Horticulture Innovation Australia

Final Report

Prioritisation of vegetable crop commodities and activities for mechanisation

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Summary

The objective of this project was to review a broad range of data related to vegetable commodity production to identify those commodities and production processes that should be prioritised for RD&E investment in mechanisation. Labour is a significant component of farm costs in some sectors of the vegetable industry, making mechanisation an attractive consideration to reduce costs.

This project developed a priority list of vegetable crops for future investment in mechanisation R&D. Prioritisation was a staged process which involved:

- reviewing a broad range of data related to vegetable commodity production (volume, value, distribution, gross margins etc.) to identify those commodities most suited to, or offering the greatest returns from, advances in mechanisation
- assessing the potential for production expansion of certain sectors if cost constraints could be relieved through mechanisation
- reviewing reports from past projects related to mechanisation in vegetable production to identify common themes or gaps
- scanning for new or near market technologies with potential for application in the vegetable industry
- consulting with reference growers on various matters related to the project to ensure relevance

The report of this work is the primary output of the project VG13081. Based on the analysis done, it is recommended that future investment in mechanisation R&D should focus on (in priority order):

Harvest

- Lettuce
- Broccoli (possibly combined with cabbage and cauliflower)

Transplanting

- Broccoli (possibly combined with cabbage and cauliflower)
- Lettuce

Research and development synergies

- Broccoli, cabbage and cauliflower (for harvest mechanisation)
- Asian and bunching vegetables – development of harvest aids to make more efficient use of labour for a large number of small scale producers

Controlled traffic farming

- Thorough investigation of the potential costs and benefits of wide span technology as the basis of a mechanized vegetable production system that would provide the most uniform production environment possible, leading to more consistent product and less reliance on differentiation and selectivity in later phases of the process.

Robotics, machine vision and sensors

- Continue research and development in robotics for a range of tasks in vegetable production, including automated data gathering and weed control
- Develop early warning pest and disease monitors for use with robotic or other platforms
- Develop real-time, in-the-field quality monitoring sensors to assist harvest scheduling, resource allocation and data acquisition at harvest
- More readily available 'plug and play' yield monitoring technology

The provision of this information to HIA and relevant groups within the vegetable industry will help

inform decisions regarding the efficient allocation of funding resources for relevant research and development in the area of mechanisation, automation, robotics and remote sensing (MARRS). This will support targeted research leading to the development of new technologies to reduce costs and increase productivity, thereby helping to maintain and improve the competitiveness of the Australian vegetable industry.

The data collated and reviewed during the conduct of this project highlight some key areas of importance for the future of R&D investment in Mechanisation, Automation, Robotics and Remote Sensing (MARRS). These include harvest systems for crops with variable maturity, opportunities for cross-industry collaboration in mechanisation R&D, robotics, adoption and adaptation of existing sensing and monitoring technologies, and changes to mechanisation to facilitate the adoption of controlled traffic as a basis for sustainable production systems.

Keywords

Mechanisation, automation, robotics, vegetables

Introduction

Compared to many exporting countries, Australia is a high cost producer of vegetables. In addition to a high cost of production, the vegetable industry faces slow growth in domestic demand, market dominance by major retailers, low export volumes, cheap imports and downward pressure on commodity prices. Labour costs are commonly reported as a major production cost, representing an average 30% of total farm costs across the national industry, but considerably higher for those sectors that rely on manual labour for tasks such as transplanting and hand harvest.

Adoption of mechanisation and automation technology presents an opportunity to significantly reduce production costs. While in some vegetable industries, all aspects of production (i.e. land preparation, planting, weed, pest and disease control, fertiliser application, irrigation and harvesting) are already highly mechanised, in others manual labour is still required for tasks such as selective harvest. Even within the mechanised activities, there are opportunities for improved on-farm mechanisation and automation. The Australian vegetable industry Strategic Investment Plan 2012 – 2017 identified the need for mechanisation R&D and improved uptake of mechanisation technologies as important factors for reducing production costs in the vegetable industry.

Further, mechanisation must be integrated with agronomic requirements and practices to optimise yield and quality within resource constraints (e.g. soil variability and water availability). Managing the impacts of variability with precision technologies is an important component of current and future approaches to mechanisation, and in fact, is essential if the full potential of automation is to be realised.

There is substantial diversity in the vegetable industry – types of crops grown, growing environments, size of production units, suitability of crops for mechanisation - more so than in any other crop growing sector. Many sectors of the Australian vegetable industry are small, compared to major overseas producers, making investment in technology development difficult to justify for the local market. Larger-scale commodity crops, which are often processed and are more likely to be traded internationally, would be best served by technological advances that reduce production costs, as this will help counter import competition and open opportunities in export markets.

A number of projects related to horticultural mechanisation in the Australian vegetable industry have been conducted over the past decade. These have tended to focus on the technological requirements of harvest of specific crops, precision agriculture and other emerging technologies relevant to on-farm production and post-harvest operations. None of the previous projects reviewed the relative importance of various crops as the basis for determining mechanisation priorities.

This project was initiated by the Marketing and Value Chain Development Design Team to prioritise vegetable commodity crops for future mechanisation R&D investment. The study produced a prioritised list of crops and activities, which can be used to inform future decisions on mechanisation and automation RD&E funding for industries that contribute to the vegetable levy. Economies of scale for R&D investment, commercial development and adoption of new mechanisation technologies can be achieved by focussing on crops that have higher value or greater production volumes, areas and enterprises, or technologies that can be applied across sectors.

In the context of this report, mechanisation is taken to include the areas of Mechanisation, Automation, Robotics and Remote Sensing (MARRS). This covers the range of opportunities available through changes to current mechanical systems, the application of automated and robotic systems to replace current practices, and the use of sensing and monitoring to provide information for improved decision making or real-time action by automated systems.

The project was led by the Tasmanian Institute of Agriculture (John McPhee (project leader) and Assoc. Prof. Colin Birch), with collaboration from the National Centre for Engineering in Agriculture, University of Southern Queensland (Dr. Troy Jensen, Dr. Matthew Tscharke,) Queensland Department of Agriculture and Fisheries and Forestry (Bill Johnson), and Macquarie Franklin Pty. Ltd. (Thom Goodwin).

Methodology

Crop prioritisation

Some 100 crops contribute to the vegetable levy. Many of these represent small volume sectors of the industry compared to the major commodity crops. The first step in the project was to establish a priority list of crops for consideration through analysis of ABS data [1-4]. There are a number of limitations to ABS data, particularly in more recent years, when there had been less segregation of data between industries. Although segregation has now been re-instated in response to industry feedback, the new approach will apply from 2013-14 onwards, which is too late to be of use for this project. The 2008-09 data set was the main data set reviewed as it was the last year information was collected on a large range of vegetable crops. Ranking decisions based on 2008-09 data were further informed by referring to more recent data (2011-12 and 2012-13), although the more recent data are less informative due to aggregation or omission.

The process used was as follows:
National data on value of production were ranked, and the top 10 crops identified. These crops were then excluded from individual state data, and from the remaining crops in state-based records, the top 10 were ranked on value of production. The combination of the national and state lists gave a list of 20 crops. This was then ranked in three different ways:

1. National value of production alone (which was the combination of national top 10 and state top 10, described above)
2. In addition to national value of production, data on the area and tonnage of production, and number of enterprises, were included, with each factor given equal weighting. The rank score for each crop was the sum of the rank score for each individual set of data such that the highest ranking crop was the one with the lowest combined score from each factor.
3. The same process as 2 (above), except that each factor was given a weighting ranging from 0.5 to 1.0. The rank score for each crop was the sum of the rank score for each set of data multiplied by its respective weighting, with the highest ranking crop being the one with the lowest combined score.

For the weightings used in method 3, values were assigned subjectively using knowledge and experience in how the application of mechanisation was likely to be influenced by the various factors. Value and volume were deemed to have the greatest influence on the anticipated productivity impacts of mechanisation, as well as being indicators of the capacity of the industry to invest in mechanisation R&D and adoption. The relative importance of the different criteria used for ranking can be explained as follows:

- Production value (weighting = 1) – a small increase in productivity in a high value industry (in terms of industry worth, not necessarily product value) has the capacity to return a large monetary benefit
- Production tonnage (0.8) and area of production (0.5) – the importance of these is determined by whether key costs, such as harvest, are tonnage or area based. In many cases of hand harvest, the key cost influencing factor may be the number of pieces harvested (e.g. heads/ha or heads harvested/person).
- Number of enterprises (0.7) – helps define the potential market for new technologies, bearing in mind that a sector with many enterprises is likely to consist of many small operators who may not have the scale or capacity to invest in new technologies. However, there may be scope for collaboration or the establishment of contractor operations which

would be sufficient to provide the scale that would warrant investment in mechanisation.

In reality, differences in the rank order of crops between methods 2 and 3 were evident only in the lower quartile of the original list of 20, so the use of weighting factors was dropped.

Gross margin analysis
Cost of production data for the top 12 crops were sourced from Gross Margin details available in Tasmania, New South Wales and Queensland. These were reviewed to identify the phases of production responsible for the highest cost, both in $/ha and as a % of the total cost of production. Six phases of production were considered, being:

- Land / Seedbed Preparation
- Seeding / Transplanting
- Irrigation
- Nutrition
- Pest & Disease Control
- Harvest

The importance of post-harvest costs was also noted, although consideration of mechanisation priorities in the post-harvest phase was not part of this project, as the development of automated systems for use in packing sheds is well advanced.

Consultation with industry
A number of growers and agri-businesses were consulted by members of the project team on various matters during the project. These consultations provided insight and ideas from across the fresh and processed vegetable sectors, in operations ranging from Tasmania to Queensland, and included one interview with a major operator in the international scene.

In addition, the project leader attended and presented a project update at a HIA organized workshop 'Priorities for Investment in Agricultural Robotics and Automation in the Vegetable Industry' in Melbourne on 18 February 2015. The workshop was attended by a number of growers, researchers and equipment suppliers, and provided an ideal opportunity to obtain additional feedback in a very efficient manner, with multiple growers present at the one time. The HIA workshop was followed by a visit and discussions with staff of the Australian Centre for Field Robotics at University of Sydney.

Review of previous reports
A number of reports were reviewed, many related to previous HAL mechanisation projects. Current and potential drivers and issues in the vegetable industries were identified [5-12]. The drivers and issues provide the scope for automation and mechanisation solutions or disruption. The current weaknesses and threats relevant to the vegetable industries were aligned with the previously identified drivers and issues.

Potential for industry expansion
One aspect considered in the identification of priority crops for mechanisation R&D was the potential for industry expansion in domestic and export markets, and the degree to which potential expansion is constrained by factors that can be addressed by reducing costs through mechanisation. Numerous reports have been written on the topic of expanding domestic demand, accessing export markets and producing for import replacement, and a number of these were reviewed for information in relation to this issue [13-19].

Opportunities for cross-industry collaboration

Many of Australia's vegetable sectors are small in comparison to major overseas producers. However, there may be opportunities for synergies in R&D investment across sectors which either face similar challenges, or exhibit similarities in the characteristics of the crops. No simple categorization of vegetables is perfect, but in terms of harvest mechanisation and automation (as an example), an effort was made to allocate the priority vegetables to five broad groupings based on the nature of the harvested part and the manipulation or handling that is required during the harvest process. The groups chosen were:

- Heads/hearts
- Melons
- Roots/tubers
- Bunching vegetables *
- Pods
- Capsicums

(* bunching vegetables are so named because of the way in which they are handled and packed at harvest.)

Due to the potential for collaboration across a number of relatively small industries, both Asian vegetables and bunching vegetables (inclusive of Asian vegetables) were assessed as an additional category in the economic analysis that is outlined in the Outcomes section of the report. This was done to determine the importance of bunching vegetables as a broad grouping relative to Asian vegetables alone and the other vegetables in the list.

Suitability for mechanisation

The suitability of specific crops for mechanisation was judged on a number of factors, the primary one being harvest. Crops with indeterminate maturity (e.g. broccoli) have always proven difficult to harvest mechanically, unless the growing environment and agronomic practices can be arranged to provide a very narrow window of maturity, allowing a single pass destructive harvest, with acceptance of some portion of the crop being over- or under-mature. This demonstrates the vital importance of assessing the entire production process when considering mechanisation, as the provision of uniform growing conditions should reduce variability at harvest. Apart from harvest, most other aspects of the crop production process are suitable for mechanisation approaches. This is seen particularly in the adaptation of sensing and imagery technologies to assist in crop management decisions.

Technology scans

Technology is a rapidly evolving aspect of the vegetable industry. Many forms of mechanisation have been used in the industry for many years, while in more recent times, there has been an expansion in the use of data collection technologies to provide information as the basis for better decision making. A broad scan was undertaken to appraise developments in new mechanisation platforms to replace or enhance existing forms of mechanisation, data acquisition and control technologies, and robotics.

Whole of industry benefits

Whole of industry benefits arising from mechanisation can be estimated by calculating possible cost reductions to the specific part of the production process to which the technology is applied. In this project, industry benefits were calculated in two stages:

1. Estimation of the per hectare benefit of technology adoption in high cost areas of the production process.
   a. Annual per hectare cost reduction associated with mechanisation was estimated by assuming the high cost areas of gross margins (i.e. transplanting and hand harvesting) declined by 40%, 50%, 60%, or 70%.
   b. The maximum amount a producer would be willing to pay for a new technology was estimated by calculating the net present value of annual per hectare cost reductions over a ten year period. Under these assumptions a vegetable grower would finance machinery, and the annual per hectare cost reduction associated with mechanisation would just offset the annual principal and interest payments. It was assumed the loan was paid off over 10 years at a real interest rate (excludes inflation) of 5%, and the salvage value of the machinery was $0.
   c. The per hectare benefit a producer would receive from mechanisation was estimated by calculating the difference between the maximum amount they would be willing to pay (as described in b, above), and the net present value using a real interest rate of 15%. The additional 10% real interest rate represents the return on investment to the grower.
2. Estimation of industry demand for new technology

Industry benefits were calculated by multiplying the per hectare benefit (as calculated in stage 1) by the industry demand for machinery (per hectare) over a 20 year period. Demand for new technology tends to follow a pattern of initial adoption by early innovators, rapid growth as the wider industry imitates the early innovators by adopting the technology, followed slowing growth as the product matures and the remainder of the industry accept the technology, or the technology is replaced by the next generation. The Bass diffusion model [20] is an accepted approach for estimating the demand for new technologies and products over time. This model enables us to predict the rate and final level of adoption in the industry. Using the Bass diffusion model the annual rate of demand can be estimated by:

$$d(t) = \frac{mp(p+p)^2 e^{-(p+q)t}}{(p + qe^{-(p+q)t})^2}$$

where:

- t is the time period (we considered annual demand over a 20 year period)
- p is a measure of the industry's desire to innovate, reflective of the prevalence of early adopters
- q is a measure of imitation, or the willingness of the remainder industry to follow earlier adopters
- m is a measure of market size (we used hectares under production as a measure of market size)

Empirical estimates of p and q were obtained from studies [21, 22].

System impacts

Developments in mechanisation need to consider the farm system and the crop production sub-system, so the benefits gained in the production process of one crop (i.e. one sub-system) can be applied to other crops in the rotation, if appropriate, and contribute to the whole farm system. It is equally important to ensure that improvements in one crop production sub-system do not introduce sub-system conflicts in another within the rotation. One of the key sustainability drivers across production sub-systems is soil management, and the consequences of traffic from harvest mechanisation which is designed without consideration of its impact on the soil conditions for the next crop – i.e. harvest conflicts elements of the crop sub-system and the farm production system. It is important that mechanisation improves productivity within the farming system, and in the industry more broadly, either through reducing input costs, improving crop performance in response to inputs, or both.

Outputs

The primary output of this project is the delivery of the final report, which provides guidance as to the areas of R&D which should be considered as priorities for future investment in relation to mechanisation.

Outcomes

Crop prioritisation

The ranking of crops based on the combination of data related to value, area and tonnage of production, and number of enterprises, gave a list with 8 crops from the national top 10, and 2 from the state top 10. Excluded from the final list were Asian vegetables and sweet potatoes, which had appeared in the original national top 10 based on value of production. Although these crops ranked 6 and 10 (respectively) in the national value of production list, and were subsequently dropped in ranking on account of other factors, they are clearly important crops in a national context, and were re-included by extending the list to 12 crops. The initial priority list is shown in Table 1.

Table 1. Prioritised list of crops for future mechanisation R&D.

1. Lettuce	7. Zucchini and Button squash
2. Pumpkin	8. Cauliflower
3. Carrot	9. Cabbage
4. Broccoli	10. Sweet corn
5. Capsicum (excluding chillies)	11. Asian vegetables
6. French and Runner bean	12. Sweet potato

Table 2 shows the rank order for each assessment criteria individually. Of the 12 crops chosen, seven rank under all criteria, and three rank under at least two criteria. Ten of the 12 crops rank highly in terms of Number of Enterprises, one measure of potential market for new technologies. Eight rank under Area, also a possible indicator of potential market for new technologies.

Table 2. Crops prioritised by four different criteria.

Rank	Production value	No of enterprises	Production tonnage	Area
1.	Lettuce	Pumpkin	Carrot	Lettuce
2.	Carrot	Zucchini and Button Squash	Lettuce	Broccoli
3.	Capsicum (excluding chillies)	Lettuce	Pumpkin	Pumpkin
4.	Broccoli	Cucumber	Cabbage	French and Runner bean
5.	French and Runner bean	Capsicum (excluding chillies)	Cauliflower	Carrot
6.	Asian Vegetables	Asian Vegetables	Celery	Sweet corn
7.	Pumpkin	Broccoli	Sweet corn	Green peas
8.	Zucchini and Button squash	Cabbage	Capsicum (excluding chillies)	Cauliflower
9.	Sweet corn	Silver Beet and Spinach	Broccoli	Zucchini and Button squash
10.	Sweet potato	Cauliflower	Sweet potato	Cabbage
11.	Cauliflower	French and Runner bean	French and Runner bean	Capsicum (excluding chillies)
12.	Celery	Carrot	Zucchini and Button squash	Sweet potato

Of the 12 crops, four are considered to be highly mechanized already, in the sense that no operations require significant manual labour resources for their completion. These crops are carrot, bean (although some specific markets rely on labour for hand harvest), sweet corn and sweet potato. However, mechanisation considerations do not relate only to labour intensive operations, so these crops were kept in the list regarding other opportunities within the broad spectrum of MARRS.

Gross margin analysis
Six phases of production were considered in the gross margin analysis, being:

- Land / seedbed preparation
- Seeding / transplanting
- Irrigation
- Nutrition
- Pest & Disease Control
- Harvest

Phases of production were considered priority targets for attention if their cost was >$2000/ha, or represented >20% of the total cost of production (excluding post-harvest). First order priorities were those crops and phases of production which met both of these criteria, shaded dark grey in Table 3. Second order priorities (shaded light grey) are those for which either the cost factor, or the % of the total cost of production, met the relevant criterion, but not both. * indicates crops for which post-harvest costs represent >20% of the production cost.

Table 3. Identification of phases of production by crop for future mechanisation R&D.

Priority crops	Land / Seedbed preparation	Seeding / Transplanting	Irrigation	Nutrition	Pest & disease control	Harvest	Post-harvest
Lettuce		light grey			light grey	dark grey	*
Pumpkin						dark grey	*
Carrot					light grey		
Broccoli		dark grey				dark grey	*
Capsicum (excluding chillies)		dark grey			light grey	dark grey	*
French and Runner bean				light grey	light grey	dark grey	
Zucchini and Button squash	dark grey					dark grey	*
Cauliflower		dark grey				dark grey	
Cabbage		light grey				dark grey	*
Sweet corn		light grey	light grey	light grey	light grey		*
Asian vegetables		light grey				dark grey	
Sweet potato		light grey					*

Notes: dark grey indicates threshold of >$2000/ha cost and >20% of production cost was exceeded
light grey indicates one threshold was exceeded
* indicates post-harvest represents >20% of total production cost

This analysis indicates that crop establishment (for transplanted crops) and harvest (for hand-harvested crops) are the areas of highest cost. Most of the high cost areas would be potentially amenable to change through mechanisation. Although not high cost areas in their own right, land preparation, irrigation, nutrition and pest and disease management are also very important, as the application of downstream technology cannot adequately rectify sub-optimal task quality in earlier phases of the production process. In keeping with the objective of considering the entire production process, it is likely that alternative approaches to tillage, and precision agriculture techniques using remote sensing and imagery, such as vari-rate irrigation, could be used to reduce costs and improve productivity.

Consultation with industry

Growers and agri-businesses consulted by members of the project team during the project included:

- Harvest Moon, Forth, Tasmania (Mark Kable, Agriculture Manager and Director)
- Qualipac, Gatton, Queensland (Troy Qualischefski, Director; Kees Versteeg, Sales and Marketing)
- Simplot Australia, Tasmania (Peter Hardman, Agricultural Services Business Development Manager)
- Harslett Farms, Warwick, Queensland (Tim Harslett, co-owner)
- Rugby Farms, Gatton, Queensland (Matt Hood, Director; Surachat Vuthapanich, Farm Manager)
- Story Farms, Cambooya, Queensland (Nathan Story, Automation Engineer)
- Vanderfield Pty Ltd, Toowoomba, Queensland (Stephen Hegarty, Precision Farming Manager)
- Nestlé North America, Michigan, USA (Todd DeKryger, Business Development Manager, Agriculture)

Consultations were done by personal on-site visits, with the exception of Nestlé, which was done by phone.

The Melbourne HIA workshop 'Priorities for Investment in Agricultural Robotics and Automation in the Vegetable Industry' was attended by a number of growers, researchers and equipment suppliers. Attending growers and agri-businesses who had not already been consulted in the course of the project included:

- Coastal Hydroponics, Gold Coast, Queensland (Belinda Adams)
- J&A Brandsema Pty Ltd, Turners Beach, Tasmania (Anthony Brandsema)
- Thorndon Park Produce, Adelaide, South Australia (Danny De Ieso)
- Kalfresh Vegetables, Kalbar, Queensland (Rob Hinrichsen)
- 'Springfield', Bathurst, New South Wales (Jeff McSpedden)

The HIA workshop provided an ideal opportunity to obtain additional feedback in an efficient manner, with multiple growers present at the one time.

The production and economic constraints identified through consultation with industry representatives are collated below under several categories which were re-occurring themes across the range of people interviewed. Many reinforce conclusions drawn from other sources of information, such as the review of previous reports.

Labour

- Unsurprisingly, the cost and availability of labour, particularly for transplanted and hand-harvested crops, was consistently raised as a driver towards greater levels of mechanisation and automation.

Scale

- Scale of operation is a key factor in the decision to purchase new technologies, some growers noting that is difficult to justify going to the 'next level' of automation for the size of enterprises. This underlies the importance of new mechanisation and automation systems to be cost effective.

Data and sensing

- Improved gathering of data (e.g. crop, yield and quality monitoring) would allow better management and achieve more uniform crops.
- The capacity to use field data in models to predict optimum harvest time would be beneficial in maximizing pack out.
- Use of UAVs to gather data on size, shape or colour would allow more precise scheduling of harvest to minimise out of specification product, and for multiple pass hand-harvested operations, allow more efficient use of labour by directing workers to those areas where the product is ready to pick.
- Greater use could be made of current and emerging technologies based around sensing and tablet apps to plan and manage operations across multiple sites.

Field variability

- Automation is more viable in 'controlled' environments, such as protected cropping, than in fields.
- Variability is inevitable in outdoor cropping, although significant advances could be made by changing mechanisation to avoid the negative soil impacts of harvest and intensive tillage. Not only would this remove the variability associated with induced soil degradation, but would also allow consistency in the formation and management of raised beds, which are a common feature of many vegetable cropping systems. Consistency in the growing environment and resources accessible to the plant are essential elements in improving the chances of success for automation.

Fit for purpose

- New mechanisation is not always the appropriate answer, sometimes changing processes can give the desired result at lower cost.
- Consider the potential to alter production systems to allow effective use of existing mechanisation technologies which are currently not used due to local market or other constraints.
- The machine needs to suit the field situation (in terms of plant spatial arrangements), not the reverse, but also consider why the current field situation exists – has it been defined by pre-existing mechanisation, or other considerations, which are limiting production potential?
- Harvest mechanisation in particular needs to be able to operate in rain and wet field conditions, on account of market demands and timeliness regarding crop maturity. For many crops (e.g. lettuce, celery, spinach, Asian greens) what is planted in one day has to be harvested in one day, regardless of weather or other constraints. Current mechanisation systems are unable to cope with these demands without extensive damage to the soil during wet harvests.

Production system

- A whole of system approach is needed, with each sub-system and system element optimized for efficiency.
- Transplanting, harvest and weed control are key operational and cost imposts in the production

process.

Precision

- The potential benefits of much more precise placement of seeds/transplants than is currently possible requires investigation.
- The performance of transplanting machines (i.e. plant spacing, depth, spacing uniformity) in variable soil conditions is currently sub-optimal, and methods of improving performance should be investigated. Accurate performance at this stage enhances the prospects of automation at harvest.

Technology

- The capacity to capitalise on the precision attributes of GNSS (Global Navigation Satellite System) guidance and PA (Precision Agriculture) technologies is limited in many enterprises through age of equipment and the difficulties in integrating data and systems between machines and contractors/owner operators. Combining equipment suitability and compatibility, skills, and understanding the technical requirements to achieve the potential of what is possible is essential to driving adoption of innovation in these fields.
- There is a place for a cheap, simple device to allow GNSS guidance capacity to be fitted to smaller and older tractors, which are common in the vegetable industry.
- Maintenance and adaptation of sensors (e.g. in relation to PA) to different field situations and crops requires the availability of suitably skilled people.
- For once over harvest, mechanisation is the preferred option. Until selectivity and automation limitations are resolved, multi-pass harvests are best improved with developments that aim to assist, rather than replace, the labour component.

Genetics

- The capacity to mechanise or automate harvest is heavily influenced by plant architecture, so the role of genetics in crop development and growth habit needs to be considered.
- Improvements in system management/genetic manipulations that result in greater crop uniformity, hence more efficient harvest, are required.

Skills

- Adoption of new systems is not just about the technology – there is also the challenge of change management and staff training in a work force comprised of both older generations and itinerant, often younger, workers.
- As use of new technologies increases, and the technology itself evolves, access to the skills required for maintenance and adaptation will be vital in regional areas, requiring the establishment of appropriate service businesses and more staff with higher levels of training.

The data collated and reviewed during the conduct of this project highlight some key areas of importance for the future of MARRS R&D investment. It is also apparent that many improvements can be made with the adoption and adaptation of existing technologies, particularly in the field of sensing and monitoring, which allows better management of crops and resources.

Review of previous reports

The following drivers, in order of priority, were identified from the review of previous HAL project reports [5-12]:

1. Automation and mechanisation technologies
2. Agronomic practices
3. Globalisation

4. Markets
5. Labour
6. Education
7. Environmental/Social expectations and legislation

The identification of mechanisation and automation as an important driver is no doubt influenced by the fact that the reports reviewed were related to projects with a mechanisation and automation focus, although, it may also illustrate that mechanisation and automation solutions are both complex, and have the potential to solve constraints to productivity and efficiency. For instance, high cost and limited availability of labour are well known and understood challenges. However, mechanically replicating and/or automating the operations undertaken by the current labour force introduces a wide range of new RD&E opportunities to allow progress in mechanisation and automation.

Many recommendations were outlined in the reviewed reports. The most important can be summarized as follows:

Whole of system approach
It is important to review the entire production system when considering mechanisation and automation. Many mechanisation decisions are made in isolation of other parts of the system. Changes in lower cost phases of the production system can simplify the design of new mechanisation for other parts of the process. The assessment must be carried out on the entire production process to determine the commercial and economic advantages, and to identify possible negative consequences of mechanisation.

Collaborative investment
Many sectors in the Australian vegetable industry do not have the scale to justify investment in mechanisation. It is essential that industries collaborate to provide economic scale for the development and commercialisation of new technologies.

Design considerations
New mechanisation systems must be cost effective, able to operate on rough terrain, sloping ground and in mud and rain. Wherever possible, platforms developed for mechanisation should be designed for multiple applications, thereby providing more opportunities to amortise the R&D and commercialisation costs. From an engineering perspective, the crop layout is the most fundamental aspect for MARRS solutions to be applied effectively.

It is noted that some constraints raised in the reports, such as the absence of mechanised lettuce harvest in the Australian industry, have solutions available overseas, but they may not be suited to the current requirements of the industry. Therefore, it is important to investigate existing solutions for possible adaptation, or to review production processes and product requirements to determine the opportunity for change that would facilitate the introduction of technologies that are used successfully in other parts of the world.

Potential for industry expansion

The most likely driver of future expansion in the vegetable industry is demand. Growth in the domestic market has been slow but steady in recent years [13]. There are opportunities for expansion in export markets, particularly Asia and the Middle East, but the driver for access is as likely to be quality and reliability of supply as it is price, although clearly being cost competitive helps [13]. Import replacement in the frozen vegetable sector is probably the most likely place for expansion opportunities based on being able to reduce the local cost of production [16]. Therefore, if local production costs can be reduced through mechanisation, and efficiencies achieved in post-harvest processing, there may be scope for expansion, particularly in the processed vegetable sector. Mechanisation advances in the processed vegetable industry would inevitably flow through to similar crops in the fresh sector.

Given that expansion will likely occur in the presence of increased demand, it is reasonable to conclude that virtually any sector of the industry could expand if the demand is present, although many sectors would not have the scale to support or facilitate expansion through investment in mechanisation. The only role that mechanisation plays in this scenario is to reduce costs and influence the competitive advantage of one supplier/country compared to another, thereby causing demand to shift in response to the capacity to supply at a lower cost.

Opportunities for cross-industry collaboration

The allocation of the priority vegetables to five broad groupings based on the nature of the harvested part and the manipulation or handling that is required during the harvest process, is shown below. Some of these have existing mechanisation technologies that may be adaptable to other crops, whereas some currently have no mechanised solution. Also shown in brackets are additional crops that don't occur in the priority list, but which may provide additional volume and scale to support future cross-sector R&D investment opportunities.

- Heads/hearts – hearted lettuce, broccoli, cauliflower, cabbage, (celery)
- Melons – pumpkin, zucchini and button squash, melon-style Asian vegetables, (cucumber)
- Roots – carrot, root-style Asian vegetables, sweet potato, (parsnip)
- Bunching vegetables – leafy Asian vegetables, (spring onions, shallots, silverbeet, spinach, radish)
- Pods – beans, (snow peas, green peas, sugarsnap peas)

While leafy Asian vegetables is the only single sector example of bunching vegetables in the priority list, inclusion of the other lower volume crops results in an overall ranking of 5 for this group (substantially higher than Asian vegetables alone at 11). There are two dominant reasons for this lift in the rankings for Asian and bunching vegetables combined – 1) the high number of producers with small areas, and 2) the collective value of production ranks third nationally, after lettuce and carrot. Therefore, if there is demand for mechanisation R&D in these combined sectors, particularly for harvest, there are a number of sectors of the industry which could contribute. Further, given the nature of the industry (i.e. large numbers of producers with small production areas), it may be necessary for approaches to mechanisation to target simpler technologies, more in the line of aids to improve the efficiency of labour, rather than higher cost automation or robotics.

Suitability for mechanisation

Of the 12 crops in the priority list, six are largely dependent on transplant technology for crop establishment, and eight are dependent on hand harvest.

There are semi-automated transplanters available in the market. Examples are in use in the broccoli industry, and these could be modified to be suitable for other crop types. All transplanters currently on the market require some level of labour input to ensure continued smooth operation, but the labour force required for semi-automated transplanters is considerably smaller than that required for older manual assisted machines. One of the limitations of current semi-automated transplanter technology lies in the ground-engaging tools. In many cases the machines require a fine, smooth seedbed, and there is limited capacity to cope with crop residues or varying moisture conditions. The capacity to work in a wider range of seedbed conditions would be useful in accommodating situations of reduced or minimum tillage, which should be an objective of the vegetable industry wherever feasible to reduce erosion and retain organic matter to improve soil and cropping system sustainability. Nevertheless, it should be possible to modify many transplanters to make them suitable for a wider range of crops. The main constraint to adoption appears to be one of scale, in that it is only producers of large areas of crop that appear to be able to justify the investment.

Mechanising the harvest operation is an altogether different proposition compared to transplanting. Of the eight crops in the list that are hand-harvested, four have a heart or head characteristic to their growth habit (lettuce, broccoli, cauliflower, cabbage), two could be broadly classified as 'melons' (pumpkin, zucchini/button squash), one is a 'bunching' vegetable (Asian greens) and the last is capsicum.

All these crops are characterised by variability in maturity. There are two choices for harvest strategy in the case of variable maturity:

1. multi-pass harvest, with the objective of recovering the highest possible marketable yield, within the constraints that each pass through the crop must return more than it costs to harvest, and does not damage the remaining product
2. single pass harvest, if the harvest can be targeted at the point of optimum maturity, and the loss due to under or over-maturity is less than the cost of multi-pass harvest.

While all of the crops of interest in the list have variable maturity, some are harvested in a single pass, while others are multi-pass.

Extensive effort has been invested in the research and development of mechanical broccoli harvesters over many years [23-26]. To date, most designs have been based on a single pass destructive harvest, with agronomic approaches used to produce a crop suited to once-over harvest, or hand-harvest used to recover early maturing plants, followed by a destructive final harvest. Efforts have been underway for some time to add selectivity to a mechanical harvester (Fig. 1. P. Dobson, pers. comm.), but the growth habit of the leaves that encircle the broccoli head have so far prevented success in imaging or sensing the head to determine readiness for harvest. If the broccoli architecture was modified through genetics to present a more exposed head, it would be much more compatible with selective mechanised harvesting. Alternatively, accepting a wider specification of head diameter to satisfy different market demands would reduce the need for selectivity.

Fig. 1. Prototype single pass broccoli harvester developed by Dobmac, Tasmania.

As noted in grower interviews, crops with once-over harvest are better suited to non-selective harvest mechanisation, while those with non-uniform maturity require resolution of selectivity limitations before automation is possible. In the latter cases, the appropriate intermediate step is to develop systems that assist, rather than replace, the labour component.

Technology scans

Technology developments of relevance to the vegetable industry can be broadly split into the following groups:

Robotics

Robotic harvest as a replacement to current hand harvest approaches has been a topic of research and development for several decades. Numerous attempts have been made to develop robotic harvesters for specific crop situations [27]. More recently, horticulture industry funded research at the Australian Centre for Field Robotics (University of Sydney) has led to the development of a generic robotic platform (the Ladybird, Fig. 2.) which could become the basis of a multi-purpose robot [28]. The approach chosen is built on the swarm robotics concept, in which the robotic platform is lightweight and, once commercialised, would be relatively cheap, and could therefore be deployed in multiple units. This has a number of advantages including:

- redundancy and reliability, in that work capacity is only reduced, rather than lost, if one machine becomes inoperable. (One possible downside of the swarm approach is the potential to create more time management and maintenance issues for growers than is the case for a single unit, such as a tractor.)
- soil loads are light in the context of compaction issues
- work capacity can be expanded or contracted relatively cheaply
- work rates for each individual unit do not have to be high

The Ladybird has successfully completed proof of concept field trials, and proof of concept tools have been added for weed control operations using precisely directed sprays or mechanical apparatus. The Ladybird can also be used as a platform for sensors which collect a range of data on the growing crop, such as NDVI images, and other sensors are being investigated which could provide early warning of the onset of disease.

Fig.2. 'Ladybird' proof-of-concept robotic platform for use in vegetables

The application of a lightweight robot to vegetable harvest is somewhat more complex than data gathering and weed control using very small amounts of precisely placed chemical. The savings in chemical achieved by precise application of herbicide to individual weeds, means the payload for the robot is in the order of kilograms. Across the diverse range of vegetables grown, harvested yields range from less than 10 t/ha to over 100 t/ha. For many crops, harvest timing is critical, and high rates of product removal from the field are required. If one of the objectives of the swarm robot approach is to reduce soil loads as a means of limiting compaction, then many light weight robots, carry payloads in the order of a couple hundred kilograms, would be required to complete harvest in a timely manner. This is not to say it is not possible, but there are many mechanical and logistical issues to address before such an approach would be commercially viable.

A more immediate application for technologies like the Ladybird would be in data acquisition and weed, pest and disease control. The capacity for swarm robots to be almost constantly in the crop means that well-targeted and preprocessed data on the growth and performance of the crop could be provided to farm managers in real-time for enhanced decision making.

Sensors coupled to real-time control systems would allow automated weed, pest and disease control, and opens the possibility for nutrient management at the individual plant level, if required. Although these aspects of crop production are not high cost, as indicated by gross margin analysis, there are some key advantages to this approach to data acquisition and response. Firstly, frequent visitation to the crop means rapid response to emerging issues related to weeds, pests, diseases and nutrition. Secondly, the amount of material used to address these issues at the individual plant level will reduce significantly compared to current practices of broad scale application. While this will reduce the costs of these inputs in the farm budget, it may be that the more important factor is the capacity of the horticultural sector to demonstrate good environmental stewardship through minimal and very targeted use of resources such as fertiliser and agricultural chemicals.

Mechanical harvesters

Specialist, small-line manufacturers in Europe and USA have developed, or are developing, harvesters for specific crops such as head lettuce, pumpkins and celery [12]. There appear to be two major barriers to uptake of these technologies in the Australian context:

- scale of operation to justify the investment
- differences in presentation and/or packaging requirements between domestic Australian and overseas markets, in some product lines.

The first of these would be of less concern for large scale producers, and uptake of new harvest technologies like this could be facilitated by contractors entering the market. Increased use of contractors would require coordination between growers, particularly given the critical timeliness associated with harvest of many fresh vegetable crops, and would also require agreement on planting schedules to minimize harvest bottle-necks.

The second would require a review of current industry practices compared to what is possible with imported machinery.

Data acquisition, sensing and control

Precision agriculture techniques are dependent on spatially accurate data sets on a range of factors that influence and reflect the growth of the crop – soil characteristics, NDVI, yield maps etc. Some of the data gathered can be used for better decision making, either within season or between seasons, while some can be used for real-time control. At this time, very few vegetable harvesters are supplied ex-factory with yield mapping capability, although one large European manufacturer is providing fittings to facilitate the installation of load cells to potato harvesters imported to the UK (J. Wilson, pers. comm.) If this proves popular with end users, it is conceivable that uptake across root crop harvesters could be rapid.

The concept of weed identification and control dates back several decades in the grain industry, and Weedseeker technology is now widely used to apply herbicide only when weeds are detected. Originally developed for weed control in the fallow phase of cropping, it is more difficult to apply this technology in actively growing vegetable crops. Developments in the identification of grass weeds in sugar cane have recently been applied to the identification of weeds in pyrethrum crops, with the objective that targeted herbicide application will be possible to selectively kill weeds in the growing crop [29, 30]. Should this prove commercially viable, the concept would no doubt have application in the broader vegetable industry. Once again, this concept does not address high cost areas such as hand harvest, but reduction in input costs would be achieved, and the environmental credentials of the industry would be enhanced.

Fig. 3. Field test unit of selective weed sprayer being used in pyrethrum

Wide span platforms

Intensive traffic and tillage is an inescapable feature of current large scale vegetable production systems, as is the need, for many crops, to harvest irrespective of the soil and weather conditions to meet market demands. The natural consequence of this is soil degradation, a topic of increasing concern and interest in the vegetable industry. Experience in the grain industry over the past 20 years has demonstrated the significant benefits that controlled traffic farming (CTF) systems can provide in terms of soil restoration and health, and ultimately, the productivity of the entire production system [31]. The application of this approach to farming is currently limited in many parts of the vegetable industry by the diversity of mechanisation used, most of which does not meet the fundamentals required for controlled traffic, namely dimensional integration of track and working widths across all machines.

The concept of the wide span gantry first emerged in 1858 [32], and following a research focus and failed attempts at commercialization in the 1980s [33-38], two new generation prototypes have recently been built in Denmark (2013) and Brazil (2014) [39, 40]. The Danish machine (Fig. 4) has been built for light tillage and onion harvest, but it is not difficult to envisage how it could also incorporate harvest functionality for a wide range of crops as a single pass mechanical harvester, a harvest aid for hand harvest, or as a platform for automated selective harvest technology with the addition of sensor activated harvest tools.

Fig. 4. Prototype wide-span gantry tractor developed by ASA-Lift, configured for onion harvest.

Controlled traffic generally has been shown to deliver many advantages for crop production, but the wide span offers a number of advantages that are specific to the technology, including:

- Increase in cropped area for some crops, providing potential yield increases of up to 20% in some crops, purely on the basis of fewer wheel tracks
- Because of fewer wheel tracks, it is possible to enhance drainage in both the crop bed and the wheel track, thereby reducing the impact of harvest traffic in wet conditions
- With better drainage, the problem of mud splash on leafy vegetables would be reduced, with consequent improvements in product recovery and reductions in post-harvest cleaning

Preliminary conservative economic modelling for the Tasmanian vegetable industry showed that wide span technology has the potential to increase gross margins by over 60%. Experience in the grain industry suggests that the greatest benefits of CTF are to be found in improvements to the entire farming system, rather than the component benefits of individual crop yield increases, or lower tillage costs etc. At this stage, barriers to the adoption of controlled traffic in many vegetable production sectors mean the industry is excluded from achieving those benefits.

Whole of industry benefits

It is difficult to estimate the likely cost of new technologies, either in terms of R&D investment, or the sale price of a commercialised product. Any estimate of industry wide benefits is subject to a number of assumptions, and the process used in this project was done purely to provide some relative estimate of the potential value to be gained across a number of industries.

NB: *Detailed economic modelling regarding these aspects is beyond the scope of this project. If particular industries or operations within the production system are targeted for future mechanisation R&D investment, it is essential that more detailed and robust predictions of the potential benefits are developed with a focus on that particular sector or process. The method of analysis will not necessarily change, but a dedicated focus on a particular industry or process within the production system is required to obtain more rigorous data to use in the model. Further, it will be necessary to use more recent ABS data with improved segregation of data on a sector or region basis, or initiate dedicated data collection activities to provide relevant data. In addition, use of industry averages for cost structures is largely meaningless given the diversity of sectors that make up the vegetable industry.*

Cost savings at the farm level
Details of the approach used have been outlined in the Methodology section. The focus of the analysis was mechanisation for crops which are currently transplanted and/or hand-harvested.

The capacity to invest is primarily a function of the size of the operation (ha of crop per year) and the savings to be generated through adoption of the new technology. Lettuce harvest is used as an example of the process used, and results relevant to a range of crops are presented in subsequent tables.

From ABS data [1-4], the harvest cost for lettuce (average of Qld and NSW data) was $9,365/ha, representing 42% of the total cost of production. Cost reductions ranging from 40 – 70% per harvest over various size operations are shown in Table 4.

Table 4. Projected savings to be achieved in lettuce harvest cost based on a range of possible cost reductions.

	Cost reduction			
Annual cropped area (ha)	**40%**	**50%**	**60%**	**70%**
1	$ 3,746	$ 4,683	$ 5,619	$ 6,556
5	$ 18,730	$ 23,413	$ 28,095	$ 32,778
15	$ 57,870	$ 72,338	$ 86,805	$101,273
25	$ 93,650	$117,063	$140,475	$163,888
50	$187,300	$234,125	$280,950	$327,775

Given the need to repay borrowings (at 5% in this example) and deliver a return on investment (10%), Table 5 outlines the cost that a producer could afford to pay for technology which would provide these cost reductions.

Table 5. Capacity to invest in lettuce harvest mechanisation for a range of cost reductions, interest rate of 5% and return on investment of 10%.

	Capacity to pay			
Annual cropped area (ha)	**40%**	**50%**	**60%**	**70%**
1	$ 19,362	$ 24,203	$ 29,044	$ 33,884
5	$ 96,812	$ 21,015	$ 145,218	$ 169,421
15	$290,436	$ 363,045	$ 435,654	$ 508,263
25	$484,060	$ 605,075	$ 726,090	$ 847,105
50	$968,120	$1,210,151	$1,452,181	$1,694,211

The annual per ha benefit is shown in Table 6.

Table 6. Potential annual per ha benefit obtained for a range of assumed cost reductions in lettuce harvest, interest rate of 5% and return on investment of 10%.

40%	**50%**	**60%**	**70%**
$1,013	$1,266	$1,519	$1,772

The annual per ha benefit arising from a similar analysis of other crops in the priority list, including both transplanting and harvest costs, is shown in Table 7.

Table 7. Potential annual per ha benefit obtained from assumed reductions in transplanting and harvest costs for a number of crops.

	Transplanting				**Harvest**			
	40%	**50%**	**60%**	**70%**	**40%**	**50%**	**60%**	**70%**
Lettuce	$195	$243	$292	$341	$1,013	$1,266	$1,519	$1,772
Pumpkin					$238	$297	$357	$416
Broccoli	$376	$470	$564	$657	$340	$425	$510	$594
Capsicum	$457	$571	$685	$800	$694	$868	$1,041	$1,215
Zucchini / Button squash	$135	$169	$202	$236	$678	$847	$1,017	$1,186
Cauliflower	$270	$338	$405	$473	$415	$519	$623	$727
Cabbage	$173	$216	$259	$302	$962	$1,203	$1,444	$1,684
Asian vegetables*	$174	$218	$261	$305	$357	$446	$536	$625
Bunching vegetables	$86	$108	$130	$151	$238	$297	$357	$416

* in this table, bunching vegetables has been added as an additional category, as outlined in the Methodology. This includes Asian vegetables plus radish, silverbeet, spinach, shallots and spring onions. The figures given are weighted averages based on area of each crop.

In Tables 7 -9, bunching vegetables have been included as an additional category, in line with discussion presented earlier.

Whole of industry savings
The benefit to the industry of reductions in the cost of production is not gained immediately on the introduction of a new cost saving technology. It is influenced by the rate and level of adoption of the new technology, and consequently the benefits accrue to the industry over a number of years. This was modelled by using the data described above in the Bass diffusion model [20].

The values selected for this modelling for mechanised lettuce harvest were:

- p – 0.013 (coefficient of innovation)
- q – 0.455 (coefficient of imitation)
- m – 7,400 ha (based on ABS data for lettuce production)
- t – 1 – 20 years

When combined with the data presented in Table 6 for a 50% reduction in the cost of harvest for lettuce, the diffusion model shows an increasing annual benefit (Fig. 5), which has reached 80% of its peak value by year 10.

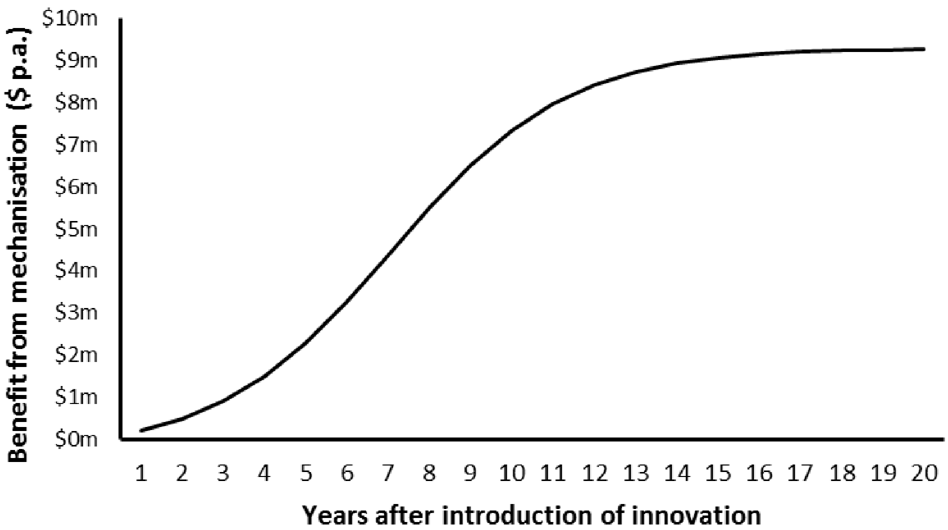

Fig. 5. Result of diffusion model for uptake of a hypothetical mechanical lettuce harvest system, showing the annual benefit returned against years after introduction of the development.

Table 8 shows the present value (PV) of the benefit obtained from the introduction of mechanised harvest, calculated by applying the same modelling procedure to the harvest cost component of other crops in the priority list. All calculations have been done on the assumption of a 50% reduction in the cost of harvest through mechanisation. The PV of the benefit is shown for 5 yearly increments from the start of the adoption process. The crops are listed in decreasing order of PV of the benefit, which is consistent at all 5 yearly intervals. Table 9 shows the PV benefit related to transplanting mechanisation, using the same approach and base assumptions.

Table 8. Estimated Present Value (PV) of benefit of harvest mechanisation benefit at 5 yearly intervals over 20 years.

Crop	5 y	10 y	15 y	20 y
Lettuce	$6.8 m	$27.0 m	$49.4 m	$64.4 m
Broccoli	$2.0 m	$ 7.7 m	$14.1 m	$18.4 m
Cabbage	$1.8 m	$ 7.1 m	$13.0 m	$17.0 m
Zucchini & Button squash	$1.4 m	$ 5.4 m	$ 9.8 m	$12.8 m
Pumpkin	$1.3 m	$ 5.0 m	$ 9.1 m	$11.9 m
Capsicum	$1.2 m	$ 4.8 m	$ 8.7 m	$11.3 m
Cauliflower	$0.9 m	$ 3.4 m	$ 6.2 m	$ 8.1 m
Bunching vegetables	$0.7 m	$ 2.7 m	$ 5.0 m	$6.5 m
Asian vegetables	$0.4 m	$ 1.5 m	$ 2.8 m	$3.7 m

Table 9. Estimated Present Value (PV) of benefit of transplant mechanisation benefit at 5 yearly intervals over 20 years.

Crop	5 y	10 y	15 y	20 y
Broccoli	$1.4 m	$7.1 m	$14.3 m	$20.4 m
Lettuce	$0.8 m	$4.3 m	$ 8.7 m	$12.4 m
Capsicum	$0.5 m	$2.7 m	$ 5.5 m	$ 7.9 m
Cauliflower	$0.5 m	$2.4 m	$ 4.9 m	$ 7.0 m
Asian vegetables	$0.3 m	$1.3 m	$ 2.6 m	$ 3.8 m
Cabbage	$0.2 m	$1.0 m	$ 2.1 m	$ 3.0 m
Zucchini & Button squash	$0.2 m	$0.9 m	$ 1.8 m	$ 2.6 m
Bunching vegetables	$0.2 m	$0.8 m	$ 1.7 m	$ 2.4 m

A number of assumptions have been made in the calculation of the estimates outlined above, including that:

- 5% is an appropriate interest rate
- 10% is an acceptable rate of return on investment, which will vary depending on individual circumstances
- the coefficients for the model match the likely adoption profile for harvest mechanisation
- area of production is an appropriate surrogate measure of the market size
- the cost reduction due to harvest mechanisation will be 50%. Clearly the benefit will vary depending on the % cost reduction achieved.

There are a number of other factors which have not been included in these calculations, such as:

- The impact of mechanisation on industry structure. It is likely that only larger farms would be able to justify investment in new mechanisation. In the case of lettuce, the average cropped area for outdoor head lettuce production is 16 ha (based on ABS statistics), which according to Table 5, would be able to afford an investment of approximately $400,000 to provide a 50% reduction in harvest cost. Predicting the cost of as yet undeveloped machinery is difficult, and it is debatable whether or not $400,000 would purchase the necessary technology, but regardless, it is unlikely that any cropped area under average size could justify the investment. With the mechanisation of larger farms, and the resultant improved competitiveness of those farms, it is likely that smaller areas would eventually cease to produce, and the production shortfall would be taken up by the mechanisation leaders.

- The impact of population increase. While the domestic market for vegetables is growing only slowly, no increase in market size has been factored into the modelling.
- The absence of newer, better technologies entering the market. It is unlikely that one technology would dominate the market place for 20 years, which would be required to match the assumption that adoption will occur smoothly from first introduction to eventual 100% uptake. Machinery technology can have very long adoption phases of up to 50 years [41, 42], and is consistent with adoption timeframes mentioned for research outcomes [43].
- Changes in financial pressures. Within an oversupplied domestic market, the natural consequence of lower cost of production is downward pressure on producers from the major supermarket chains, as they seek to improve their margins. While those who have achieved lower production costs through mechanisation will remain viable, it is important to note that the monetary 'benefit' identified in the modelling outlined above will not necessarily accumulate to individual growers or the industry more broadly. It may be that the main benefit is that the industry maintains its place in the market in the face of increased competition from low cost imports. In the words of one grower interviewed as part of this project – 'the SMARTER the (vegetable) industry gets, the WORSE off it becomes', arguing that in domestically oriented industries, the consumer gets the benefit of improved efficiency. The Productivity Commission also noted that consumers capture the bulk of the benefits from research and innovation [43].

System impacts
There are two key ways in which the broad scope of mechanisation, automation, robotics and remote sensing can improve productivity in the vegetable industry. These are:

- *Reducing labour costs* – this is primarily the focus of developments such as higher capacity machinery, automation and robotics, and is particularly relevant for those parts of the production process which currently require a high number of labour units – e.g. manually assisted transplanting, hand harvest. This tends to be a crop specific issue, although developments for one crop may have flow on benefits for similar crops.
- *Improving crop performance and input resource use* – this is primarily the focus of precision farming technologies, and systems which reduce the impact of traffic and tillage within the farming system, which may include lightweight robotic approaches, and/or controlled traffic systems based on larger machinery. This is an issue which impacts all crops, so in many cases, developments for one crop will find application, perhaps with modification, in many other crops.

Reducing labour costs
Harvest – crops with high labour requirements at harvest include lettuce, pumpkin, broccoli, capsicum, beans (for specific markets), zucchini and button squash, cauliflower, cabbage and Asian/bunching vegetables. Reducing the labour component of harvest requires automation and/or robotics for crops which are r piece harvested, and particularly for crops which are subject to multi-pass harvest due to uneven maturity. However, there may be intermediate steps that can be adopted to improve harvest efficiency, such as sensors to assist with determination of maturity, leading to more efficient allocation and direction of labour resources.

Transplanting and seeding – crops with high transplant costs include lettuce, broccoli, capsicum, cauliflower, cabbage and Asian/bunching vegetables. However, there are well developed automatic transplanters available in the market which may be applicable, with adaptation, to some, if not all, of these crops. Scale of operation may be a primary barrier to adoption of these technologies, as larger operations are able to justify such investments. Further to the automation aspects of transplanting technology, there is a need to improve the ground engaging technologies used on transplanters to allow more effective operation in zero or minimum tillage environments. This will be required as systems evolve and adapt to situations such as cover cropping, residue retention and strip tillage, which are required to improve the sustainability of soil management in vegetable production. Future developments in robotics may also find application in transplanting.

A second option for reducing labour costs in crop establishment is the opportunity to replace transplanting operations with direct precision seeding. Many transplanted crops (e.g. broccoli) exhibit non-uniform maturity characteristics, and transplanting is seen as one way of minimising the impact of this on harvest schedules. Replacing transplanting with direct seeding usually introduces more variability in the development of the crop, as well as requiring a longer growing season in the field. Further, most precision seeders for fine seeded crops (e.g. lettuce) are designed to work in intensively tilled seedbeds, and seeders rarely match transplanters in their capacity for precise placement. With these points in mind, there are a number of factors which influence crop performance that need to be traded against labour costs if the move is made from transplanting to direct seeding. From an R&D perspective, factors related to ground engaging tools, uniformity of emergence and precision placement of seeds (with respect to depth and position in the row) need to be addressed if direct seeding is to be a viable alternative to transplanting.

Improving crop performance and input resource use
The technologies required to better manage crop production and input resources are not necessarily crop specific, and developments in this area could find widespread use in many sectors of the industry, depending on cost and scale. The relevant technologies fall into two main areas:

- sensing and monitoring for improved (or automated real-time) decision making
- mechanisation to overcome the current barriers to implementation of controlled traffic farming systems in vegetable production.

<u>Sensing and monitoring</u> – The vegetable industry lags significantly behind other industries (e.g. grain) in the adoption and application of what are broadly known as precision agriculture (PA) techniques [7]. PA involves monitoring of crops using spatially referenced technologies to identify differences in performance which can be addressed using variable management techniques. The information obtained from such sensing and monitoring technologies can be used to inform management decisions for remedial action, or for real-time response through the use of robotic and automated systems. The use and further development of these technologies has the capacity to make very substantial reductions in chemical use, and improvements in crop management, leading to higher yield and quality. Current developments in sensing and robotics point to the possibility for individual plant management (e.g. nutrient supply, pest/disease management), which will ultimately lead to very efficient use of input resources.

The final arbiter of crop management and performance is yield and quality. The development of yield and quality sensors for 'plug and play' use on vegetable harvesters is a key development that is required for the vegetable industry to capitalise on the sensing, monitoring and data management that is the basis of precision agriculture. Yield and quality mapping are the keys to successful implementation of PA, and at present there is a serious lack of commercially available, reliable sensors of this purpose. Yield and quality both determine the returns generated by vegetable crops, and improved pack-out is an important goal of vegetable growers. Technologies which improve pack-out may be just as financially important as those which reduce labour in many cases.

Controlled traffic farming – Current vegetable production systems are characterised by intensive traffic and intensive tillage, both of which have long term detrimental impacts on soil sustainability and productivity. The use of controlled traffic to effectively address this issue is constrained in some sectors of the industry due to incompatible machinery designs, particularly harvesters. The adoption of controlled traffic in vegetable production would be a fundamental system change which could improve the performance of almost every other part of the production system, leading to more effective application of other technologies, such as sensing and robotics, while increasing yield and quality [44]. While some sectors of the industry, particularly those that rely on hand harvest, can adopt controlled traffic relatively easily with current tractors, other sectors require significant change of the type demonstrated by the development of wide span (WS) technology, which would allow all operations, including harvest, to take place from a common track width machine [40]. The introduction of WS technology would change the soil management approaches used in vegetable production, resulting in large reductions in tillage requirements, and leading to improvements in soil conditions and crop management and the possible introduction of zero-till production practices.

The development of light weight robotics also offers a solution to the soil degradation effects of the heavy machinery widely used in vegetable production. However, even with light weight machines, it will still be necessary to operate under a controlled traffic system in order to maintain the best possible soil conditions for crop growth. Further, the defining requirement for the design of machinery in vegetable harvest systems is materials handling, with over half of the cumulative weight of harvested wheel traffic being produce. Therefore, even light weight robotic systems will need to be operated under a controlled traffic system to maintain desirable soil conditions.

Summary

This project reviewed data and factors which influence vegetable production costs, in an effort to identify priority areas for future investment in mechanisation research and development. With the wide range of crops covered by the vegetable levy, any consideration of mechanisation opportunities is a complex issue. It was not possible to arrive at one priority for R&D investment in mechanisation due to the complexities of the industry and the number of opportunities present to progress technologies relevant to the vegetable production process. Key points are highlighted below:

Reducing labour costs

Hand harvesting, and to a lesser extent, transplanting, are the areas of greatest cost in the production process, as a consequence of high labour input for some crops.

- Harvest – lettuce offers the greatest potential for savings in per hectare harvest cost (Table 7), and the highest potential return on R&D investment at the industry level (Table 8). Cabbage and capsicum rank second and third (Table 7). However, if there are synergies to be obtained through R&D into broccoli, cabbage and cauliflower harvest mechanisation together, the estimated NPV is approximately 70% of that obtained for lettuce, making those crops a second order priority for harvest mechanisation R&D. Robotics is clearly of interest in hand-harvested crops due to the capacity to significantly reduce labour costs. Apart from the technical challenges of manipulations, materials handling and logistics are key issues to resolve for an operation that often has very strict timeliness constraints and heavy loads to transport.

- Transplanting – capsicum and broccoli have the greatest potential for per hectare savings through mechanisation (Table 7). Broccoli offers the highest potential return on R&D investment at the industry level (Table 9), followed by lettuce. Although a lower cost operation than harvest for most crops, transplanting mechanisation opportunities may be easier to pursue, as R&D investment could build on current semi-automatic transplanter technology with a focus on adaptation to suit different crops and soil conditions. Transplanting is also likely to be an easier step for robotic solutions because:

- transplant supply and selection technologies are already well developed
- the materials handling loads and logistics for transplants are significantly less than for harvest.

Improving crop performance and input resource use

The cost of purchased inputs to vegetable production (e.g. fertiliser, agricultural chemicals, water) may be significantly less than labour in most crops, but is still an important consideration in the economics of production. Further, the environmental credentials of the industry are very dependent on how society perceives the use (or mis-use) of these inputs. Therefore, for both economic and environmental reasons, inputs should be managed carefully and at the level that provides for the needs of the crop, and no more.

- Sensing and monitoring for improved (or automated real-time) decision making – the vegetable industry can capitalise on many data acquisition advances made in other industries, such as grain. A wide range of sensors is available to monitor many aspects of crop performance, although their application in the vegetable industry lags significantly behind their use in other industries. One important issue in the vegetable industry is the general lack of off-the-shelf yield monitors, which are a critical element in the application of precision agriculture management techniques. Another technology of great value would be harvester-mounted real-time quality monitors, which may measure quality based on shape, size or colour. This is a more difficult task than yield monitoring, but given the very useful trend in the grain industry of generating profit maps using yield data, the equivalent in vegetables requires both spatially referenced yield and quality data.

- Mechanisation for controlled traffic farming (CTF) in vegetable production – one of the foundations of vegetable industry sustainability is the soil resource, and increased mechanisation, in conjunction with the dimensional incompatibility of many machines, has led to intensive traffic and tillage regimes in many production systems. Controlled traffic offers a solution to this cycle, but only if machinery working and track widths can be integrated to confine all traffic to permanent traffic lanes which are isolated from crop production zones. The recent development of Wide Span prototypes suggests a new direction for field crop mechanisation with particular relevance to vegetable production. At this stage, the primary requirement for the vegetable industry is to stay abreast of developments with this technology, and to investigate the potential benefits for the industry through in-depth investigation and economic modelling based on previous HAL-funded work related to the Tasmanian vegetable industry.

- Robotics – high labour costs for harvest (in particular) are a driver for the development of robotics in the vegetable sector. Therefore, it might be expected that opportunities for this technology should be discussed under *Reducing labour costs*. However, given current industry-funded developments at the Australian Centre for Field Robotics (University of Sydney), the short-term commercial potential of robotics may lie more in the area of sensing and monitoring, and in making more effective use of inputs such as fertiliser and agricultural chemicals. The capacity for the prototype robotic platform (Ladybird) to regularly traverse the field without human input allows collection of high density data on crop performance, pest and disease threats and other factors influencing crop growth. These data can be used either to inform farm management decisions, or initiate automatic responses from the robot, such as targeted spraying of individual weeds. The capacity to image and monitor at the individual plant level opens many possibilities for targeted application of crop inputs, and hence much more effective use of those inputs compared to current broad scale application methods. Proof of the commercial viability of the robot for these tasks would be a sound basis on which to further develop the capabilities for harvest.

Evaluation and Discussion

Feedback on various aspects of the project was obtained through grower consultations, and particularly at the HIA organized workshop 'Priorities for Investment in Agricultural Robotics and Automation in the Vegetable Industry' in Melbourne on 18 February 2015. A progress report was presented at that workshop, which gave the growers and industry representatives present the opportunity to comment on direction, methods and preliminary findings and conclusions.

Recommendations

The vegetable industry is diverse and complex. No single mechanisation opportunity is a priority for all sectors of the industry. Therefore a number of priorities are listed here for potential future R&D investment, divided between those which are crop specific and those which could apply to all vegetable production systems, regardless of the crop. Each has a different focus, although some areas of interest clearly overlap. For example, robotics in the context of harvest has a very strong labour reduction focus, whereas in the context of data acquisition and crop management, the focus is more about reducing inputs, although labour would still be reduced. Likewise, wide span technology is very much about soil sustainability and reduction of inputs, although greater labour efficiency is also a benefit.

Crop based priorities
Priority crops in terms of potential return to the industry:

Harvest

- Lettuce
- Broccoli (possibly combined with cabbage and cauliflower)

A priority in this area should be to investigate the potential to either add selectivity to current mechanical broccoli harvesters, or find ways to improve crop uniformity to allow single pass destructive harvest, which is currently feasible.

Transplanting

- Broccoli (possibly combined with cabbage and cauliflower)
- Lettuce

Semi-automatic transplanters are already in use in broccoli production, but cost relative to scale of production appears to be a constraint. A priority in this area should be to investigate the potential to adapt existing semi-automatic transplanters to a wider range of crops and soil conditions, and hence provide more options to amortise cost. The option of direct seeding for some crops should be investigated.

Synergies of R&D

- Broccoli, cabbage and cauliflower (for harvest mechanisation)
- Asian and bunching vegetables – development of harvest aids to make more efficient use of labour for a large number of small scale producers

Production system based priorities
Generic fields of R&D with potential application over many sectors of the industry

Controlled traffic farming

- Thorough investigation of the potential costs and benefits of wide span technology, or other controlled traffic options, as the basis of a mechanized vegetable production system that would provide the most uniform production environment possible, leading to more consistent product and less reliance on differentiation and selectivity in later phases of the process.

Robotics, machine vision and sensors

- Continue research and development in robotics for a range of tasks in vegetable production, including automated data gathering and weed control

- Develop early warning pest and disease monitors for use with robotic or other platforms
- Develop real-time, in-the-field quality monitoring sensors to assist harvest scheduling, resource allocation and data acquisition at harvest
- More readily available 'plug and play' yield monitoring technology

Scientific Refereed Publications

None to report

IP/Commercialisation

Not applicable

References

1. *7503.0 - Value of Agricultural Commodities Produced, Australia, 2008-09*.
2. *7121.0 - Agricultural Commodities, Australia, 2011-12*.
3. *7121.0 - Agricultural Commodities, Australia, 2012-13*.
4. *7503.0 - Value of Agricultural Commodities Produced, Australia, 2012-13*.
5. *VG08087 - Opportunities and challenges faced with emerging technologies in the Australian vegetable industry (Technology platform 5: Emerging technologies for production and harvest)*, 2010.
6. *VG08087 - Opportunities and challenges faced with emerging technologies in the Australian vegetable industry (Technology platform 1: Supply chain and logistics)*, 2010.
7. *VG05060 - Scoping study to assess the application of precision agriculture for vegetable production*, 2006.
8. *VG10108 - Workshop on precision agriculture and mechanisation in the vegetable industry*, 2011.
9. *VG12050 - Emerging technologies in horticulture seminar*, 2013.
10. *HG09044 - Mechanisation, automation, robotics and remote sensing (MARRS) for Australian horticulture*, 2010.
11. *VG05073 - Mechanical harvest of selected vegetables - feasibility study*, 2006.
12. *VG11702 - Study Tour - Lettuce Harvester*, 2012.
13. *Australian Vegetable Export Opportunities*. 2013 [cited 2015 05 March]; Available from: http://ausveg.com.au/resources/Australian%20Vegetable%20Export%20Opportunities_AUSVEG_HAL.pdf.
14. *VG10047 - Economic survey of Australian vegetable growers, 2010-11, 2011-12 and 2012-13*, 2013.
15. *VG12086 - Investigating the costs associated with the production, sale and distribution of vegetables*, 2014.
16. *VG12083 - Understanding the nature, origins, volume and value of vegetable imports (MS report)*, 2014.
17. Bensley, T. *Exporting vegetables to China – examining opportunities and barriers (online)* 2013 [cited 2015 05 March]; Available from: www.richardcolbeck.com.au/clients/richard/downloads/item471/exporting_vegetables_to_china_-_examining_opportunities_and_barriers._tegan_bensley_30.5.13.pdf.
18. Walmsley, A. *Veg industry to tap Asia and UAE markets*. 2015 [cited 2015 05 March]; Available from: www.goodfruitandvegetables.com.au/news/magazine/industry-news/general/veg-industry-to-tap-Asia-and-uae-markets/2722975.aspx.
19. *Comments on the Australia-China Free Trade Agreement Joint Feasibility Study*. 2005 [cited 2015 05 March]; Available from: http://www.dfat.gov.au/trade/agreements/chafta/Documents/2NAG_17_GrowCom.pdf.
20. Bass, F., *A new product growth model for consumer durables.* Management Science, 1969. **15**(5): p. 215-227.

21. Lillien, G., A. Rangaswamy, and A. De Bruyn, *Principles of Marketing Engineering*. 2nd ed. 2013: DecisionPro Inc. .
22. Sultan, F., J. Farley, and D. Lehmann, *A meta-analysis of diffusion models'.* Journal of Marketing Research, 1990. **27**(1): p. 70-77.
23. Lenker, D.H., *Mechanization of the selective harvesting of cauliflower and lettuce.* Proceedings, international symposium on fruit, nut, and vegetable harvesting mechanization, Bet Dagan, Israel, 5-12 October 1983., 1984: p. 240-245.
24. Lenker, D.H., et al., *Development and performance of a selective cauliflower harvester.* Transactions of the ASAE, 1978. **21**(1): p. 6-11.
25. Plumb, B.E., *Harvesting and handling of fresh broccoli and cauliflower.* Paper, American Society of Agricultural Engineers, 1984(84-1073): p. 10 pp.
26. Tillett, N.D. and J.B. Holt, *Water jet cutting of cauliflower stems for mechanical harvesting - a feasibility study.* Divisional Note, AFRC Institute of Engineering Research, UK, 1987(DN 1402): p. 33pp.
27. Bac, C.W., et al., *Harvesting robots for high-value crops: State-of-the-art review and challenges ahead.* Journal of Field Robotics, 2014. **31**(6): p. 888-911.
28. *VG12104 - An intelligent farm robot for the vegetable industry (MS report)*, 2014.
29. Rees, S. and C. McCarthy. *Real-time processing technique for image analysis-based weed spot spraying at commercial ground speeds*. in *5th International Workshop: Applications of Computer Image Analysis and Spectroscopy in Agriculture, 12-14 July, 2014*. 2014. Montreal, Canada.
30. Rees, S., et al., *Development and evaluation of a prototype precision spot spray system using image analysis to target Guinea Grass in sugarcane.* Australian Journal of Multi-disciplinary Engineering, 2011. **8**(2): p. 97-106.
31. Tullberg, J.N., D.F. Yule, and D. McGarry, *Controlled traffic farming--From research to adoption in Australia.* Soil & Tillage Research, 2007. **97**(2): p. 272-281.
32. Halkett, P.A., *On guideway agriculture: Being a system enabling all the operations of the farm to be performed by steam-power.* The Journal of the Society of Arts, 1858. **7**(316): p. 41-58.
33. Chamen, W.C.T., *Gantry tractors as a basis for traffic control?* Landwards, 1997. **52**(1): p. 10-14.
34. Chamen, W.C.T., E. Audsley, and J.B. Holt, *Economics of gantry- and tractor-based zero-traffic systems*, in *Soil compaction in crop production.* 1994. p. 569-595.
35. Chamen, W.C.T., et al., *Assessment of a wide span vehicle (gantry), and soil and cereal crop responses to its use in a zero traffic regime.* Soil & Tillage Research, 1992. **24**(4): p. 359-380.
36. Holt, J.B. and N.D. Tillett, *The development of a 9 metre span gantry for the mechanised production and harvesting of cauliflowers and other field vegetables.* Journal of Agricultural Engineering Research, 1989. **43**(2): p. 125-135.
37. Hood, C.E., et al., *Straddle vehicles for horticultural crop production - a review.* Acta Horticulturae 1987(210): p. 35-42.
38. Tillett, N.D. and J.B. Holt, *The use of wide span gantries in agriculture.* Outlook on Agriculture, 1987. **16**(2): p. 63-67.
39. Pedersen, H.H., *Harvest Capacity Model for a Wide Span Onion Bunker Harvester*, in *Automation and System Technology in Plant Production, CIGR section V & NJF section VII conference, 30 June - 2 July 2011*, I.A. El-Hameed, Editor 2011, NJF, Nordic Association of Agricultural Scientists: Herning, Denmark. p. 44-46.
40. Pedersen, H.H., et al., *A Wide Span Tractor concept developed for efficient and environmental friendly farming*, in *Land Technik AgEng 2013*2013: VDI-Verlag, Dusseldorf, Hannover. p. 47-53.
41. Salter, A.J. and B.R. Martin, *The economic benefits of publicly funded basic research: a critical review.* Research Policy, 2001. **30**: p. 509-532.
42. Alston, R., P.G. Pardey, and V.W. Ruttan. *Research Lags Revisited: Concepts and Evidence from U.S. Agriculture*. Staff Paper 2008 [cited 2015 25 March]; Available from: http://purl.umn.edu/50091.

43. *Rural Research and Development Corporations. Productivity Commission Inquiry Report No 53, February 2011*. 2011 [cited 2015 25 March]; Available from: http://www.pc.gov.au/__data/assets/pdf_file/0006/109995/rural-research.pdf.
44. Dickson, J.W., D.J. Campbell, and R.M. Ritchie, *Zero and conventional traffic systems for potatoes in Scotland, 1987-1989.* Soil & Tillage Research, 1992. **24**(4): p. 397-419.

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