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Independent report

Automation in horticulture review

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Foreword from Professor Simon Pearson

I have been working in UK Horticulture for the last 30 years. It is one of the most vibrant, competitive and innovative sectors of our agri-food economy. More recently, I have enjoyed working with and helping to develop cutting-edge agri-robotic systems and technologies that have the potential to automate and transform labour productivity on farms.

The sector's ultimate output, fresh fruit and vegetables, as well as ornamental plants, are essential to the health and wellbeing of all in society. However, despite the capital intensity of many horticultural production systems, critical elements of the industry have a high dependency on seasonal migrant labour to harvest crops. This dependency has become all the more apparent following the end of free movement between the UK and the EU and the onset of the Coronavirus (COVID-19) pandemic.

It was an immense honour to co-chair this review into automation for the horticultural sector, in a personal capacity, with the Secretary of State for Defra. The key questions of this review were how, to what extent, and when can these new robotic technologies, and currently available automation, ease the horticulture sectors ; dependency on seasonal labour. In simple terms, 'what do we need to do to turbo-charge automation in the horticulture sector.

The review ran at a significant pace. In just 6 months, we conducted a preliminary cross-sector survey and hosted 6 roundtables with input from more than 75 stakeholders across horticulture, agri-robotics, automation, academia and the public sector. While the review demonstrated the diversity of the sector, the common willingness to engage and embrace change was striking and heartening. I am grateful to everyone who gave up their time to help us put together a clear picture of the barriers and opportunities.

We found a horticulture sector that was actively seeking to adopt technologies when proven, but also an active and emerging cluster of UK agri-robotic expertise funded by both private and public sector investment.

From the outset of the process, we have been clear that robotics and automation technologies are not likely to be the single solution that resolves all labour pressures in the sector. However, the review has sought to articulate a series of recommendations for the government to consider that could have the power to transform labour productivity over the medium to longer term. These recommendations have focussed on how to create an enabling environment to accelerate robotics development and on-farm adoption.

The review proposes interventions that reflect the sheer diversity of horticulture, and it highlights how that same diversity poses a challenge to wide-scale agri-robotic adoption. We recognise that robotic systems are expensive to develop and tend to be designed to replicate a limited range of human tasks. On this basis, it is likely that robotic development will focus on the larger crops or where the cost of automation is relatively low, and many tasks and crop groups may never be automated.

I hope the review will become a pillar that supports a host of novel initiatives to underpin the resilience of UK horticulture, while fostering a new high-tech UK industry in advanced robotics for the agri-food sector.

It is encouraging to see the development of automation and agri-technology and sustainable food production being recognised nationally as key drivers within the industry going forward. The recent UK government Food Strategy (https://www.gov.uk/government/publications/government-food-strategy) recognises their key role in dealing with the cost-of-living crisis, providing affordable food production whilst ensuring that farmers and food producers can make a living. I look forward to seeing how these factors will be implemented, and how we can all play a vital role in ensuring affordable, sustainable food in the future.

Thank you again to everyone who contributed. I was struck by the enthusiasm and optimism of everyone I spoke to, and I hope that this report will kick-start further discussions that generate a step change in automation in horticulture.

Professor Simon Pearson

Co-Chair of the Review of Automation in Horticulture

Director, Lincoln Institute for Agri-Food Technology and Professor of Agri-Food Technology, University of Lincoln

Executive summary

Horticulture has long been dependent on seasonal migrant labour from the European Union (EU) for growing and harvesting both edible and ornamental produce. Following the end of free movement between the UK and the EU and the introduction of the UK's points-based immigration system, the sector's dependency on low skilled migrant workers from the EU needed reassessing and readjusting.

In response, the UK government announced various policy interventions and reviews to help support and prepare the sector. On 22 December 2020 the UK government announced an extension of the Seasonal Workers Pilot for 2021, expanding the number of visas from 10,000 to 30,000, and a Review of Automation in Horticulture to be conducted by Defra.

While the review was to work alongside the newly extended and expanded Seasonal Workers Pilot, as well as efforts to attract more UK residents into agricultural work, its remit and purpose were clear. The review was to bring together experts across horticulture, technology and supporting industries to understand what would be required to accelerate the development and uptake of automation technologies, in both the edible and ornamental horticulture sectors, in support of the wider aim of reducing the sector's reliance on low skilled migrant workers.

To gather support and participation by industry, it was agreed the review would be co-chaired by the Right Honourable George Eustice MP, Secretary of State for Environment, Food and Rural Affairs, and Professor Simon Pearson, Director of the Lincoln Institute for Agri-Food Technology and Professor of Agri-Food Technology at the University of Lincoln.

The review immediately undertook a preliminary cross-sector survey to help inform the agendas of a series of advisory roundtables attended by sector experts. These roundtables covered a strategic overview and deep dives into horticultural subsectors, technology development and a wide range of supporting mechanisms. These roundtables informed the state of automation in horticulture and the corresponding development pipeline with regards to its potential to displace seasonal labour.

The review was to culminate with the publication of this report, with recommendations setting out future actions the UK government and the horticulture sector may wish to pursue. The intention was not for the recommendations to be binding on government, but for government to consider and determine which to take forward.

The findings and recommendations from the report will also contribute to decisions regarding any future seasonal agricultural workers schemes.

Key findings

The review identified 6 key clusters of technologies that could help accelerate the adoption and development of automation in horticulture.

The first 3 technology clusters are widely available for mass adoption (considered the first wave). They use established automation technologies for operations that are either simple in operational environment or task. Overall, they offer minor labour savings but can increase worker productivity by reducing the ergonomic burden of tasks.

Optimised production systems

Optimised production systems (such as improved infrastructure, canopy architectures, ergonomics, crop varieties, equipment, and management systems that maximise efficiency whilst also reducing waste) offer a broad range of opportunities where enhanced growing systems can be designed or implemented to drive harvest productivity. They can be implemented quickly and offer medium labour savings at a sector level.

Packhouse automation

Packhouse automation performs low variation tasks in a controlled environment and, subject to capital and skills constraints, could be implemented in some production sites within 3 to 5 years. But there is a lower ratio of packhouse to field workers and this constrains labour savings at a sector level.

Field rigs and mechanical systems

Field rigs and mechanical systems are used in field operations to automate harvesting and husbandry tasks partly or fully. They can be implemented relatively quickly, likely within a few years, and shared learning across horticulture would offer low labour savings at a sector level.

The remaining 3 technology clusters are currently in development pipelines (forming the second and third waves). Many of the systems identified in the review are in prototype stages, or at what the industry terms technology readiness levels 5 or 6, with some devices undertaking farm trials. This stage of development between academia and commercialisation is also known as the ‘valley of death’ due to the large capital required for development activities.

Further details on the valley of death and Technology Readiness Levels (TRL) can be found at Annex A: Technology Readiness Levels in horticulture.

Autonomous selective harvesting

Autonomous selective harvesting utilises mobile robotic systems that autonomously navigate growing environments, identifying and harvesting crops. Autonomous selective harvesting offers high labour savings at a sector level but if left to market forces will unlikely be commercially available until well after 2030.

Augmented work

Augmented work can be achieved through a range of technologies. These systems, including those enabled by Artificial Intelligence (AI) or collaborative robotics, improve a worker’s productivity through technology, often depending on a worker’s cognitive abilities and dexterity for the more complex aspects of a task. Augmented work, such as assisted harvesting or produce packing, could be implemented in the medium term, probably before 2030, and offers medium labour savings at a sector level.

Autonomous crop protection, monitoring and forecasting

Autonomous crop protection, monitoring and forecasting delivers incremental environmental and resource productivity to farms. This suite of autonomous systems (such as robotic sprayers, light treatments or fruit counting) helps underpin the transition towards full crop harvesting robotics and are considered critical technical steppingstones. Innovation that automates crop protection, monitoring and forecasting could be implemented in the medium term, probably before 2030, and offers low labour savings at a sector level.

Barriers to adoption and development of automation

The review found many factors impeding the adoption and development of automation technologies.

In terms of adoption, access to knowledge and know-how was challenging for growers. This was due to:

- the fragmented and diverse nature of horticulture
- a lack of independent robotics and automation information
- a lack of independent business support

- inconsistent messaging
- challenges identifying the limited number of technology integrators who will build systems for horticultural applications

Due to uncertainty in the duration, security and scale of production contracts, growers can lack the confidence to invest. Growers were also concerned whether the policy environment, specifically the future of the Seasonal Workers Pilot, would have sufficient scale and duration for them to confidently bridge the transition towards greater automation.

Equally, raising capital for investment can be problematic, especially for highly innovative equipment such as robotics, since to validate funding risk financiers require evidence of machinery track record, depreciation rate and performance. Grants to purchase equipment have offered some support, but they were not designed with the sole purpose of funding horticultural automation. This has resulted in unsuitable criteria for grants, for instance, a requirement that they increase job numbers.

Where sectors have successfully automated, they have done so by removing variation and standardising components. However, variation is inherent in horticulture, along with fast changing packaging and customer requirements that increase production system uncertainty, automation cost, and complexity.

In the development pipeline space, the barriers are no less confounding, and collaboration and knowledge sharing efforts must be improved. Developers can struggle to understand the needs of the end user, and there is significant fragmentation across the development pipeline with limited collaboration on common problems between technology developers and the horticultural supply chain. The lack of clarity around the boundaries for pre-competitive research has also hindered development of some systems and reinforced fragmentation among technology developers.

The UK government's innovation funding has successfully supported the work of many robotic and automation companies operating within the horticultural sector. But the review suggested that further business support might ease and widen access to this funding route. Stakeholders can have difficulty navigating the complex funding landscape and applying for suitable programs. Furthermore, on-farm trials are critical but can carry significant financial risk to the growers. UK government support for growers to mitigate these risks could widen participation and increase the rate of adoption.

Barriers such as horticulture practices, skills, standards and regulation must also be overcome if technology in development is to make a future impact. For example, infrastructure and horticultural practices have been optimised for human workers, and it is unlikely the current crop varieties, growing architectures and infrastructure are optimal for automation and robotics. This will probably need to change. Additionally, as mobile robotics are data intensive and telecommunication dependent, limited rural connectivity could stifle the technology adoption.

The skills required to install, operate, and maintain the next generation of automation will be Science, Technology, Engineering and Maths (STEM) based, and there is a risk that horticulture may not be attractive enough to ensure skills are local, abundant and available on demand. Skills development programs for the automation of the sector will need to be considered, especially how workforces can be trained to operate and maintain robotic systems.

While standards, best practice and regulation can be a harmonising tool that encourages innovation, without clear standards innovators might relocate or cease their development efforts and growers will not be able to insure systems. Health and safety are key concerns for all stakeholders, and data ownership and cyber security need to be addressed.

Added benefits

Several participants at the roundtables argued that there were better reasons to automate than simply reducing seasonal migrant labour. While this review, including its findings and recommendations, focuses on how automation can reduce the sector’s seasonal labour dependency, the roundtables revealed the many motivations driving stakeholders to adopt and develop automation technologies for horticulture.

Thus the review’s recommendations, summarised in the next section and outlined further in section 4, could enable increased productivity, increase food system related innovation and lead to more sustainable horticultural practices and, for these reasons, could equally support Net Zero, help level up rural economies and contribute to many of the UN Sustainable Development Goals. (https://sdgs.un.org/goals)

Recommendations

There are various barriers that prohibit the sector from adopting currently available automation technologies, as well as those stifling the development of robotic systems from early prototype to commercial and scaled adoption.

The following recommendations would help overcome these barriers. They are built around 3 key themes of 'mind the gap', 'collaboration' and 'technology alone is not a solution' and suggest actions that will help create an enabling environment to increase the adoption of automation technologies by the horticulture sector and accelerate the technology development pipeline. They are not intended to be binding on government, but for government to consider.

Mind the gap

The need for a secure source of labour in the period before mass-adoption of automation technology is feasible.

Recommendation 1: Defra should consider pursuing a long-term Seasonal Workers Scheme for edible and ornamental horticulture starting in 2022

A long-term Seasonal Workers Scheme would help to stabilise workforce pressures in the sector, helping growers to better evaluate their labour needs over time and incentivising long-term capital investments in automation technology.

While a new Seasonal Workers Visa Route has been announced for 2022 to 2024, the length of any future schemes should ideally match the period preceding the feasible mass-adoption of automation technology.

Collaboration

The need for cooperative leadership and engagement between the UK government, industry, and academia to increase the mass adoption of automation and accelerate technology in the development pipeline.

Recommendation 2: Defra should consider convening a consortium that brings together UK government departments, horticulture industry and technology companies to drive significant adoption of available and proven technologies by growers

A cross-industry consortium would help to remediate the significant fragmentation between technology providers and end users, as well as:

- fast-track the adoption of available technologies across horticulture, and the transfer of proven technologies across sub-sectors
- increase collaboration across the supply chain
- increase knowledge transfer and the sharing of risk at all stages of adoption

Recommendation 3: Defra should consider launching a robotic crop harvester mission to fast-track innovative research and development of systems currently in the 'valley of death'

A highly focussed mission-led approach, underpinned by the UK government's leadership and funding, and supported by technology companies and the horticulture sector, would help accelerate the development of automation technology.

A mission-led approach of this kind has the potential to disrupt horticultural practices whilst securing global leadership in horticultural production and automation technologies.

Technology alone is not a solution

There is a need to provide the necessary infrastructure, funding, guidance and regulations to support this sectoral revolution.

Recommendation 4: Defra should consider leading a review of financial and fiscal support for automation in horticulture

Current processes, criteria and mechanisms for financial support in this area, in particular grant conditions, are discouraging some growers from engaging with sectoral innovation.

Defra should consider assessing whether current arrangements are suitable for increased adoption and accelerated development of such technologies and make changes where necessary.

Recommendation 5: the sector should identify, develop, and share automation infrastructure best practice among growers to help them transition from labour-intensive to technology-intensive operations

The horticultural sector should look to establish a working group to identify and disseminate novel harvest practices and infrastructure development plans that are more conducive to automation environments. The business need for rural data connectivity should also be considered.

Recommendation 6: the sector should develop its future skills pipelines and consider ways to attract and retain skilled staff

The horticultural sector should lead a review into future skills requirements to inform and build skills pipelines which ensures existing and new workers have the required skill set for the future of their work.

This should consider how to make the sector more attractive to work in, through career development and leveraging regional strategies. The Institute for Agriculture and Horticulture (TIAH) is a welcome industry initiative that could have an important role to play here.

Recommendation 7: the sector should seek greater representation for horticulture and technology supply chain delegates at regulatory-legislative working groups on next generation robotics

The sector should seek greater representation for horticulture and the automation supply chain delegates on regulatory working groups so that it can influence the next generation of legislation related to health and safety, data ownership and the security of automation technologies, ensuring they are workable on farms.

Section 1: Introduction

What do we mean by horticulture?

Horticulture is a subsection of agriculture that includes both edible and ornamental crops. A non-exhaustive breakdown of key groups within horticulture:

- bines and vines
- edible
  - fruit
    - top and orchard fruit
    - soft fruit
  - vegetables and salads
    - protected vegetables
    - field vegetables
- ornamental
  - pot plants
  - flowers and bulbs
  - hardy ornamental nursery stock
  - tree and forest nurseries

According to the Agriculture and Horticulture Development Board (AHDB) Grown in Britain report (https://projectblue.blob.core.windows.net/media/Default/Imported%20Publication%20Docs/AHDB%20Horticulture%20/Grown%20in%20Britain%20Low%20res.pdf), there are over 300 types of edible crops and many more types of ornamental plants grown in Great Britain (England, Wales and Scotland), with most of this production supplying the domestic UK market. In 2020, the UK horticulture sector was worth over £4.1 billion (this valuation is taken from the latest horticulture statistics (https://www.gov.uk/government/statistics/latest-horticulture-statistics) on GOV.UK).

Significantly, each horticultural crop grown has its own unique husbandry, harvesting and handling needs. Labour requirements vary between farms. Each farm grows a unique portfolio of crops, in a range of environments, with infrastructure that has been put in place over many years.

Horticultural crops also have distinct growing seasons and seasonal workers are employed at key times, often performing a range of tasks including harvesting crops in semi-controlled or outdoor environments, transporting crops across challenging terrain and working in pack houses to process and pack harvested crops. While these tasks are considered low-skilled they require considerable human stamina, cognition and dexterity.

The labour challenges in horticulture

Horticulture remains a sector where a labour-intensive business model dominates. This can be partly attributed to the history of labour in the sector, where for many years, low-skilled seasonal workers from the EU have been integral to the harvesting of horticultural crops.

While the number of workers needed varies throughout the year - with crops needing to be harvested from January all the way to December - Defra estimates that approximately 50,000 to 60,000 seasonal workers have been needed annually to bring in the harvest.

With the end of free movement between the UK and the EU and the introduction of the UK's points-based immigration system, the sector's dependency on low skilled migrant workers from the EU needed reassessing and readjusting. In response, the UK government announced various policy interventions and reviews to help support and prepare the sector, including the extension and expansion of the Seasonal Workers Pilot and the Defra led review of automation in horticulture in December 2020, and the new 3-year Seasonal Workers Visa Route in December 2021.

This review aimed to better understand how to accelerate development and increase adoption of automation technologies.

What we mean by automation?

Automation in its simplest form is where an operational system performs tasks with little or no human input, often performing dull, dirty or dangerous tasks previously carried out by humans. Automation in this way can be achieved through purely mechanical components performing low variation tasks at speed, or via computation and robotics enabling automation of more varied and complex tasks.

In terms of impacting labour demand, automation in this way presents both challenges and opportunities for the horticulture sector. Horticulture in the UK is inherently variable in both operating environments and crops, and this variation has made 'automation by mechanical components' to replace labour very challenging. Recent technological advances in computation and robotics, on the other hand, may present greater opportunities to impact future labour demand but only when it is developed and commercially available.

Section 2: Opportunities to increase adoption and accelerate development of automation

Automation comprises a wide range of technologies. While some systems have been successfully proven in the sector and are available to purchase, other more advanced systems are still in development and are not yet market ready.

The review identified 6 key technology clusters that fall into these categories. Three are widely available for mass adoption (the first wave) and the remaining three are in the development pipeline (second and third waves). These have been plotted on a time-impact axis in figure 1.

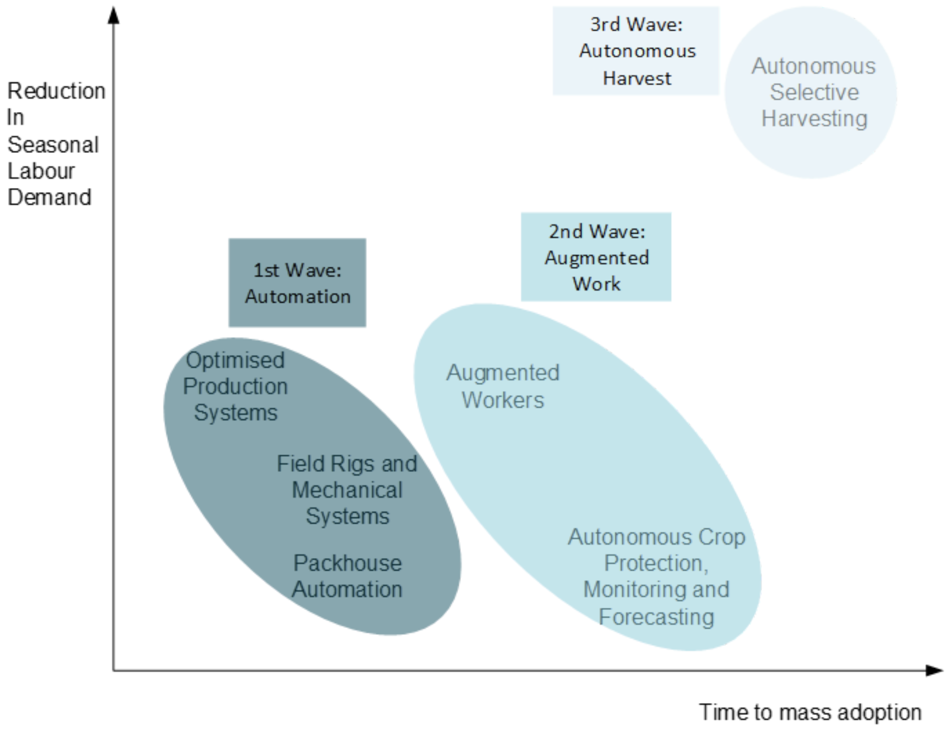

Figure1: an impact-time analysis of technology clusters, with the X-axis representing time to mass adoption, and the Y-axis representing reduction in seasonal labour demand.

Figure 1 shows:

The first wave titled ‘Automation’ containing:

- Optimised Production Systems (with a very short time to mass adoption and medium impact on seasonal labour demand)

- Packhouse Automation (with a short time to mass adoption and very low impact on seasonal labour demand)
- Field Rigs and Mechanical Systems (with a short time to mass adoption and low impact on seasonal labour demand)

The second wave titled ‘Augmented Work’ containing:

- Augmented Workers (with a medium time to mass adoption and medium impact on seasonal labour demand)
- Autonomous Crop Protection, Monitoring and Forecasting (with a long time to mass adoption and very low impact on seasonal labour demand)

The third wave titled ‘Autonomous Harvest’ containing:

- Autonomous Selective Harvesting (with a very long time to mass adoption and a very large impact on seasonal labour demand)

What is available now?

The first wave of automation technologies has been proven in the sector and widely available for adoption. These include:

Optimised production systems

Optimised production systems use growing systems and crop architecture design to drive harvest labour productivity, with the review showing that considerable incremental innovation and capital investment across the sector is required to achieve this. This might include investment in:

- new fixed infrastructure (such as packhouses and glasshouses)
- equipment (such as field operations, latest packing and grading technology)
- digital and communication technology (such as upgraded broadband)
- crop production systems (such as crop varieties, latest canopy architectures)
- decision support, continuous improvement frameworks and business management systems (such as upgraded Enterprise Resource Planning, Lean, Six Sigma, labour management and planning software)

The review anticipates that these investments will need to be ongoing but given the specifics of the labour challenge and lack of availability of automation solutions for many crop tasks, there is no evidence that this measure alone will create any labour productivity step change.

Optimised production systems - time and cost

Implementing production optimisation principles is a well-known process, which can be done in-house or by a consultancy. Once implemented, improvements in production systems are near instantaneous. While individual changes can be low cost, optimising a whole growing system could require significant investment.

Optimised production systems - labour saving benefits

Increased worker productivity in all areas of production.

Packhouse automation

This form of automation relates to technology that automates pack house activities (such as transporting crops indoors, packaging and grading). Pack houses are controlled environments, with automation available for specific tasks and crops.

Packhouse automation - time and cost

Off the shelf systems can be purchased and installed within a matter of months. Bespoke systems typically have longer lead times and higher cost, depending on the task and machine complexity. Where other growers have previously commissioned bespoke systems, some technology providers will sell similar systems off the shelf. Packhouse operations can be year-round, which reduces the payback period of investments.

Packhouse automation - labour saving benefits

Depending on the specific business and production system, some limited but nevertheless significant labour savings in packhouse operations could result. This reflects evidence that for many crops, but not all, the majority of the low skilled staff are found in field operations with fewer in packhouse roles. In addition, many businesses, but not all, have invested in some form of packhouse automation. Labour savings will be limited to those farms which have not already implemented packhouse automation.

Field rigs and mechanical systems

Field rigs and mechanical systems are used to automate harvesting and husbandry tasks fully or partly. As with pack house technologies, these systems are often unique to a single crop, with adoption level varying across crops.

Field rigs and mechanical systems - time and cost

Both off the shelf and bespoke systems are available. System complexity means initial cost of rigs can vary significantly. New systems can be developed with early adopters often paying more for an unproven system. The seasonality of tasks leads to longer payback times.

Field rigs and mechanical systems - labour saving benefits

There will be some reduction in worker demand, with increased productivity for remaining workers resulting, as systems reduce the ergonomic burden of tasks. More advanced systems can be more autonomous, often displacing a larger proportion of workers. There might be an opportunity to share learnings on rig development and operation across different crop sectors within horticulture (for example, field vegetables to cut flower field harvesting). Innovation and improvement are being made in this area, with the potential for more automated rigs working across a wider range of crops.

What is in the development pipeline?

Second and third wave technologies are all in the development pipeline for horticultural applications. Edible horticultural systems are currently at prototype levels, with ornamental applications at early concept phase. The technology in these clusters include:

Autonomous selective harvesting

Autonomous selective harvesting involves mobile robots autonomously navigating the growing environment, inspecting, harvesting and transporting crops. These cutting-edge harvesters are complex systems that will need a range of innovative technologies including advanced robotics, complex sensing and vision systems, autonomous mobile platforms, Artificial Intelligence (AI) enabled robotic control and novel robotic graspers.

Autonomous selective harvesting - development progress and time

Some systems, for a small range of edible crops, are currently at prototype stages Technology Readiness Level (TRL) 5 and 6, specifically parts of the system (sub systems) have been tested in labs and whole system prototypes are in testing stages. The most advanced systems are in the field or farm testing stage. Ornamental systems are at concept stage, with very few technology developers focusing on these crops.

No consensus was reached on time to market, but selective harvesting at scale is likely to take the longest development time and, if left to market forces, will not be available for widescale adoption until well after 2030.

Autonomous selective harvesting - labour saving benefits

If systems become available and adopted at scale, seasonal labour demand would dramatically fall, as most labour is used on selective harvesting of crops that cannot be harvested mechanically. Current development is focused on crops with higher profit

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margins and large markets (such as soft fruit, labour intensive salads and vegetables), with the possibility of technology being transferred across the horticultural subsectors after commercialisation.

Augmented work

Augmented technologies are those that enhance the performance of a worker. This can be achieved with collaborative robotics, AI for decision support, autonomous guided vehicles, exoskeletons, or more bespoke wearable technologies (such as a vacuum glove for berry picking).

Augmented work - development progress and time

Augmented worker technology is likely to be found at all stages of the development pipeline. The challenge is adapting technologies to specific applications and operating environments. These systems will be less complicated than a fully automated solution and, in theory, could be developed and widely adopted in a shorter timeframe than their fully autonomous counterpart.

Augmented work - labour saving benefits

Increased productivity of augmented workers would reduce the overall demand for seasonal labour.

Autonomous crop protection, monitoring and forecasting

These technologies involve autonomous vehicles and the use of advanced sensors or actuators in systems that treat and monitor crops, with some capable of forecasting plant yields. This includes more complex systems using sensors on mobile platforms that are deployed to perform targeted husbandry tasks and crop care. The development of these autonomous mobile platforms accelerates the transition towards robotic harvesting. All robotic harvesters need to be mounted on a suitable and most likely, autonomous vehicle.

Autonomous crop protection, monitoring and forecasting - development progress and time

Some systems (such as robots that treat crops with Ultraviolet-C radiation) are currently in on farm testing (TRL 7 to 8), with trial participants willing to be early adopters. These systems are complex, yet simpler than robotic harvesters. These systems are likely to form the bases of many robotic harvesters and are therefore likely to reach market before harvesting systems.

Autonomous crop protection, monitoring and forecasting - labour saving benefits

Innovative autonomous platforms and accurate forecasting could optimise work schedules to maximise productivity. As such the direct impacts on labour demand will be minor, but they are a critical enabling technology that will ultimately underpin full robotic harvesting systems. In addition, these systems could enhance labour productivity, reduce the number of dangerous tasks performed by workers and offer environmental benefits.

Journey to autonomous horticulture

Figure 2a shows the 3 waves of automation technologies that will transform horticulture in the short, medium and long term. As these technologies are adopted, both the number of seasonal workers required and the nature of the tasks they perform will change. A summary of this transition from large quantities of low skilled migrant seasonal workers to fewer higher skilled and more attractive roles can be seen in figure 2b.

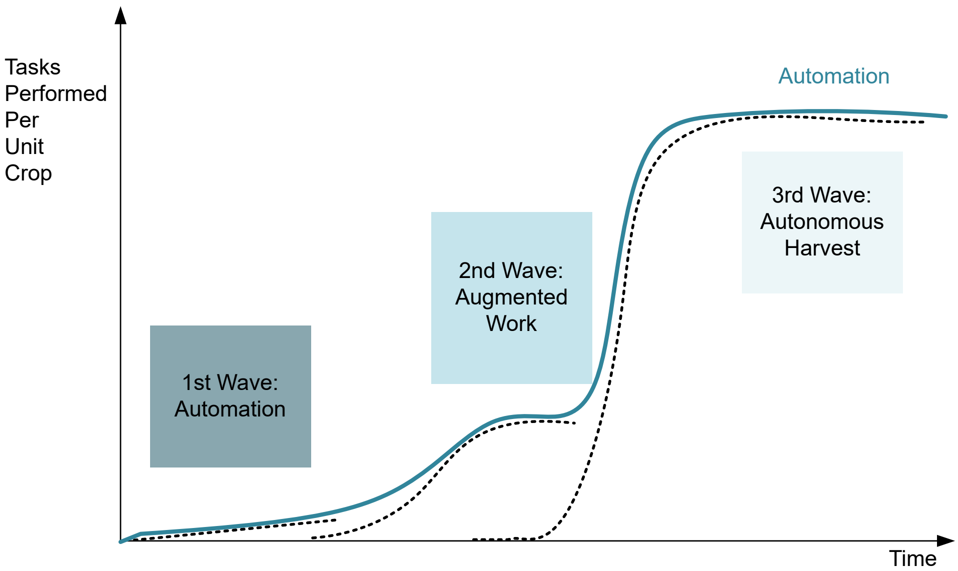

Figure 2a: An impact to time graph of the three waves of automation technology with the X-axis being Time and the Y-axis Tasks Performed Per Unit Crop.

Figure 2a shows 3 S-curves combining over time to create a total automation line:

- the first wave (Automation) is a very minor increase over the short term
- the second wave (Augmented Work) starts as the first wave ends and has a moderate magnitude in the Y-axis
- the third wave (Autonomous Harvest) starts as the second wave ends and has a significantly large magnitude

The overall automation line ramps up and plateaus in the medium term, followed by a much larger S-curve that eventually plateaus at a much higher level, as more tasks in horticulture are performed by automation.

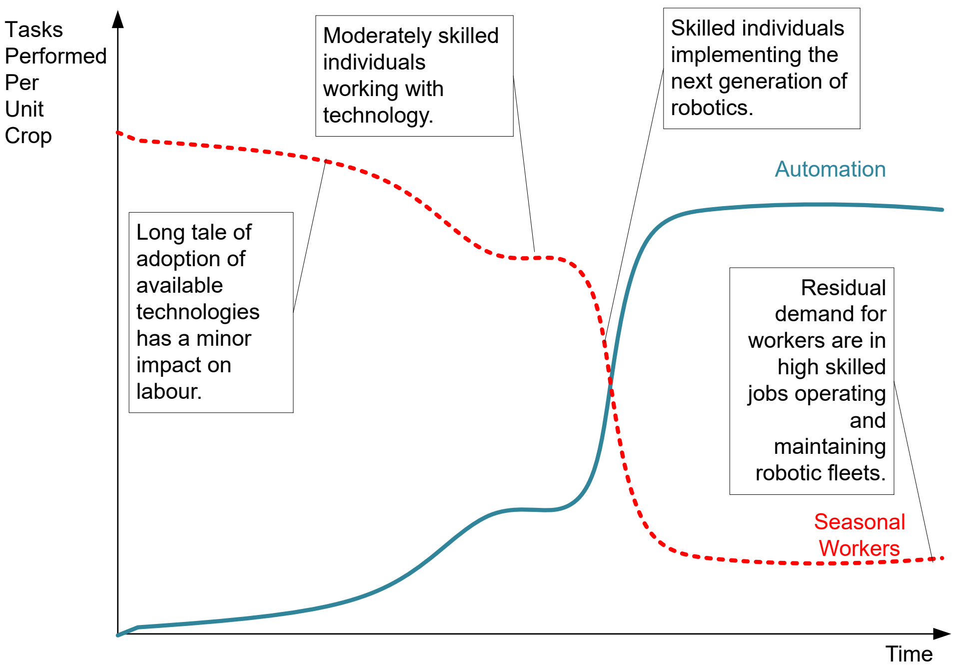

Figure 2b: An Impact-time graph of the 3 waves of automation technology with the X-axis being Time and the Y-axis Tasks Performed Per Unit Crop.

The automation line from figure 2a is the same, with a dotted red line inverted vertically representing the number of seasonal workers required per unit crop. This implies that the total tasks performed per unit crop remains constant, but as automation is implemented the tasks are shifted from seasonal workers to automation.

There are 4 key annotation points:

1. At the end of the short-term adoption: 'Long tail of adoption of available technologies has a minor impact on labour'.
2. At the medium-term plateau following the second wave of automation: 'Moderately skilled individuals working with technology'.
3. On the steep rise of the third wave of autonomous horticulture: 'Skilled individuals implementing the next generation of robotics'.
4. At the final plateau at the long timescale, the seasonal worker plateau is low: 'Residual demand for workers is in high skilled jobs operating and maintaining robotic fleets'.

Section 3: Barriers to adoption and development of automation

Why have currently available technologies not been widely adopted?

We have seen that there are 3 technology streams that are proven and commercially available, but adoption levels vary significantly across horticulture. The key barriers to adoption, identified by the review process, are discussed in more detail below. They follow the journey of a grower gaining knowledge of a system, building up the confidence to invest, making the investment and utilising the new technology.

Access to knowledge and know how

Knowledge dissemination is the first step towards adoption. If growers do not understand which technologies are available and suitable for their operations, they cannot build a business case.

Access to knowledge and know how - fragmentation

Horticulture is a collection of unique sub-sectors with broad and diverse requirements – it is therefore naturally fragmented. Efforts to disseminate information have been focused within sub-sectors, limiting industry wide knowledge sharing. Cross sector knowledge sharing between horticulture and automation companies is challenging, given the specialised nature of both sectors. Retailer supply chains offer some opportunity for cross-sector discussion, but competition between retailers could inhibit precompetitive collaborative efforts.

Growers are more inclined to adopt a system if they have seen it work in an environment and business comparable to their own, making early adopters critical for knowledge transfer. There are limited incentives for early adopters to spend their time disseminating knowledge about their new operations. Some grants have a condition that growers share knowledge, however this is not widespread. Given most UK growers supply the domestic market, there is a competitive advantage in not widely publicising new technologies.

Technology providers have a business incentive for sharing knowledge about their systems, but they can struggle to reach growers. This review found no central knowledge sharing platform currently being used widely by both growers and technology providers.

Access to knowledge and know how - lack of independent information and business support

Technical knowledge across horticultural stakeholders varies significantly, and many growers would benefit from an independent source of automation expertise. Furthermore, there is no clear source of independent business support, or advice, for automation in horticulture.

Henry Dimbleby's independent report into the UK food system, a review of England's food chain from field to fork, recommended the setting up of a 'What Works Centre' and there are already initiatives being developed along these lines. These should be developed, but in a way that creates a 'go to' body and does not end up adding to the confusing landscape.

Access to knowledge and know how - inconsistent messaging

Current messaging implies that automated systems in development are available to purchase now, or that automation is at least 10 years away. There is no independent verification process for systems that are 'commercially available'. Clarity regarding specifically available systems and a detailed development pipeline is required.

Terminology for automation and robotics can also vary across knowledge sources, which makes it challenging to identify options available to an individual grower.

Access to knowledge and know how - integrators who will take on horticultural projects

Automation integrators are technology specialists that combine off the shelf technologies to build an overall bespoke system. They normally work across multiple sectors and, once they have created a system, often exploit the concept by selling the system to others.

Growers have approached integrators to commission systems and have been disheartened by the lack of interest in horticultural applications. The specialised nature and scale of horticultural subsectors means the potential market for building a new system is small. Additionally, the pool of UK integrators is in high demand across all sectors, so they might decline more technically challenging projects. There is no central information point signposting growers to integrators who will work on horticultural commissions, which means many growers have lost momentum in adopting automation.

Building confidence to invest

Once a grower understands and identifies a technology that could be beneficial to adopt, they need to build confidence in the business case before making a significant investment.

Building confidence to invest - uncertainty in the future of seasonal migrant worker supply

Without confidence in seasonal labour supply, growers have no certainty for business planning and are unlikely to make long term investments. Growers are currently on an emergency footing, planning one season ahead, with many in the sector voicing concerns over the future of the Seasonal Workers Pilot. Automation has a payback period over many seasons, so very few growers will commit to long term investments when the future of their business is uncertain.

Compounding this, currently available technologies are likely to require workers to work alongside the automated systems. If no workers are available, the systems simply cannot be used. In this scenario, production would stop, and businesses would be more likely to fail faster after making the investment.

Building confidence to invest - risk averse mindsets in late adopters

Late adopters often require a shift in mindset towards automation. This cultural change required for some individuals in horticulture would be substantial as automation requires a significant investment of resource. Late adopters would require additional support as in-house capacity to explore automation business cases is often not available.

Building confidence to invest - high costs and long returns on investments

Automation generally has high up-front costs (Capital Expenditure or Capex) which, when combined with the seasonality of horticultural operations, can result in long payback periods (Return on Investment or ROI). Growers have stated that given the short timescales and fragility of retailer contracts, they might be reluctant to invest in high Capex systems that have ROIs longer than retailer contracts.

Raising the capital for investment

A grower may have the capital to implement their automation business case, but many will need to access loans or grants to help with the initial expenditure. Horticulture is a competitive sector with tight profit margins and, in 2019 to 2020, the average Farm Basic Income (comparable to net profit) from the Farm Business Survey (https://www.gov.uk/government/statistical-data-sets/farm-business-income-net-farm-income-and-cash-income-time-series) for UK horticultural farms was £42,400.The Capex for the hardware of an off the shelf autonomous system, before it is integrated and installed on site, can easily surpass this average Farm Basic Income.

Raising the capital for investment - unsuitable criteria for grants and planning applications

New automated packhouses are sometimes required, as the large machine footprints can be incompatible with legacy infrastructure. Planning permission and grant conditions require the creation of new jobs. The assumption that the number of jobs created is a direct measure of the benefits of a business case to a local area is not appropriate for automation technologies in horticulture. Since automating production drives labour productivity, it might reduce the overall labour needs of a business but increase the skill levels of remaining roles.

Sharing equipment between farms is not often possible, due to short harvest windows. However, when sharing is logistically possible it is not always permitted. Some financial mechanisms prohibit farms using equipment purchased via government funds to be used on other farms, with the recipient of the grant acting as a contractor.

Limiting grants to specific systems means that the most transformative technology for a farm might not be covered by a grant. Each farm has a diverse crop portfolio and unique infrastructure, and some may not be able to implement more advanced technologies until their basic infrastructure is upgraded. Optimising production could involve a series of small investments and yield higher labour savings than one high-cost system, but some grant support would only cover the latter investment.

Successful utilisation of systems

Once a grower has purchased and installed a system, they need to use it successfully in production.

Successful utilisation of systems - variation

Sectors that have successfully utilised automation have done so by reducing variation in processes, products and standardising components.

Variation is inherent in horticulture due to the biologically diverse nature of production. Crop variation can be reduced to some extent, through new crop varieties, novel production systems and growers reducing the range of crops they grow, but this presents new challenges and has a significant lead time.

Sector-made variation is a different matter. This review found a significant variety of Stock Keeping Units (SKUs) currently used across horticulture to offer consumers choice. While flexible packhouse automation is available, there is significant cost to create and operate systems which can handle multiple packaging types. To create futureproof automation, growers and technology providers must understand the possible futures of packaging. There have been cases where new packaging and supply chain requirements have rendered automation obsolete before a system is paid off. The variation in potential packaging requirements means many growers cannot successfully use automation for their packhouse operations.

What is stopping the development and adoption of the next generation of technology?

While the review found encouraging progress, the challenges to take most of these robotic systems from early prototype to commercial and scaled adoption are significant.

Collaboration and knowledge sharing

Many key development stages require knowledge transfer and collaboration for successful progression along the development pipeline. Some of the barriers for collaboration and knowledge sharing are common for all innovation, others are unique to automation for horticultural applications.

Collaboration and knowledge sharing - understanding the end user

Early pipeline developers lack knowledge of end user needs unless they have a growing background, are grower funded or have a grower as a development partner. Having a clear understanding of end user needs captured in the original design specification is key for technical and commercial success. A lack of end user understanding increases the burden on the grower providing test beds and can significantly delay development progress.

There are a range of government-funded research centres across the UK, though there is some fragmentation across these centres. Automation for horticultural applications sits across multiple centres with no clear single 'owner', which makes knowledge sharing and collaboration across the technology development community challenging. These centres, if organised effectively, have the potential to technically support and enable collaboration between developers and end users.

Collaboration and knowledge sharing - fragmentation between technology developers

While there is some collaboration between academics, developers and growers, there is less collaboration between technology developers. Many of the private sector robotic developers are private equity funded and understandably protect their intellectual property. Research and development fragmentation across Research and Technology Organisations (RTOs) and academia is also visible. There are examples of duplication where many stakeholders have been working on the same common problem.

Collaboration was discussed around commonalities, as it would be a more effective use of limited development resources, accelerating technologies to market and increasing the chance of success. However, significant concerns were raised around financial backing from private investors, liability and attitudes to intellectual property prohibiting collaboration. Legal understandings between developers could address these concerns but could be costly and take significant time to negotiate.

Finance and grant conditions

There are different financial mechanisms that can be accessed, depending on the TRL of a system. These include academic research grants, which primarily apply to early-stage development, and innovation grants, which help with early prototyping through the 'valley of death'. After successful farm trials, the funding streams shift to the private sector, with venture capitalists and more traditional financing becoming available for proven technology.

Finance and grant conditions - successful research funding bids

Grants are awarded through open competition, with written proposals forming the basis of applications. Many applicants find writing grant proposals a steep learning curve and may not have the time to utilise fully the available support.

Finance and grant conditions - unclear research funding

Many stakeholders have difficulty navigating the complex funding landscape, with some applying for funding programs for which they are not eligible. This is likely true of both technology developers and growers who lack experience of research funding but may have the most innovative concepts.

Finance and grant conditions - financial risk of field trials

On-farm trials are a critical stage of development and growers are keen to collaborate with developers by providing access to test beds if the process is de-risked. There are still a number or risks to the grower that remain - for example, crops are not guaranteed to be suitable for sale where a trial is unsuccessful.

Finance and grant conditions - attracting private sector funding

Venture capitalists are interested in automation for horticulture, but largely lack the confidence to invest, given the crowded marketplace and the significant working capital required to scale hardware-based technologies. These investors would like to pick winners to back, but their watchful waiting has resulted in stalled funding for some developers.

One suggested answer to this issue is to link automation funding to sustainable development to make it more attractive to investors. However, sustainable analysis requires external independent assessors, which is costly.

Finance and grant conditions - adoption business models

Business models are a factor to consider, as technologies in development get closer to market. Though costs are falling exponentially, early adopters are likely to wait until there is a viable ROI before investing in emerging technology. One popular suggestion to solve this would be a rental model based on providing technology as a service, rather than outright ownership. Rental would offer maintenance, operation support and potentially reduce the debt burden on farmers. However, there are various concerns around data ownership, insurance, and liability, that would need to be addressed. Additionally, current horticultural financial support is not yet structured to accommodate these innovative business models.

Finance and grant conditions - manufacturing scale

Manufacturing scale is a factor to consider, as technologies in development get closer to market. When new systems become available for mass adoption, a party will need to refine the design for mass manufacture. Commercial exploitation takes significant investment, and sector demand needs to be demonstrated to provide confidence for a manufacturer to make this large investment. The manufacturability and production scale will significantly impact the lead time of new technologies. There will be a delay between technology being proven and technology being widely adopted.

Infrastructure and horticultural processes

The environment in which an autonomous system operates will create additional technical challenges and requirements.

Infrastructure and horticultural processes - systems have been optimised for humans

Farm infrastructure and practices have been optimised for humans and are unlikely to be accommodating to robotics. Due to long crop lead times (such as top fruit), changes to crop architecture or growing systems can provide significant risk to growers, particularly where technology is not yet proven. However, initial improvements can be targeted, identifying characteristics in crops and infrastructure that are optimal for automation. This can allow the development of new crop varieties and farm infrastructure that will enable automation to be successful.

Infrastructure and horticultural processes - rural connectivity

Farms are often rural, with limited data connectivity. Mobile robotics can require significant data connectivity. Rural infrastructure will require significant upgrades before advanced technologies like mobile robotics can be implemented.

Skills

Skills required to develop, install, operate, and maintain the next generation of automation technologies will likely be Science, Technology, Engineering and Maths (STEM) based. Traditional horticulture has limited need for engineering and digital skills, with new innovations driving the need for STEM skills.

Skills - attractiveness of horticulture

Sometimes technology fails, and it is not commercially viable for a system to be down for a long period of time when a grower's window for harvest is short. Where problems occur, a skilled individual needs to be on site within a matter of hours. This requires maintenance services to be local, abundant and on-demand in a sector that is geographically dispersed. Identifying, attracting, and retaining these in-demand individuals in horticulture will be a significant challenge.

Standards and legislation

Clear and suitable regulations are essential for the next generation of automation technologies. Most robotic regulations were designed for industrial robots in traditional manufacturing settings. Agricultural regulations largely apply to farm machinery under direct human supervision. Both are not well suited for the next generation of mobile robotics operating autonomously in fields that could have public right of ways across.

Drones are one exception, with regards to legislation, and have been successfully deployed by some in horticulture due to regulations being driven by other sectors.

Standards and legislation - health and safety of systems

Standards are not legally binding; they represent good practice. They can be a harmonising tool which generate international consensus, and international standardisation allows technologies to be used safely across the globe. Standards build confidence in technology practices, and developers are likely to locate their company in a country with clear standards. Without clear, robust standards, it is likely innovators will relocate, or cease their development efforts.

Clear standards for robotics in horticulture would allow for autonomous operations. Currently, the lack of clear standards for mobile horticultural robotics means systems in development require direct human supervision to operate. The use of these robot companions is workable for system testing but is not commercially scalable. Standards would contribute to the commercial viability of unsupervised mobile robotics and provide reassurance to insurance providers.

Clarity of which standards and regulations are applicable to horticultural applications is critical for safe adoption of technology. This knowledge barrier could result in unsafe implementation of technology, or more likely lower adoption levels across the sector.

Standards and legislation - data and cyber security

Data ownership is a challenge that is faced by all sectors looking to employ AI and advanced data systems. These issues will be central to the commercial application of robotics in horticulture. Robotic operating platforms can have significant variation, with more open software platforms trading security for increased collaboration. Efforts to develop secure and collaborative operating platforms are being led by the automation research community.

Standards and legislation - emerging ethical considerations and acceptance by society

Ethical development is not a single barrier to overcome, but a continuous process that will need suitable consideration at all stages of the journey to an automated future, a positive consumer perception of UK horticultural practices is key for these systems to be successfully adopted. There have long been ethical concerns and debates around AI, robotics and data, and as the future of automation is realised new ethical considerations will emerge (Rose, Lyon, de Boon, Hanheide and Pearson, 2021). It is likely that other sectors will adopt these technologies before agriculture, but the risk should not be underestimated.

Section 4: The way forward

This review identified the various barriers stifling both the adoption of currently available automation technologies and the development of robotic systems from early prototype to commercial and scaled adoption.

To help overcome these barriers, the review proposes a series of recommendations. They are not intended to be binding on government, but for government to consider. They are organised into the 3 keys categories or 'themes' which cover the general problem areas relating to automation acceleration and adoption:

1. 'Mind the gap' or the need for a secure source of labour in the period before mass-adoption of technology is feasible.
2. 'Collaboration' or the need for cooperative leadership and engagement between the government, industry and academia to increase the mass adoption of automation technology and accelerate technology in the development pipeline.
3. 'Technology alone is not a solution' or the need to provide the necessary infrastructure, funding, guidance and regulations to support this sectoral revolution.

Mind the gap

This theme aims to build on the work of this review process through securing seasonal workers until the next generation of automation can be adopted, thus building confidence in the future of automation and horticultural labour availability. The review established that the current available technology will not have a significant impact on the labour needs of the sector in the short term, or even the medium term. The 'gap' is the time between now and when the next generation of automation is available for adoption.

Recommendation 1: Defra should consider pursuing a long-term Seasonal Workers Scheme for edible and ornamental horticulture starting in 2022

A long-term Seasonal Workers Scheme would help to stabilise workforce pressures in the sector, helping growers to better evaluate their labour needs over time and incentivising long-term capital investments in automation technology.

While a new Seasonal Workers Visa Route has been announced for 2022 to 2024, the length of any future schemes should ideally match the period preceding the feasible mass-adoption of automation technology.

One clear and definitive outcome from the review roundtables was the sector's desire for a long-term Seasonal Workers Scheme to supersede the Seasonal Workers Pilot (2019 to 2021). Seasonal migrant labour is critical to maintaining UK horticulture production and, while a new Seasonal Workers Visa Route has been announced for 2022 to 2024, this labour supply should be maintained until automation technologies are developed, proven and mass adopted. Doing so would provide certainty for horticulture and address the lack of confidence to invest in technology, enabling open discussions around the future of automation to take place without fear of losing the critical migrant labour supply.

Collaboration

Collaboration is required to address the vast fragmentation across the development pipelines and within the horticultural supply chains. Collaboration requires UK government leadership and engagement from across the sectors.

Recommendation 2: Defra should consider convening a consortium that brings together UK government departments, horticulture industry and technology companies to drive significant adoption of available and proven technologies by growers

A cross-industry consortium would help to remediate the significant fragmentation between technology providers and end users, as well as:

- fast-track the adoption of available technologies across horticulture, and the transfer of proven technologies across sub-sectors
- increase collaboration across the supply chain
- increase knowledge transfer and the sharing of risk at all stages of adoption

This recommendation builds on the success of the roundtable discussions of the review which, thanks to industry participation, revealed advanced insight into automation progress in the sector. Defra should consider taking a leadership role for the next 3 years, bringing together stakeholders from across horticulture, its supply chains and technology providers to drive adoption of available automation technologies.

This review identified a lack of access to independent knowledge on currently available automation and a series of missed opportunities by the sector to learn from early adopters of technologies. A consortium would address such fragmentation, and inconsistent messaging could be replaced with clear guidance generated by consensus among attendees. This knowledge sharing platform could also identify integrators who work in horticulture and disseminate this information widely.

Additional benefits include:

- bringing risk averse growers into the conversation who, without support, are unlikely to adopt new technologies
- driving adoption by building longer term relationships with growers, allowing for growers to invest in high-cost equipment with long returns on investments
- reducing variation in horticultural practices
- encouraging shared buy-in from across the supply chain

Recommendation 3: Defra should consider launching a robotic crop harvester mission to fast-track innovative research and development of systems currently in the 'valley of death'
A highly focussed mission-led approach, underpinned by the UK government's leadership and funding, and supported by technology companies and the horticulture sector, would help accelerate the development of automation technology.

A mission-led approach of this kind has the potential to disrupt horticultural practices whilst securing global leadership in horticultural production and automation technologies.

This review found that growers cannot invest in multiple systems for multiple tasks or crops due to the high cost of technology. A common platform that sub-systems can be added to would be more economically viable for growers. The software and operating system used in robotics is proprietary for the hardware (meaning they have been developed specially for the equipment and have a unique user interface).This means that each system is likely to require unique user training, making a common base platform and software interface more attractive for growers.

Mission-led collaborative research and development efforts would remove the fragmentation between technology developers and create a framework that respects core intellectual property, while allowing for development of shared systems. Including growers in a collaborative way would ensure that developers understand the needs of the end users, increasing the chance of commercial success. This should be underpinned by government leadership and funding.

Once systems have become commercially viable, they will require private sector investment to scale manufacturing for exploitation. A high-profile mission approach will likely increase the attractiveness of the successful systems for private sector funding by de-risking capital investment.

Technology alone is not a solution

Technology cannot be successfully adopted and exploited without the appropriate supporting mechanisms. The availability of technology alone will not lead to mass adoption and the transformation of the sector. This final theme of recommendations addresses the other barriers that need to be removed to enable adoption of current and new technologies.

Recommendation 4: Defra should consider leading a review of financial and fiscal support for automation in horticulture
Current processes, criteria and mechanisms for financial support in this area, in particular grant conditions, are discouraging some growers from engaging with sectoral innovation.

Defra should consider assessing whether current arrangements are suitable for increased adoption and accelerated development of such technologies and make changes where necessary.

Current financial support for horticulture was not designed for complex automation. Some criteria for grants are not fit for purpose and growers who cannot access traditional loans may fail to adopt automation technologies without additional support. While these mechanisms are being reviewed, it would be prudent to make changes to funding suitable for the next generation of automation, preferably in a way that accommodates for both ownership and leasing arrangements. A review could also consider super capital funding to allow for larger Capex systems to be purchased and machinery to be shared, where logistically possible.

Innovation funding is critical for technology development, but there are significant challenges in writing successful bids and navigating the complex funding landscape. A financial review also needs to consider not only the quantity and type of fiscal support, but its accessibility for innovators and growers.

The financial risk of hosting field trials is a significant burden on growers and is more acute than other production sectors, due to the seasonal and perishable nature of horticultural products. A financial review should identify and implement mechanisms to de-risk field trials for growers, otherwise UK based innovation in horticulture will stop.

Recommendation 5: the sector should identify, develop, and share automation infrastructure best practice among growers to help them transition from labour-intensive to technology-intensive operations

The horticultural sector should look to establish a working group to identify and disseminate novel harvest practices and infrastructure development plans that are more conducive to automation environments. The business need for rural data connectivity should also be considered.

There is a need to increase knowledge sharing at all stages of development and technology adoption. While the consortium in recommendation 2 would offer significant opportunity for technical knowledge dissemination, it is recommended that a longer-term source of independent information and business support for adopting automation is identified or created by the sector.

It is critical that developers understand grower needs, and that growers understand the limitations of future technologies. The technical complexity of automated harvesting is challenging, and it may not be successful without changes to horticultural practice and infrastructure, including internet connectivity. Best practice to make growers automation-ready would help reduce variation at a sector level, document end user requirements and lead to swift adoption of the next generation of automation.

Recommendation 6: the sector should develop its future skills pipelines and consider ways to attract and retain skilled staff

The horticultural sector should lead a review into future skills requirements to inform and build skills pipelines which ensures existing and new workers have the required skill set for the future of their work.

This should consider how to make the sector more attractive to work in, through career development and leveraging regional strategies. The Institute for Agriculture and Horticulture (TIAH) is a welcome industry initiative that could have an important role to play here.

The skills required at each stage of the technology development pipeline, and at each stage of adoption, will significantly differ. It is recommended that the sector identify the skills they are likely to need in the future and start building a skills pipeline to ensure the required skills are available as the technology develops. This requires coordinating the skills pipeline with the development pipeline progress.

Attracting and retaining skilled individuals within horticulture will be critical to ensure the next generation of automation technologies can be successfully implemented. It is recommended the sector identify and implement changes to make horticulture as attractive as possible, as the skills needed are likely to be highly desirable to other sectors.

Recommendation 7: the sector should seek greater representation for horticulture and technology supply chain delegates at regulatory-legislative working groups on next generation robotics

The sector should seek greater representation for horticulture and the automation supply chain delegates on regulatory working groups so that it can influence the next generation of legislation related to health and safety, data ownership and the security of automation technologies, ensuring they are workable on farms.

There is no clarity on how current standards and regulations apply to the next generation of automation in horticultural applications, which means there are concerns around health and safety, data ownership and cyber security. It is recommended that the sector review current guidance and seek to develop new standards, where appropriate. This clarity will attract global innovators and allow for systems to be commercially adopted.

The wave of new technologies that will be used in the next generation of horticultural automation are being implemented across many sectors. This means that legislation may be in development and the horticultural sector must engage with these efforts to ensure these new regulations will address their concerns and are feasible to implement on farm.

References

Rose, D. C., Lyon, J., de Boon, A., Hanheide, M., and Pearson, S. (2021, May). Responsible development of autonomous robotics in agriculture. Nature Food, 2, 306-309. Retrieved June 2021, from www.nature.com/articles/s43016-021-00287-9.pdf (https://www.nature.com/articles/s43016-021-00287-9.pdf)

Annex A: Technology Readiness Levels in horticulture

Technology Readiness Levels (TRL) are used to define the current state of a system in the development pipeline (see Table 1 for definitions). TRL 1 to 3 is research based, with TRL 4 to 6 focusing on building technology and system prototypes. TRL 7 is when system development and on farm testing becomes key. TRL 8 and 9 is commonly known as commercialisation, where systems are redesigned for mass manufacture. Time to market and time to mass adoption of technology are not the same - once a system is market ready it could take years to scale production and install systems on farms.

Cost of research and development activities, and chance of technical success, increase with each TRL. Early TRL activities (TRLs 1 to 4) are low-cost and often covered by academic funding, commercial funding becomes available once a system is proven (TRL 7). This gap between research and full private funding is known as the valley of death, due to the significant financial loss before commercial success (see figure 3).

The definition of TRLs used in this report is from the House of Commons - Technology and Innovation Centres - Science and Technology Committee (https://publications.parliament.uk/pa/cm201011/cmselect/cmsctech/619/61913.htm#:~:text=Technology%20Readiness%20Levels%20%28TRLs%29%20are%20a%20technology%20management,observed%20and%20reported.%20Technology%20concept%20and%2For%20application%20formulated.)

Table 1: the TRL definitions and interpretation for horticultural automation

TRL	Definition from the House of Commons - Technology and Innovation Centres - Science and Technology Committee	Interpretation for horticulture
9	Actual technology qualified through successful mission operations.	Systems are widely used and proven across horticulture.

TRL	Definition from the House of Commons - Technology and Innovation Centres - Science and Technology Committee	Interpretation for horticulture
8	Actual technology completed and qualified through test and demonstration.	Early adopters have used a system in production for a few growing seasons.
7	Technology prototype demonstration in an operational environment.	System has successfully operated on farm for at least one season.
6	Technology model or prototype demonstration in a relevant environment.	System has performed the horticultural task in a farm-like environment (such as outdoors on soil). This can be a short video showing the prototype perform the task at a sub-production rate.
5	Technology basic validation in a relevant environment.	Technical sub-systems (such as base units, sensors, cameras and mechanical grippers) have been tested in a farm-like environment.
4	Technology basic validation in a laboratory environment.	Technology sub-systems have been tested in an engineering lab.
3	Analytical and experimental critical function and/or characteristic proof-of-concept.	Observe workers performing the task you are attempting to automate.
2	Technology concept and/or application formulated.	Research has found technology that could be applied to a horticultural task.
1	Basic principles observed and reported.	Technology has abilities that are defined through research.

Figure 3: Profit and loss plotted against TRL (Technology Readiness Level).

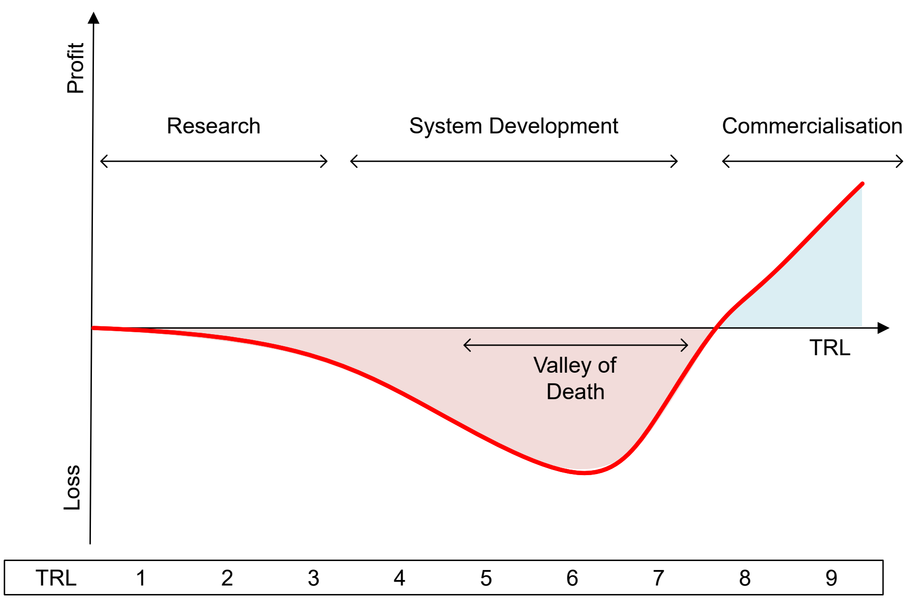

Figure 3 shows:

- from 1 to 3 the line declines from the origin into minor loss. This section is labelled ‘Research’

- from 3 to 7 the line declines much faster and forms a local minimum between 6 and 7. This whole section is labelled ‘System Development’
- from 7 to 9 the gradient becomes positive with the line crossing into profit between 7 and 8. This section is labelled ‘Commercialisation’
- the significant loss between TRL 5 and 7 is labelled the ‘Valley of Death’, due to its valley-like profile

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