tech discovers silver linings in the pandemic, Agric. Hum. Values 37 (3) (2020) 587–588.

[12] H. Barrett, D.C. Rose, Perceptions of the fourth agricultural revolution: what's in, what's out, and what consequences are anticipated? Sociol. Rural. 62 (2) (2022) 162–189.

[13] D.C. Rose, J. Lyon, A. de Boon, M. Hanheide, S. Pearson, Responsible development of autonomous robotics in agriculture, Nat. Food 2 (2021) 306–309.

[14] A. Bechar, C. Vigneault, Agricultural robots for field operations. Part 2: operations and systems, Biosyst. Eng. 153 (2017) 110–128.

[15] R. Sparrow, M. Howard, Robots in agriculture: prospects, impacts, ethics, and policy, Precis. Agric. 22 (2020) 818–833.

[16] Devlin, S. (2016). Agricultural labour in the UK. https://foodresearch.org.uk/publications/agricultural-labour-in-the-uk/.

[17] NFU. 2019. Future of Food 2040. https://www.nfuonline.com/archive?treeid=116020.

[18] P. Baur, A. Iles, Replacing humans with machines: a historical look at technology politics in California agriculture, Agric. Hum. Values (2022), https://doi.org/10.1007/s10460-022-10341-2.

[19] E. Duncan, A. Glaros, D.Z. Ross, E. Nost, New but for whom? Discourses of innovation in precision agriculture, Agric. Hum. Values 38 (2021) 1181–1199.

[20] C.R. Eastwood, A. Renwick, Innovation uncertainty impacts the adoption of smarter farming approaches, Front. Sustain.Food Syst. (2020), https://doi.org/10.3389/fsufs.2020.00024.

[21] T. Martin, P. Gasselin, N. Hostiou, et al., Robots and transformations of work in farm: a systematic review of the literature and a research agenda, Agron. Sustain. Dev. 42 (2022) 66.

[22] J. Lowenberg-DeBoer, B. Erickson, Setting the record straight on precision agriculture adoption, Agron. J. 111 (4) (2019) 1552–1569.

[23] T. Groher, K. Heitkämper, C. Umstätter, Nutzung digitaler technologien in der Schweizer Landwirtschaft, Agrarforschung Schweiz 11 (2020) 59–67.

[24] M. Ryan, S. van der Burg, M.J Bogaardt, Identifying key ethical debates for autonomous robots in agri-food: a research agenda, AI Ethics (2021), https://doi.org/10.1007/s43681-021-00104-w.

[25] T. Daum, Farm robots: ecological utopia or dystopia? Trends Ecol. Evol. 36 (9) (2021) 774–777 *(Amst.)*.

[26] K. Rijswijk, L. Klerkx, M. Bacco, F. Bartolini, E. Bulten, et al., Digital transformation of agriculture and rural areas: a socio-cyber-physical system framework to support responsibilisation, J. Rural Stud. 85 (2021) 79–90.

[27] S. Rotz, E. Gravely, I. Mosby, E. Duncan, E. Finnis, M. Horgan, et al., Automated pastures and the digital divide: how agricultural technologies are shaping labour and rural communities, J. Rural Stud. 68 (2019) 112–122.

[28] J.P. Vasconez, G.A. Kantor, F.A.A. Cheein, Human-robot interaction in agriculture: a survey and current challenges, Biosyst. Eng. 179 (2019) 35–48.

[29] S. Basu, A. Omotubora, M. Beeson, C. Fox, Legal framework for small autonomous agricultural robots, AI Soc. 35 (2020) 113–134.

[30] J. Lowenberg-DeBoer, K. Behrendt, M.H. Ehlers, C. Dillon, A. Gabriel, et al., Lessons to be learned in adoption of autonomous equipment for field crops, Appl. Econ. Perspect. Policy (2021), https://doi.org/10.1002/aepp.13177.

[31] K. Bronson, Looking through a responsible innovation lens at uneven engagements with digital farming, NJAS Wagening. J. Life Sci. 90–91 (2019), 100294.

[32] M. Carolan, Automated agrifood futures: robotics, labor and the distributive politics of digital agriculture, J. Peasant Stud. 47 (2020) 184–207.

[33] J. Vik, A.M. Melås, E.P. Straete, R.A. Søraa, Balanced readiness level assessment (BRLa): a tool for exploring new and emerging technologies, Technol. Forecast. Soc. Change 169 (2021), 120854.
[34] A. Matese, S.F. Di Gennaro, Technology in precision viticulture: a state of the art review, Int. J. Wine Res. 7 (2015) 69–81.
[35] Q. Zhang, M. Karkee, A. Tabb, The use of agricultural robots in orchard management, in: J. Billingsley (Ed.), Robotics and Automation For Improving Agriculture, Burleigh Dodds Science Publishing, 2019, pp. 187–214.
[36] G. Adamides, C. Katsanos, I. Constantinou, G. Christou, M. Xenos, T. Hadzilacos, Y. Edan, Design and development of a seni-autonomous agricultural vineyard sprayer: human-robot interaction aspects, J. Field Rob. 34 (8) (2017) 1407–1426.
[37] K. Legun, K.A. Burch, Robot-ready: how apple producers are assembling in anticipation of new AI robotics, J. Rural Stud. 82 (2021) 380–390.
[38] K.A. Burch, K. Legun, Overcoming barriers to including agricultural workers in the co-design of new AgTech: lessons from a COVID-19-present world, Cult. Agric. Food Environ. 43 (2) (2021) 147–160.
[39] P. Baxter, G. Cielniak, M. Hanheide, P. From, Safe human-robot interaction in agriculture, in: Proceedings of the HRI*;18: Companion of the 2018 ACM/IEEE International Conference on Human-Robot Interaction*, 2018, pp. 59–60. *March 2018*.
[40] O. Spykman, A. Gabriel, M. Ptacek, M. Gandorfer, Farmers' perspectives on field crop robots – evidence from Bavaria, Germany, Comput. Electron. Agric. 186 (2021), 106176, https://doi.org/10.1016/j.compag.2021.106176.
[41] F.R. von Veltheim, H. Heise, German farmers' attitudes on adopting autonomous field robots: an empirical survey, Agriculture 11 (2021) 216.
[42] F.R. von Veltheim, L. Theuvsen, H. Heise, German farmers' intention to use autonomous field robots: a PLS-analysis, Precis. Agric. 23 (2022) 670–697.
[43] K. Devitt, Cognitive factors that affect the adoption of autonomous agriculture, Farm Policy J. 15 (2) (2018) 49–60.
[44] C. Kester, H.W. Griepentrog, R. Hörner, Z. Tuncer, A survey of future farm automation – a descriptive analysis of survey responses, in: J.V. Stafford (Ed.), Precision Agriculture '13, Wageningen Academic Publishers, Wageningen, 2013, https://doi.org/10.3920/978-90-8686-778-3_97.
[45] Redhead, F., Snow, S., Vyas, D., Bawden, O., Russell, R., Perez, T., Brereton, M. (2015). Bringing the farmer perspective to agricultural robots. *CHI'15 Extended Abstracts, Apr 18-23.* 10.1145/2702613.2732894.
[46] D.C. Rose, W.J. Sutherland, C. Parker, M. Lobley, M. Winter, et al., Decision support tools for agriculture: towards effective design and delivery, Agric. Syst. 149 (2016) 165–174.
[47] A. Bryman, Social Research Methods, Oxford University Press, Oxford, 2016, p. 5th Ed..
[48] C. Nye, M. Lobley, Farm Labour in the UK - Accessing the Workforce the Industry Needs, Centre for Rural policy Research. University of Exeter, 2021. ISBN 978-0902746-51-0.
[49] J.A. Turner, L. Klerkx, K. Rijswijk, T. Williams, T. Barnard, Systemic problems affecting co-innovation in the New Zealand agricultural innovation system: identification of blocking mechanisms and underlying institutional logics, NJAS Wagening. J. Life Sci. 76 (2016) 99–112.
[50] M.H. Ehlers, R. Finger, N. El Benni, A. Gocht, C.A.G. Sørensen, et al., Scenarios for European agricultural policymaking in the era of digitalisation, Agric. Syst. 196 (2021), 103318.
[51] A. Fleming, E. Jakku, S. Fielke, B.M. Taylor, J. Lacey, et al., Foresighting Australian digital agricultural futures: applying responsible innovation thinking to anticipate research and development impact under different scenarios, Agric. Syst. 190 (2021), 103120.
[52] G. Cofré- Bravo, L. Klerkx, A. Engler, Combinations of bonding, bridging, and linking social capital for farm innovation: how farmers configure different support networks, J. Rural Stud. 69 (2019) 53–64.
[53] A.P. Barnes, I. Soto, V. Eory, B. Beck, A. Balafoutis, et al., Exploring the adoption of precision agricultural technologies: a cross regional study of EU farmers, Land Use Policy 80 (2019) 163–174.
[54] S. Fielke, B. Taylor, E. Jakku, Digitalisation of agricultural knowledge and advice networks: a state-of-the-art review, Agric. Syst. 180 (2020), 102763.
[55] L. Klerkx, E. Jakku, P. Labarthe, A review of social science on digital agriculture, smart farming and T agriculture 4.0: new contributions and a future research agenda, NJAS Wagening. J. Life Sci. 90–91 (2019), 100315.
[56] M. van der Veen, Agricultural innovation: invention and adoption or change and adaptation? World Archaeol. 42 (1) (2010) 1–12.
[57] J.A. Paschen, M. Ayre, B. King, N. Reichelt, R. Nettle, Shaking it up: the realities of 'doing' co-innovation in a privatised agricultural advisory and extension system, J. Rural Stud. 87 (2021) 338–351.
[58] L. Klerkx, D. Rose, Dealing with the game-changing technologies of agriculture 4.0: how do we manage diversity and responsibility in food system transition pathways? Glob. Food Sec. 24 (2020), 100347.
[59] A. Lajoie-O'Malley, K. Bronson, S. van der Burg, L. Klerkx, The future(s) of digital agriculture and sustainable food systems: an analysis of high-level policy documents, Ecosyst. Serv. 45 (2020), 101183.
[60] L. Vinsel, D. Russell, The Innovation Delusion: How Our Obsession with the New Has Disrupted the Work That Matters Most, Currency, New York, 2020.
[61] K. Bronson, P. Sengers, Big tech meets big Ag: diversifying epistemologies of data and power, Sci. Cult. 31 (1) (2022) 15–28 *(Lond)*.
[62] C.R. Eastwood, F.J. Turner, A.J. Romera, Farmer-centred design: an affordances-based framework for identifying processes that facilitate farmers as co-designers in addressing complex agricultural challenges, Agric. Syst. 195 (2022), 103314.
[63] D.C. Rose, C. Parker, J. Fodey, C. Park, W.J. Sutherland, L.V. Dicks, Involving stakeholders in agricultural decision support systems: improving user-centred design, Int. J. Agric. Manag. 6 (3–4) (2018) 80–89.
[64] U. Kenny, Á. Regan, D. Hearne, C. O'Meara, Empathising, defining and ideating with the farming community to develop a geotagged photo app for smart devices: a design thinking approach, Agric. Syst. 194 (2021), 103248.
[65] E. Jakku, P.J. Thorburn, A conceptual framework for guiding the participatory development of agricultural decision support systems, Agric. Syst. 103 (9) (2010) 675–682.
[66] L. Klerkx, R. Nettle, Achievements and challenges of innovation co-production support initiatives in the Australian and Dutch dairy sectors: a comparative study, Food Policy 40 (2013) 74–89.
[67] GOFAR. (2020). Australian market of agricultural robotics: the autonomy code of practice, issues and needs of Australian Farmers - PART 1. https://www.agricultural-robotics.com/news/australian-market-of-agricultural-robotics-the-autonomy-code-of-practice-issues-and-needs-of-australian-farmers-part-1.
[68] D.C. Rose, J. Chilvers, Agriculture 4.0: broadening responsible innovation in an era of smart farming, Front. Sustain. Food Syst. 2 (2018) 1–7.