Hort Innovation

Final Report

A strategic approach to weed management for the Australian Vegetable Industry

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A strategic approach to weed management for the Australian Vegetable Industry (VG15070)

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Content

Summary

Weeds are a persistent problem for Australian vegetable producers, with significant impacts on crop profitability, yield, quality and management. There have been substantial advances in sustainable weed management in other industries in Australia in the last 20 years, but there has been little recent attention on developing such weed control techniques in vegetables. An earlier scoping study (Hort Innovation *Project VG13079: Weed Management for the Vegetable Industry - Scoping Study*) identified current weed control strategies and research needs, and the most common weeds (e.g. fat hen, wild radish, nutgrass). This project sought to improve weed management options and information available to Australia's vegetable growers, focusing on the following industry research, development & extension priorities.

Understanding weed seed banks. Soil samples were collected from vegetable farms in major production regions across Australia, and weed seeds counted by species at different depths in the soil profile. The composition, diversity and size of soil seed banks varied markedly depending on location, crop/s grown, weed species present, and the specific weed and crop management practices followed. However, heavy-seeding annual broadleaf weed seeds were predominant. Research into supplementary weed control methods also contributed to an improved understanding of how some of these priority weeds may be managed. Several cultural weed management practices were assessed to determine how they can be used to reduce weed seed banks.

Integrated weed management (IWM) guidelines for Australian vegetable producers. All project activities (literature review, industry consultation, field data collection, and field and pot trials) contributed to guidelines on IWM strategies for Australian vegetable production. These addressed weed impacts, IWM principles and practices, and detailed descriptions of weed control methods within IWM, including implementation, integration with other methods, and advantages and disadvantages.

Robust economic analysis of weed management costs. Detailed farm-level economic evaluations were completed on 19 vegetable farms in four states. Across the 19 farms evaluated, the weighted average reduction in operating profit due to weeds was found to be $2,090 per hectare. About two-thirds were due to weed control costs, and one third to revenue loss due to weeds. On almost all the case study farms, farm-level impacts of introducing an 'innovative' weed control practice was evaluated against the previous approach. The economic impact of introducing a new practice was positive in 11 cases, and negative in five cases.

Extension resources for weed management in vegetable production. The IWM guidelines developed during the project were summarised and published in Australia's first Vegetable Industry Weed Manual, to provide Australian vegetable growers with best practice weed management information, collated in one place. A key component of the larger Manual was translated into Vietnamese, Chinese and Khmer to ensure access to IWM resources in non-English speaking vegetable growing communities. Comprehensive IWM guidelines were published specific for the 11 priority weed species. Detailed farm case studies were completed to illustrate effective pathways to weed seed bank reduction using contrasting approaches. These materials as well as their key principles were promoted via industry communication channels and social media, and provide a lasting legacy of information to the vegetable industry.

Keywords

Integrated Weed Management; cultural weed management; weed seed bank; cover crops; hand weeding; economics; extension.

Introduction

Weeds are a persistent problem for many vegetable producers in Australia because of the favourable growing conditions, regular soil disturbance and the lack of registered herbicides able to selectively control broadleaf weeds in many broadleaf vegetable crops (e.g. cucurbits) and minor crops (e.g. parsley). Weeds reduce crop yield and quality, interfere with sowing and harvesting operations, and may act as hosts for pests and diseases, and therefore affect both productivity and profitability.

Progress has been made towards IWM in Australian broadacre grain and cotton crops in the last 20 years (Sindel 2000, Charles 2013, Preston 2019) but less so in vegetable production, despite limited earlier studies looking at experimental herbicides, organic mulches and brassica biofumigants (Henderson 2000, Macleod & al 2002), biodegradable mulches (Limpus 2012), and organic weed control methods (Kristiansen et al. 2007, Kristiansen et al. 2008). A gap analysis of IWM in field-grown vegetable crops found that the vast majority of producers were using "low or basic IWM" practices and that such producers considered that IWM practices related to organic production only (Thompson 2012). This finding is concerning given that the grains and cotton industries have demonstrated that IWM is key to the continuing productivity of conventional growers. The few producers who were using "high IWM" practices expressed support for investigating new IWM practices and technologies using research and development (R&D) funds, a perception shared by consultants and research/extension personnel (Thompson 2012). Chivers (2012) also highlighted the value of alternative weed management methods, recommending research on farming systems approaches to weed management (equivalent to IWM) and novel technologies such as thermal methods (e.g. steam, flame).

The Australian vegetable industry has recognised the need to better understand the impact of weeds on vegetable production, to identify and improve upon relevant 'best practice' IWM, and to deliver information on IWM to Australia's vegetable growers to improve industry-wide management of weeds. Project VG15070 represented a continuation of a series of projects funded by Hort Innovation in the last decade to address this issue, including *Project VG10048: Sustainable Broadleaf Weed Control in Cucurbit Crops* (Sindel et al. 2011, Coleman et al. 2015) and *Project VG13079: Weed Management for the Vegetable Industry - Scoping Study* (Kristiansen et al. 2014a).

The earlier study on cucurbits (VG10048) highlighted some common weed problems and management methods used by that sector of the vegetable industry. The second scoping study (VG13079) found that most farmers integrated a number of control methods (essentially using IWM), because no single technique alone would effectively manage weeds in the crop during the entire growing season. However, there was little systematic understanding of how to apply IWM principles in vegetable production.

Project VG15070 therefore sought to improve the vegetable industry's understanding of the burden of weeds and how to manage them most effectively, expanding the knowledge and resources available to vegetable growers to encourage and facilitate adoption of current best practice IWM. Working where possible with other Hort Innovation-funded projects and industry partners, a four and a half-year project was completed, focusing on several research and extension objectives:

1. Identifying strategies to optimise management of the most important weeds of vegetable production in Australia, and extending these strategies to the industry.
2. Quantifying the weed seed bank on Australian vegetable farms, and linking the quantity and species richness of weed seed present with IWM strategies.
3. Quantifying the extent to which a range of supplementary (non-herbicide) weed management practices may be introduced more widely into vegetable production to further enhance IWM.
4. Assessing the farm-level economic impact of weeds on vegetable production, including the dollar-impact of introducing a range of innovative weed management approaches into IWM strategies.
5. Developing and delivering a range of educational resources and events on IWM to improve uptake of best practice, including the first Vegetable Industry Weed Manual.

Methodology

Task 1: IWM in high priority weeds

Priority weeds were determined based on prevalence and impact in the Australian vegetable industry, as identified in Kristiansen et al. (2014a). Based on this work and preliminary consultation with the industry, 11 priority species were selected.

Detailed literature reviews were completed of each priority species, including relevant Australian and overseas literature and focusing on identification, ecology, impacts and management in a vegetable production/tillage context (Appendix 1.1).

Research into supplementary weed control methods (Appendices 3.1 to 3.8) also contributed to an improved understanding of how these significant weeds may be managed, using a variety of approaches other than (or in combination with) herbicides and fallow/bed formation tillage. Participation in a wide range of industry extension activities (e.g. field days, webinars), often in collaboration with VegNET staff and other RD&E agencies, provided valuable industry input and feedback on our findings and the information needs of vegetable farmers.

This information was collated into a series of extension outputs, in the form of a detailed weed management guide for each of the 11 priority weed species (Appendices 1.3 to 1.13).

Task 2: Seed bank management

Methods of paddock sampling and weed seed bank enumeration were identified in a search of relevant literature. This review covered soil sampling patterns in cultivated paddocks, replication and representative soil core depths; and viable weed seed counting methods, including seed emergence (counting germinating weed seed in watered trays) and seed extraction (extracting weed seeds from soil by sieving, and counting by species under a microscope). A UNE Masters candidate contributed a review paper to this topic as part of their research.

These reviews prescribed the methodology used to conduct a national baseline assessment of the weed seed bank, involving a sample of vegetable farms in each Australian State as well as the Northern Territory, and completed in 2017 and 2018 (Figure 1 and Figure 2). The resulting weed seed bank was assessed against current and recent paddock management practices on each farm where samples were collected. Specific details on the methodology are available in Appendices 2.1 to 2.3.

Figure 1. Collecting soil cores for weed seed bank enumeration, Cambridge, Tasmania, 2017.

Figure 2. Weed seed bank enumeration by germinating viable seed within soil samples, 2017.

Task 3: Supplementary weed management practices

Given the breadth of activities covered in the project under the umbrella of supplementary weed management practices, full methodologies are available in the appendices (Table 1).

Literature reviews were completed of the various supplementary weed management methods addressed by the project, to guide research activities and extension material development. In the case of practical research activities (field and pot trials) the literature reviews guided development of a method specific to each experiment.

Table 1. Appendices related to supplementary weed management practices included with this report.

Appendix	Topic
2.1, 3.1, 3.2 and 3.3	Cover crops – general principles and characteristics of common cover crop varieties, competitiveness with weeds, and experimental plan for cover crop field trials and glasshouse weed seed enumeration
3.1	Crop rotation – principles, effectiveness and different approaches
3.1 and 3.4	Hand weeding – principles and efficiencies, and experimental plan
3.1	Irrigation management – principles, and surface and sub-surface targeted irrigation
3.1	Crop orientation – principles, results of relevant trials, and implications for vegetable production
3.1	Tillage – implications for the weed seed bank
3.1	Robotic weeding – how it works and potential benefits
3.1	Thermal weed control (soil solarisation, steam weeding and flame weeding) – how it works, general approach, weed control effectiveness and limitations
3.5	Allelopathic potential of cover crops to reduce weed seed germination and to suppress weed growth
3.6	Organic herbicides – types of organic herbicides, efficacy and limitations, experimental design

Appendix	Topic
3.7	Plastic mulch management of nutgrass (*Cyperus rotundus*) –biology and control, benefits and limitations of plastic mulch, experimental design
3.8	Tillage management of pigweed (*Portulaca oleracea*) – biology, characteristics and control, effectiveness of tillage in weed management, experimental design

Task 4: Economics of weeds and their management

Although the economic impact of weeds on Australian vegetable production has previously been estimated at the national level (Sinden et al. 2004, McLeod 2018), information on the farm-level economic impacts of weeds in this industry is limited. Previous research suggests that vegetable farmers have difficulty in reliably estimating the economic impacts of weeds within their crops. This research also indicates that there is a variety of innovative weed control practices, which may have been recently developed or have potential for more widespread adoption as part of an Integrated Weed Management (IWM) program. These practices have not necessarily been widely adopted amongst Australian vegetable growers, and evidence of their farm-level economics is lacking.

The review of literature conducted for this activity also highlighted a 'collective action' dimension of farm-level weed control that arises from weed management, including adoption of innovative weed control practices on one property affecting weed populations on neighbouring properties. This dimension had been under-researched in respect of Australian vegetable production.

Given these knowledge gaps, the following research Objectives for Task 4 were identified:

1. evaluate the farm-level economic impacts of weeds in vegetable production;
2. evaluate the farm-level economic impacts of adopting innovative weed control practices in vegetable production; and
3. explore vegetable growers' perceptions of collective action problems in benefiting from innovative weed control practices.

A case study approach was followed in pursuing each of these research objectives. Each of the cases centred on a single crop grown within a particular vegetable growing property and region. The cases were drawn from New South Wales, Victoria, Tasmania and Western Australia, and were selected as far as possible to be suitable for data collection to address all three research objectives.

The method used to address Objective 1 was the *loss-expenditure approach* applied in previous national evaluations of the economic impacts of weeds in Australia. The method in pursuing Objective 2 involved the farm business management technique of *partial budgeting*. Data for Objective 3 was sourced by asking case-study growers who had adopted one or more innovative weed control practices three targeted questions, based on relevant previous research. Collection of data from each case study grower across all objectives was standardised by using a common interview schedule.

Further details on methodology are available in Appendix 4.1.

Task 5: Industry communication and extension

Digital resources were collected during field visits for research, including photos and video footage. Much of this content later provided a significant contribution to written and video-based extension resources, as well as documenting key research activities.

The project's online presence included a Facebook page , web page and Youtube video channel. These were used to promote field and research activities, forthcoming extension activities such as field days and webinars, and to make written and video extension resources and other publications available to the industry.

The content and format of the key extension output from the project, the Vegetable Industry Weed Manual (*Integrated Weed Management for the Australian vegetable industry*; Appendix 5.1) was developed through the following process:

Key findings and outputs from previous Hort Innovation-funded research, in particular the literature review and final report for VG13079 'Weed Management for the Australian Vegetable Industry' (Kristiansen et al. 2014b).

A new review of relevant literature on weed management practices not covered in previous industry-funded research, including supplementary weed management practices (Appendix 3.1), and IWM principles (Appendix 1.2).

A close review of similar industry-specific IWM manuals, notably the publications available to Australian broadacre grains and cotton producers (Charles 2013, Preston 2019).

Other notable IWM and related weed management extension materials or other publications identified via industry search (e.g. Henderson & Bishop 2000, DAFF 2010, DAFF 2012, DAFF 2013).

Key findings of research activities in Tasks 1-4, as determined to be relevant to industry extension.

Industry consultation (vegetable growers, agronomists, IDOs) on proposed table of contents as well as draft document.

This process sought to ensure that the Manual was closely aligned to industry requirements for IWM information, and met vegetable-industry specific IWM priorities. Other written extension outputs were developed following a similar review process.

The Manual was delivered in three parts to allow vegetable growers to refer to particular sections based on need:

- Part 1: The impact of weeds.
- Part 2: The principles.
- Part 3: Methods of integrated weed management in vegetable production.

An introduction was also produced to list all extension resources available as part of the project (Manual, case studies, priority weed species management guides).

Part 2 of the Vegetable Industry Weed Manual 'The principles' (Appendix 5.1) was selected for translation into languages other than English to ensure a wider reach of the key extension messages regarding adoption of IWM principles amongst Australia's English as a second language (ESL) vegetable grower communities. We consulted with the VegNET IDO team to determine that this document should be translated into Vietnamese, Chinese, and Khmer to maximise its impact amongst ESL vegetable grower communities:

- Vietnamese-Australian vegetable growing communities with a significant number of ESL speakers in SA, WA, NT and Qld.
- Chinese-Australian vegetable growing communities with a significant number of ESL speakers in NSW and SA.
- Cambodian (Khmer)-Australian vegetable growing communities in NSW and NT.

Translated IWM materials are provided as Appendix 5.2.

The project team was fortunate to have access to the Hort Innovation-funded VegNET IDO network. Regional-based IDOs were an invaluable resource to research and extension activities, frequently called on to arrange local meetings and presentations, provide local expertise, facilitate contact with local vegetable growers and other experts to participate in data collection or project trials, communicate project outputs, and provide feedback on draft extension materials. Our experience has been that regional IDOs add significant value to research projects by facilitating appropriate engagement of researchers with the vegetable industry.

Articles were prepared for publication in industry magazines to disseminate preliminary findings and their implications to industry, notably on the cover crop trials carried out as part of Task 3, and the main findings of the economics study (Task 4). See Appendices 5.6 to 5.15.

Project findings as well as IWM principles were also promoted through participation in the SoilWealth and Integrated Crop Protection seminar series.

Outputs

Project outputs anticipated at the commencement of the project were listed in the project monitoring plan (Table 4 of the Monitoring and Evaluation Plan, submitted with MS102 in January, 2017). Each of these are listed below, as well as additional outputs that were produced during the course of the project.

Start and end of project communications – 4 outputs produced

Media Release – November 2016.

Re-engagement with VG13079 industry stakeholders (growers, agronomists, extension staff) – November/December 2016.

Regional stakeholder feedback meetings (see Milestone Report MS104) – January-December 2017 (Figure 3).

Post to be made on project Facebook page, advising of project completion – May-June 2021 (planned).

Figure 3. Grower meeting Mt Barker, South Australia, May 2017.

Vegetable Industry Weed Manual – 7 outputs produced

The Manual, 'Integrated weed management for the Australian vegetable industry' was published in several Parts (compiled together as Appendix 5.1 and Appendix 5.2).

- Introduction (Appendix 5.1).
- Part 1: The impact of weeds (Appendix 5.1).
- Part 2: The principles (Appendix 5.1).
- Part 3: Methods of integrated weed management in vegetable production (Appendix 5.1).
- Translations of '*Part 2: The principles*' into Khmer, Chinese and Vietnamese (Appendix 5.2).

IWM packages for high priority weeds – 11 outputs produced

High priority weed management packages were made freely available on the project web site, but also promoted via social media and relevant industry communications channels and networks.

- Amaranth (*Amaranthus* spp.); Appendix 1.3 – May 2021.
- Blackberry nightshade (*Solanum nigrum*); Appendix 1.4 – February 2020.
- Chickweed (*Stellaria media*); Appendix 1.5 – May 2021.
- Common sowthistle (*Sonchus oleraceus*); Appendix 1.6 – May 2021.
- Dwarf nettle (*Urtica urens*); Appendix 1.7 – July 2018.
- Fat hen (*Chenopodium album*); Appendix 1.8 – February 2018.
- Marshmallow (*Malva parviflora*); Appendix 1.9 – August 2019.
- Nutgrass (*Cyperus rotundus*); Appendix 1.10 – September 2018.
- Pigweed (*Portulaca oleracea*); Appendix 1.11 – February 2019.
- Potato weed (*Galinsoga parviflora*); Appendix 1.12 – May 2021.
- Wild radish (*Raphanus raphanistrum*); Appendix 1.13 – January 2021.

Project web presence – 3 outputs produced

- Project web page – November 2016.
- Facebook page* – November 2016.
- Youtube channel – April 2018.

* The number of Facebook followers was initially reported at 65 in Milestone Report MS105 (August 2018). As the frequency and variety of posts grew, so too did the reach of the page. By August 2020 (MS109) the page had 259 followers. At the time of writing (17/5/21) the page had 455 followers.

Case studies: video and fact sheet – 9 outputs produced

Videos

- *Diligent hand weeding and pre-planting herbicides*. The Loose Leaf Lettuce Company, Gingin, WA – July 2019 (509 views*).
- *Innovation in Integrated Weed Management*. Schreurs & Sons, Clyde, Vic – November 2019 (491 views*).
- *Managing weed seed banks using stale seed beds and inter-row cultivation*. Schreurs & Sons, Clyde, Vic – November 2019 (184 views*).
- Implications of summer cover cropping for weed management
- *Part 1: practical perspectives on cover crop varieties with Mario Muscat*. Greater Local Land Services, Richmond, NSW – July 2020 (131 views*).
- *Part 2: delivering information to the industry with Peter Conasch*. Greater Local Land Services, Richmond, NSW – July 2020 (53 views*).
- *Implications of winter cover cropping for weed management*. Ivankovich Farms and David Grays Aglink, Myalup, WA – August 2020 (244 views*).

* Number of video views as at 10/5/21.

Fact sheets

- Effective Integrated Weed Management – Case Study. Diligent hand weeding ultimately pays off. The Loose Leaf Lettuce Company, Gingin, WA; Appendix 1.14 – January 2020.
- Effective Integrated Weed Management – Case Study. Managing weed seed banks through stale seed beds and inter-row cultivation. Schreurs & Sons, Clyde, Vic; Appendix 1.15 – March 2020.
- Nutgrass (*Cyperus rotundus*) – Management considerations using plastic mulch. Research Note; Appendix 1.16 – February 2019.

Industry newsletter articles – 10 outputs produced

- 2017. Developing a strategic approach to managing weeds. *Vegetables Australia*, May/June, pp. 36-37. Appendix 5.6.
- 2018. On-farm trial. Weed management effectiveness through winter cover cropping. *WA Grower*, Winter, pp. 22-23. Appendix 5.7.
- 2018. Managing weeds using cover crops – Forthside Trial Update. *VegNET Tasmania Monthly Update*, October. Appendix 5.8.
- 2018. Managing weeds through winter cover cropping: results from year 1 of Myalup trial. *WA Grower*, Summer, pp. 16-18. Appendix 5.9.
- 2019. Winter cover crop effects on weeds: results from Tas and WA trials. *Vegetables Australia*, January/February, pp. 16-17. Appendix 5.10.
- 2019. Managing important weed species on Australian vegetable farms. *WA Grower*, Winter, pp. 24-26. Appendix 5.11.
- 2020. R&D Investment Spotlight on 'A strategic approach to weed management for the Australian vegetable industry'. *Growing Veg Businesses – January 2020*. Appendix 5.12.
- 2020. Assessing the economic impact of weeds in Australian vegetable production. *Vegetables Australia*, Autumn, pp. 40-41. Appendix 5.13.
- 2020. Diligent hand weeding ultimately pays off. *WA Grower*, Autumn, pp. 18-19. Appendix 5.14.
- 2020. What do weeds cost Australian vegetable growers? *WA Grower*, Winter, p. 17. Appendix 5.15.

Webinars and other videos – 7 outputs produced

Webinars

- *Integrated Weed Management for the Australian Vegetable Industry* – September 2016 (36 attendees, 649 Youtube views*).
- *Integrated Weed Management (Part 1): A practical approach for vegetable growers* – November 2020 (49 attendees, 140 Youtube views*).
- *Integrated Weed Management (Part 2): How cover cropping can improve IWM for vegetable growers* – December 2020 (21 attendees, 127 Youtube views*).
- *Integrated Weed Management (Part 3): The future of integrated weed management in vegetable farming* – February 2021 (42 attendees, 158 Youtube views*).

* Number of video views as at 10/5/21.

Other videos

- *VG15070 Cover crop trial, Myalup Western Australia, April 2018* – April 2018 (535 views*).
- *VG15070 Cover crop trial, Myalup Western Australia, April 2018. Preliminary Results* – September 2018 (123 views*).
- *A strategic approach to weed management for the Australian Vegetable Industry* – September 2019 (72 views*).

* Number of video views as at 10/5/21.

Other publications – 1 output produced

- 2020. Cover crops for Australian vegetable growers. Published as part of Hort Innovation-funded *Project VG16068 – Optimising cover cropping for the Australian vegetable industry*, with contributions regarding weed management from the VG15070 team.

Field days – 4 outputs produced

- *October 2018, Forthside, Tasmania*. Presentation of cover crop preliminary results from Tas, WA and NSW at the Tasmanian Institute of Agriculture Forthside Vegetable Research Facility Open Day. Approximately 40 attendees. More details available in Milestone Report MS106.
- *February 2019, Devon Meadows, Victoria*. Presentation on 'Integrated management options for nutgrass (*Cyperus rotundus*)' at a nutgrass management workshop hosted by RMCG and VegNET Victoria. There were 23 attendees.
- *June 2019, Myalup, Western Australia*. Field day at Ivankovich Farms, Mylaup, site of a project winter cover crop trial (Figure 4), on 'Cover cropping: implications for weed management'. Presentation of preliminary results from WA, Tas and NSW cover crop trials, and a presentation by Mr Marc Hinderager (AHR) on cover crop agronomy. Approximately 35 attendees. More details available in Milestone Report MS107.
- *October 2019, Richmond, New South Wales*. Field presentation of cover crop preliminary results from NSW, Tas and WA at the Greater Sydney Local Land Services-hosted event 'Putting R&D Into Practice Farm Walk and Talk', Richmond Lowlands demonstration farm. Approximately 30 attendees. More details available in Milestone Report MS108.

An additional field day was planned for Gatton, Qld in 2020, but plans were cancelled due to COVID-19.

Figure 4. Field day, Myalup, Western Australia, 20 June 2019.

Milestone reports – 8 outputs produced

- MS102 – February 2017.
- MS103 – August 2017.
- MS104 – February 2018.
- MS105 – August 2018*.
- MS106 – February 2019.
- MS107 – August 2019.
- MS108 – February 2020.
- MS109 – August 2020.

* A mid-term project review, originally scheduled for completion alongside MS105, was deemed unnecessary following consultation with Hort Innovation.

Outcomes

The project sought to address the following end-of-project outcomes[1]:

- Improved ability to manage high priority weeds.
- Improved ability to manage weed seed banks.
- Improved implementation of supplementary weed management methods.
- Increased profitability of vegetable farms through improved weed management efficiency and reduced risk.
- Improved awareness, extension and adoption of IWM practices in the vegetable industry
- Greater awareness and adoption of IWM strategies within the industry.
- Improved extension capacity and resources for IWM in vegetable production.

Outcome 1: Improved management of high priority weeds

Eleven 'high priority' weed species were chosen as a focus for this project (Figure 5). These species were chosen given their prevalence and impact within the Australian vegetable industry, as identified in the project VG13079 (Kristiansen et al. 2014b) and via early consultation with industry stakeholders for this project.

Figure 5. Fat hen (Chenopodium album) is an example of the rapid-growing and heavily-seeding annual broadleaf weeds commonly found on Australian vegetable farms, and is one of the industry's most important weeds.

Detailed literature reviews were completed to collate existing knowledge regarding the ecology, impacts and management of each species (Appendix 1.1).

Interaction of the priority weed species *C. album* with cover crop varieties was explored in two separate postgraduate student projects at UNE. These included assessing the effect of cover crops on the growth and reproduction of *C. album* emerging at different times in relation to cover crop emergence (Appendix 3.3) and evaluating the performance of aqueous extract of cover crops at different levels of concentration in reducing the germinable proportion of *C. album* seed, and suppressing *C. album* germination and early growth (Appendix 3.5). The grass weed

[1] Listed in Table 4 of the VG15070 M&E plan (submitted with Milestone Report MS102 in February 2017).

species annual ryegrass (*Lolium rigidum*) was also included to explore the effects of cover crops on grass weeds. The management principles identified in these studies are likely to be equally relevant to the other heavily seeding annual broadleaf and grass weed species comprising most of the high priority weeds explored in this project.

Management of *C. album*, *C. rotundus* and *P. oleracea* was explored by UNE Masters candidate projects, discussed in more detail in 'Outcome 3: Improved weed management'.

Management of all priority weed species was indirectly explored through other cultural weed management field trials and experiments completed during the project, including cover crop field and pot trials (Appendices 3.2, 3.3 and 3.5), and hand weeding implement comparative field trials (Appendix 3.4). These projects are also discussed in more detail in 'Outcome 3: Improved weed management'. Literature reviews were completed of a range of other cultural practices (Appendix 3.1). In each case, the general principles of weed management identified through these activities apply to high priority weed species as they do to other weed species of vegetable crops, for example weed suppression through cover crop competition, timing of weed control activity, and management of the weed seed bank (see also Task 2).

Compiling the key findings of the activities listed above, detailed IWM brochures were produced for each of the 11 high priority species (Appendices 1.3 to 1.13). These materials will make a significant ongoing contribution to integrated management of high priority weeds of Australian vegetable production beyond the life of the project, detailing IWM principles and strategies for implementation. Various other relevant outputs (such as the Vegetable Industry Weed Manual, case studies) will also have a significant role to play beyond the life of the project.

Evaluation of research activities and extension materials included regular feedback from vegetable growers, agronomists, and extension professionals. This was carried out to ensure relevance and value of the activities and outputs.

Outcome 2: Improved management of weed seed banks

Effective weed seed bank management is a cornerstone of effective IWM in vegetable production, as gradual depletion of the weed seed bank is directly linked to gradual reduction in weed competition with vegetable crops. No single approach to IWM in order to deplete the weed seed bank is applicable across the industry, given the large variety of crops grown, growing regions, and grower and farm circumstances.

Baseline data on weed seed banks

New knowledge on the characteristics of the weed seed banks of Australian vegetable farms was developed through collection and analysis of baseline weed seed bank data from several vegetable growing regions nationally.

The methodology for weed seed bank data collection and assessment was based on reviews of literature (Appendix 2.1 and Appendix 2.2), with the seed bank data explored in relation to crop and farm management history (Appendix 2.3).

A survey was carried out across seven vegetable growing regions in Australia. Soil samples were collected from 36 vegetable farms to a depth of 20 cm. Weed seeds for each sample were counted and identified to species or genus level. Effect of paddock management practices on abundance and species richness of the weeds in soil seed banks were analysed.

A total of 63 weed species were recorded in the weed seed banks, dominated by annual species (28 species). *Portulaca oleracea* was the most widely distributed species occurring in 20 out of 36 survey sites while *Eleusine indica* had the highest average abundance (11,878 seeds/m^2). *Oldenlandia corymbosa* L. had the highest average abundance (16,342 seeds m^{-2}) has only occurred at one location in NT. The average size of seed bank to a depth of 20 cm across the farms was 9,727 seeds/m^2, while average species richness (number of weed species present per site) was 6.58 ± 0.51 species. Weed diversity was found to be highest in the deepest (10–20 cm) soil layer.

The research showed that within the same general cropping system (vegetable production in Australia), the composition, diversity and size of soil seed banks varied markedly depending on location, crop/s grown, weed species present, and the specific weed and crop management practices followed. However, there was a general similarity in the characteristics of species present in the weed seed bank of vegetable cropping, being heavy-seeding broadleaf weed species that can be difficult to manage within most vegetable crops, as well as heavy seeding grass weed species.

Farm sites where a fallow period had been included in the current cropping season had the largest seed bank size (40,611 seeds/m^2), suggesting that diligent management during the fallow to restrict weeds from producing seed is critical to longer-term reduction in the weed seed bank. Such management may include cover crops, herbicides or tillage, steam or flame weeding, or employment of stale or false seed beds in crop beds formed during the fallow in preparation for planting the next crop. Other paddock management practices did not significantly affect the abundance or species richness of weeds in the seed bank.

Using a similar methodology, the weed seed banks associated with different fallow cover crop treatments were quantified across four cover crop sites nationally over two growing seasons. This research activity is discussed in more detail in 'Outcome 3: Improved weed management using supplementary methods' (see also Appendix 3.2).

Effective management of the weed seed bank

Detailed case studies (Figure 6) demonstrated the effectiveness of applying different approaches to IWM, under different circumstances, with the same goal of reducing the weed seed bank. These illustrate that diligent application of IWM practices, and willingness to innovate, has allowed vegetable growers to reduce the weed seed bank over time in ways that may be applied to most Australian vegetable farms.

Figure 6. Carl Larsen (RM Consulting Group) and Adam Schreurs (Schreurs & Sons, Clyde, Victoria) participated in a case study on the process of on-farm innovation, and more specifically on the introduction of stale seed beds and inter-row tillage to improve weed management.

The economic value of applying these and other IWM practices diligently and effectively was also quantified, and found to be profitable in the longer-term (Appendix 4.1). The various project research outputs and case studies also provided useful examples of weed management to add greater depth to the Vegetable Industry Weed Manual (Appendix 5.1).

These research outputs and extension materials leave a legacy of new information to vegetable growers, linking particular IWM practices in different crops to more (or less) effective management of the weed seed bank.

Outcome 3: Improved weed management using supplementary methods

The project sought to improve understanding of a variety of supplementary weed management practices, including how they are best implemented to maximise effectiveness in suppressing weeds either in the crop fallow, or within growing cash crops. Supplementary methods explored included green manure and biofumigant cover crops, hand weeding, crop rotation, irrigation, and crop orientation.

Reviews of the literature were completed on several supplementary weed management approaches and emerging technologies, with a focus on vegetable-specific literature where available (Appendix 3.1). Topics included cover crops; crop rotation; irrigation management; crop row orientation; hand weeding; tillage; robotic weeding; and thermal weed control. This review provided a more detailed update to information collated in precursor project VG13079, and contributed to the content of extension materials, notably the Vegetable Industry Weed Manual (Appendix 5.1).

Evaluating cover crop suppression of weeds

Four regional trials were completed to explore the implications of growing different cover crop varieties during non-cash crop fallow periods on the weed seed bank and weed burden in subsequent vegetable crops (Figure 7). A range of grass, legume and brassica cover crop varieties were trialled. Two summer cover crop trials (Gatton, Qld and Richmond, NSW) were complemented by two winter cover crop trials in Forthside, Tasmania, and Myalup, WA (Appendix 3.2).

Cool and warm season cover crop treatments, as well as sowing rates, were selected based on industry recommendations. Measurements taken across two cover crop rotations, and subsequent cash crops, included cover crop canopy cover, counts of weeds by species, biomass of weeds and cover crop, and the quantifying the soil weed seed bank for all treatments by weed species, at different depths of the soil profile.

The field trials were complemented by a review of literature on the agronomy of various cover crops that may be suitable to Australian vegetable growers, which incorporated where possible a summary of the key factors influencing their relative capacity to suppress weeds (see Appendix 3.1).

Figure 7. Cover crop biomass sample collection, Myalup, Western Australia, 2019.

Cover crops are planted by vegetable growers as a strategy primarily to improve soil health. However in this study, it was demonstrated that cover crops can be used to simultaneously suppress weeds and to reduce the soil weed seed bank. Vigorous cover crops appear to achieve this by allowing weeds to germinate, but then preventing them from establishing and setting seed through competition. The mechanisms that underpin this include:

- high biomass production by the cover crops,
- establishing a dense canopy cover,
- rapid germination and early growth,
- competition with weeds for resources, including water, nutrients and light,
- selecting varieties that suit the season, soil type and climate, and
- implementing suitable farming practices to ensure good cover crop growth.

It should be noted, however, that these general mechanisms may not always reflect the nuances of a particular site or cover crop. Based on this research and field observation, we therefore suggest the following key principles for effective and targeted weed suppression and for reducing the soil weed seed bank.

1. Plant cover crop varieties to suit the season, that are vigorous, and that can achieve a dry weight biomass of approximately 3 t/ha.
2. Choose a variety suited to the cash crop rotation, for example a brassica cover crop variety may not suited where a brassica cash crop is being planted next, due to the risk of disease carryover.
3. Cover crops require water and nutrients to maximise their performance and benefits in weed suppression. Ensure a vigorous cover crop through good crop agronomy, by providing the cover crop with similar resources and management as a cash crop, including during cover crop establishment.
4. Plant varieties that target the most important weed problems. For example, competitive cool season cover crops can help with winter weeds, and vice versa for summer.
5. Aim for good canopy cover and light exclusion early in the cover crop rotation, or if this is not possible aim for light exclusion before weeds establish and mature. Selecting a suitable sowing rate is important.
6. Terminate cover crops before they set seed and become volunteer weeds in subsequent cash crops.
7. In a bad year, cover crops may not establish well, and hence be ineffective at weed suppression. In this case, if weeds are a priority, other options are worth considering such as a bare fallow or stale/false seed bed.
8. A bare fallow encouraging weed growth but terminated and incorporated before weeds set seed can be effective at reducing the weed seed bank.

Evaluating the role of cover crop emergence time on weed suppression

The relative timing of weed emergence and the interaction of crop–weed competitive traits can determine the efficacy of cover crops as a weed control strategy. We sought to assess the effect of cover crops on the growth and reproduction of weeds emerging at different times in relation to cover crop emergence (Figure 8; Appendix 3.3). A factorial glasshouse experiment with three weed emergence times (BEFORE, WITH, AFTER cover crop emergence), two weeds (fat hen, *C. album* and annual ryegrass, *L. rigidum*), and three cover crop treatments (Nemat, *Eruca sativa*; cereal rye, *Secale cereale*; and no cover crop) was conducted. Plant height, tillers, biomass and weed seed production, and light reduction were measured.

E. sativa reduced weed height and shoot biomass (~90%) more than *S. cereale* (~30%), and only in the AFTER treatment. *C. album* seed production was also reduced by *E. sativa* for AFTER emergence (~70%). *E. sativa* and *C. album's* traits (rapid growth rate, spreading habit, broad leaves) were more competitive than *S. cereale* and *L. rigidum* (clumping habit, lower stature). The study confirmed the need for timely weed control prior to planting cover crops. This will reduce weed growth and reproduction in the short term and decrease additions to the weed seed bank, providing potential longer-term benefits. The selection of appropriate cover crop species depends on the type of weeds and ensuring rapid emergence of cover crop in weed-free fields are important for integrated weed management through cover cropping.

Figure 8. Pot trial to evaluate the ability of cover crop varieties to compete with weeds of vegetable crops.

Evaluating the biofumigant effects of cover crops on weed germination and growth

A related UNE Masters candidate project was completed to evaluate the performance of aqueous extract at different levels of concentration from *E. sativa* and *S. cereale* in reducing the proportion of germinable *C. album* and *L. rigidum* seed in a replicated petri dish trial, and in suppressing germination and early growth of these weed species through regular application of the extract in a replicated pot trial (Appendix 3.5).

The results showed that *S. cereale* and *E. sativa* both possessed allelopathic potential. The germination of both weeds was impacted greatly under the influence of aqueous extracts of both cover crop varieties, however the germination reduction was greater in *L. rigidum* seed as compared to *C. album* seed.

The pot trial showed that the level of concentration of extracts significantly affected the shoot and root biomass of *L. rigidum* while there was no significant effect of the extracts on *C. album* growth. However, application of cover crop extracts affected the growth of weeds *positively*, i.e. the application of aqueous extracts of both cover crop species resulted in the increase in shoot and root biomass of the weed species, especially of *L. rigidum*.

The unexpected pot trial result was attributed to the fact that the cover crop extracts acted as a fertiliser, and consequently with the increase in concentration the weeds also contributed to good weed growth. Allelopathic potential of cover crops is likely to be affected by soil make up and soil microbial activities.

In the field, the leachates and decomposing biomass from cover crop species may be more likely to act as a green manure than a biofumigant in the field. Weed suppression from biofumigant cover crops may be attributable to rapid ground cover establishment of cover crops in weed-free fields, and direct suppression of subsequently germinating weeds through competition, supporting the results of the study detailed in Appendix 3.3.

Evaluating hand weeding implement effectiveness, efficiency and ergonomics

A field trial was completed on University of New England rural properties to evaluate the agronomic, ergonomic and economic performance of different hand weeding tools (Figure 9; Appendix 3.4). We conducted a multifactorial experiment comprising two sites (Loam and Clay), two weed ages (Early and Late), four hand weeding tools (chipping hoe, stirrup hoe, rotary cultivator and a stirrup + tine tool) and unweeded control. All treatment combinations including the unweeded control were replicated three times. Agronomic efficiency was evaluated based on the reduction in weed load from pre-weeding to 3 and 10 days after weeding, economic efficiency based on time taken to weed, and ergonomic efficiency based on heart rate and energy expenditure of the weeder.

Among the tools, the chipping hoe provided higher weed control efficiency than the rotating hoe and combined tool, and showed a lower average heart rate and work load than the combined tool. This suggested that the light weight chipping hoe provides better weed control while also reducing the work load of weeding staff than heavier tools. Tools did not differ in their economic performance but weed age was related to economic performance, with a nearly 50% higher cost being associated with late weeding. The experiment suggested that a successful hand weeding strategy requires information on the holistic performance (agronomic, ergonomic and economic) of hand weeding tools.

Figure 9. Field trial to evaluate different hand weeding implements, Armidale, NSW, 2019.

Evaluating supplementary weed management methods

Several other UNE Masters candidates addressed the issue of supplementary management of weeds in vegetable production systems through their research projects.

One evaluated the performance of different organic herbicide options (eucalyptus oil, vinegar, and salt) in suppressing germination of *C. album*. Considerable suppression of weed seed was obtained using both vinegar and eucalyptus oil, but only moderate control of growing plants (particularly at early growth stages), contrasted with the conventional herbicide glyphosate (Appendix 3.6).

Another evaluated black, translucent and clear polyethylene mulch films for their ability to manage *C. rotundus* in a replicated pot trial. Under black film, *C. rotundus* plants were found to produce fewer leaves than under clear or translucent films of different colours, though in field conditions *C. rotundus* remains highly capable of piercing black plastic film. Under clear and translucent films, *C. rotundus* leaves became relatively soft and unable to pierce the film layer, potentially due to higher temperature. Tuber production was also somewhat lower under clear and translucent film (Appendices 1.16 and 3.7).

A third carried out a pot trial to determine the effect of tillage on different life stages of *P. oleracea*, three, six and eight weeks post-germination, and in two soil types (clay and sandy). The study confirmed the benefits of tilling *P. oleracea* seedlings soon after their emergence, finding that they were more vulnerable to damage and less able to recover and re-grow. Reduction in plant cover, plant count, leaf number and biomass was found to be higher in young seedlings (three weeks post-germination), followed by medium seedlings (six weeks post-germination; Appendix 3.8).

Outcome 4: Increased vegetable farm profitability through improved weed management

The report 'Economics of weeds and their management' (Appendix 4.1) includes a detailed evaluation of 19 vegetable farms in NSW, Tas, Vic and WA. This was the first time in which the cost of weeds at the individual vegetable crop level has been explored in Australia.

Across the 19 farms evaluated, the weighted average reduction in operating profit due to weeds was found to be $2,090 per hectare. This was comprised of $1,403 per hectare net costs due to weeds, and $687 per hectare revenue lost due to weeds. The figure was approximately 6 times higher on organic farms, where herbicide is not available and growers must rely on more labour-intensive alternatives.

On 16 of the 19 case study farms, farm-level impacts of introducing an 'innovative' weed control practice was evaluated against the previous approach. 'Innovations' included fallow cover cropping (biofumigant and non-biofumigant), diligent hand weeding to reduce the weed seed bank, thermal weed control, stale seed beds, and inter-row cultivation (Figure 10). The economic impact of introducing a new practice was positive in 11 cases, and negative in five cases. In four of the five negative cases, a range of non-weed control benefits were noted, but could not be valued in dollar terms.

Figure 10. Although it is not feasible to use in all vegetable crop species, inter-row cultivation can improve management of weeds within the growing crop.

Start-up costs of innovation were often high (for example, purchasing specialised inter-row tillage or thermal weed control equipment, or heavy upfront investment in hand weeding to reduce weed seed set within crops), however these investments tended to pay for themselves over time as the weed burden reduced. A clear link between effective IWM strategies and increased vegetable farm profitability has therefore been demonstrated, and it is hoped that this information helps to encourage greater uptake of IWM, with a focus on positive innovation, by more vegetable growers in Australia.

Outcome 5: Awareness, extension and adoption of IWM practices in the vegetable industry

Outcome 5(a) improved awareness of IWM principles and practices in vegetable production

Integrated weed management (IWM) has been defined as 'a sustainable management system that combines all appropriate weed control options' (Sindel 2000). The most suitable IWM approach will depend on crop, climate, weed type/s and extent of burden, and resources available to the grower (time, staff and money). Philosophy towards weeds and towards farm management, and weed management objectives, will also determine the type and mix of weed control methods adopted, as well as level of diligence in application.

Increasing awareness and adoption of Medium or High IWM practices (a focused, planned and diligently implemented IWM strategy involving a range of mutually supportive and appropriately timed methods) has been shown by the economic impact study to provide longer-term economic benefits in many cases at the farm level.

A review of literature was completed to summarise the key objectives and principles of IWM, reasons to adopt an IWM approach and barriers to adoption, and how it can improve management of weeds within vegetable crops (Appendix 1.2). This review contributed towards the content and messages of project extension, discussed below.

Outcome 5(b) delivering extension of IWM principles and practices to the vegetable industry

Previous unpublished research (Thompson 2012) proposed a continuum of IWM. The research indicated that the majority of vegetable growers were using 'Low or Basic IWM', comprising a relatively limited set of fallow and pre-plant weed management practices such as herbicide, tillage and stale seed beds, as well as reactive practices in response to germinating weeds within the crop (selective herbicides, inter-row cultivation, hand weeding). Relatively few vegetable growers were found to be using 'Medium IWM' or 'High IWM' strategies. These comprised the above basic approach as well as: more detailed weed monitoring and surveying; herbicide rotations; a variety of supplementary weed management practices such as crop rotation, cover cropping, farm biosecurity and hygiene; herbicide resistant-weed monitoring and control; management of weeds before seed set within and adjacent to the crop; and continual evaluation and adjustment of the IWM strategy to ensure ongoing effectiveness.

Increasing industry awareness of all available IWM practices and their relevance in different vegetable production contexts was a key objective of many of the extension events, multimedia resources and written materials produced by this project. Using the terminology established by Thompson (2012) the goal was to facilitate adoption of Medium to High IWM during and beyond the life of the project amongst a higher proportion of Australian vegetable growers, by encouraging vegetable growers to consider, trial and if relevant implement new approaches to weed management within their current IWM strategy. Relevant extension activities and materials included:

- The Vegetable Industry Weed Manual.
- The IWM packages for high priority weeds.
- Case studies of IWM and cover cropping.
- Industry newsletter articles.
- Webinars.
- Field day presentations.

The written and multimedia extension materials produced on IWM during this project provide a library of resources to industry extension and support staff (such as the VegNET project IDOs, private and government agronomists) as well as directly to vegetable growers. These materials may continue to be used in the longer term to encourage adoption of more complex but more effective, and ultimately more profitable, IWM approaches by a greater proportion of vegetable growers.

Monitoring and evaluation

Key Evaluation Questions (KEQs; Table 2) were developed to guide the more detailed project M&E Plan, and were based on the project objectives and methodology. The M&E Plan was submitted with Milestone Report MS102 in February, 2017. Outputs and outcomes that addressed each KEQ are discussed below.

Table 2. Key Evaluation Questions

Level/Domain	KEQs
1. Effectiveness	How well has the project delivered on its stated objectives to benefit growers, advisors and the industry?
	a. Has the project developed improved management strategies for high priority weeds in vegetable production?
	b. Has the project developed new information on the role of weed seed banks on vegetable farms, and integrated weed seed bank management into weed management strategies?
	c. Has the project evaluated the effectiveness of supplementary cultural weed management methods?
	d. Has the project developed on-farm cost-benefit analysis data relating to weed management strategies?
	e. Has the project developed appropriate extension materials to deliver best practice integrated weed management material to growers, including existing techniques and those developed further during the research?
2. Relevance	How relevant are the project outcomes to growers, advisors and the industry?
3. Process Appropriateness	a. Has the project engaged growers, advisors, researchers and other industry stakeholders appropriately in the undertaking the research, development and extension activities?
	b. Has the project engaged appropriately with the intended beneficiaries of the activities to deliver the research and extension outcomes, including growers, advisors, researchers and other industry stakeholders?
	c. Have relevant methodologies been used for data collection and experimentation?
4. Efficiency	Have the weed management techniques developed during the project been shown to improve efficiency and cost-effectiveness for farmers, based on the trial activities and economic analysis undertaken for the project?

1. Effectiveness in delivering on stated objectives to benefit the industry

1(a). Developing improved management strategies for high priority weeds

The project has successfully identified priority weeds of Australian vegetable crops, developing improved IWM strategies that are generally applicable to weeds of vegetable crops, with some approaches explored that are specific to particular priority weed species. IWM approaches specific to priority weed species have been extended to the Australian vegetable industry in a series of weed management fact sheets.

- Complete detailed reviews of existing literature on 11 priority weed species, selected for their confirmed importance to vegetable production in Australia, and their behavioural representativeness of other notable weeds of vegetable crops. In addition to generally applicable IWM principles, the literature review identified some aspects of management specific to each weed species, based on their particular ecology and behaviour (Appendix 1.1).

- Determine the capacity of cover crops to suppress the growth of the priority weed species *C. album* and the common grass weed species *L. rigidum*, including competitive suppression of growing plants as well as potential biofumigant effects (Appendix 3.3 and Appendix 3.5).
- Evaluating the performance of different organic herbicide options (eucalyptus oil, vinegar, and salt) in suppressing germination and growth of *C. album* (as part of a UNE Masters project, Appendix 3.6).
- Determine the most suitable plastic mulch films to use in reducing the rate of growth and reproduction of the priority weed species *C. rotundus* (as part of a UNE Masters project; Appendix 3.7).
- Determine the impact of tillage on different post-germination ages of *P. oleracea*, with results confirming that tillage is most successful (in terms of damage to the plants and reduced potential for recovery and re-growth) sooner after emergence (as part of a UNE Masters project; Appendix 3.8).

Based on the resources above, information on best practice IWM for each priority weed species was published as a series of fact sheets (Appendices 1.3 to 1.13)

1(b). Developing new information on the role and integrated management of weed seed banks on vegetable farms

Data compiled during the project has led to an improved understanding of the nature and composition of weed seed banks of vegetable farms in different parts of Australia, and linked these to above-ground weed biomass, particular crops and differing approaches to IWM (Appendix 2.3).

Complete a review of literature to determine the most appropriate method of weed seed bank assessment in cultivated cropping (Appendices 2.1 and 2.2).

Collect soil samples from a number of farms in each of several key vegetable production regions across Australia to build a representative sample of the weed seed bank found on vegetable farms. Count the number of viable weed seed of different species found at different depths in the soil profile.

Collect detailed management information from each vegetable farm where soil samples were collected, to enable possible links between weed seed counts, species present and species diversity within the seed bank, and management practices to be identified.

Complete analysis that related the weed seed banks of each sample farm at different depth profiles with surface-level weed biomass, weed counts, crop/s grown, IWM approach, soil and climate, and other relevant characteristics.

1(c). Evaluating the effectiveness of supplementary weed management methods

Earlier research identified supplementary weed management approaches worthy of further consideration as part of vegetable IWM (Kristiansen et al. 2014a). This project explored ways of improving and/or implementing these supplementary weed management methods as part of vegetable crop IWM to manage priority and other weed species through literature review and field and pot trials.

In some cases, new information regarding performance of alternative approaches was successfully developed as a result of pot and field trials. In other cases literature reviews were completed to summarise the current state of the art regarding a particular supplementary weed management method, and potential relevance and application to vegetable crops.

Supplementary methods explored during the project included:

- Green manure and biofumigant cover crops – field trials across several production zones for winter and summer cover crops, as well as pot trials.
- Hand weeding using various weeding implement options – field trials to explore efficiency, effectiveness and user-friendliness.

Literature reviews of:

- Crop rotation principles, including relevant factors, different approaches and their effectiveness.
- Irrigation management technologies and principles, including surface-level drip irrigation and sub-surface drip irrigation systems and their applicability.
- Crop row orientation principles, to maximise crop competitiveness with weeds.

- Tillage practices, including the effect of tillage frequency and depth on the weed seed bank.
- The emergent and rapidly evolving technology of robotic weeding systems, and its potential benefits to vegetable growers.
- Thermal weed control, including soil solarisation using plastic film, surface steam weeding and sub-surface steaming of the weed seed bank, and surface flame weeding.

1(d). Developing on-farm cost-benefit analysis data relating to weed management strategies

This project provided the first opportunity to develop detailed cost-benefit data related to weed management in vegetable crops (Appendix 4.1). Of particular relevance for encouraging the uptake of new approaches to more effective IWM, the case study approach taken towards economic evaluation allowed 'business as usual' IWM on a number of different vegetable farms to be contrasted with a modified approach, in which vegetable growers had chosen to introduce a new approach to manage weeds more successfully.

In most cases the vegetable growers participating in this study who had introduced an 'innovative' weed control practice into their IWM strategy achieved demonstrable improvements in the longer-term profitability of their crop. It is hoped that the case studies of successful IWM innovation highlighted in Appendix 4.1 encourage more vegetable growers to make positive changes to their overall weed management approach beyond the life of this project.

1(e). Developing appropriate extension materials to deliver best practice to the industry

Information developed during the research activities regarding priority weed species, weed seed banks, supplementary weed control methods, and the economics of weed management, were incorporated with existing information on weed management in vegetable crops (as well as related information from other similar agricultural sectors such as broadacre grains production) to deliver a variety of written and multimedia extension resources to the industry. This was the first time in which a comprehensive set of extension materials had been developed regarding IWM in Australian vegetable crops.

The aim of all extension materials and activities arising from the project was to provide the vegetable industry with information on current and sustainable best practice weed management, with a range of new information being made available to vegetable growers via the various field and pot trials carried out as part of the project. In addition to focusing on particular weed management practices or combinations of practices), the extension materials and activities emphasised the need for all vegetable growers to continually evaluate their current IWM approach, and to be willing to trial and adopt new approaches in response to emerging weed control challenges. As the project evolved, the team considered that an innovative mindset regarding weed management was just as important to vegetable growers as the mix and type of weed management methods available, in leading to successful control of weeds.

Messages regarding IWM practices, and IWM innovation were delivered effectively to the industry: by providing extension using a range of methods to maximise audience reach (fact sheets, case studies, videos, webinars, field day presentations); by utilising existing industry research, extension and outreach networks to reach vegetable growers; and by providing a library of useful resources to vegetable growers as well as extension professionals that will remain relevant beyond the life of the project.

2. Relevance of project outcomes to industry

Industry-funded research, development and extension must be relevant to end-users to ensure that investment in the RD&E activities is justifiable and provides a good return on investment. In the case of this project, end users of the project outcomes and outputs include vegetable growers, as well as industry extension professionals, other researchers in related areas, as well as private and government agronomists.

Over the course of the project, the project team sought to ensure that project outcomes and outputs would be relevant to this end user audience, and would therefore be most likely to encourage beneficial practice change. Literature reviews were completed in a number of areas across the project pertaining to research and extension, to ensure that outcomes as well as outputs took account of the latest information from relevant Australian and overseas research and extension.

Frequent consultation with industry (vegetable growers, agronomists, extension professionals, Hort Innovation) on many aspects of project activity. Further details on industry consultation are included below in '3(a). Engagement of industry stakeholders appropriately in completing project RD&E activities' and '3(b). Engagement of industry stakeholders appropriately in delivering project RD&E outcomes'.

3. Appropriateness of processes

3(a). Engagement of industry stakeholders appropriately in completing project RD&E activities

The project team engaged with vegetable growers, their advisors, other researchers and related Hort Innovation-funded projects and extension professionals in planning and completion of project activities.

Design of field and pot experiments, including relevance of design to 'real world' vegetable farm operating environment, to ensure that resulting data was applicable to vegetable farms. Relevant stakeholders assisting with this process included agronomists, other researchers for example those conducting field trials on cover crops, and vegetable growers.

Evaluating the suitability of particular cover crop varieties for winter and summer cover crop trials in discrete growing regions. For this aspect of the project, the team consulted closely with members of the VG16068 Soil Wealth and ICP team.

Evaluating the variety of hand weeding implements on offer, and their suitability for and likelihood of being used by vegetable growers and their staff. Advice was received from vegetable growers regarding which hand weeding implements were likely to be used on vegetable farms, and at what stage/s of weed and crop growth.

Identifying the most relevant vegetable growers to host field research, including willingness to take part, and capacity to manage field sites with minimal project team input where appropriate. In this regard, assistance from regional Industry Development Officers involved in the Hort Innovation-funded VegNET project was particularly beneficial.

Identifying the most relevant vegetable growers to participate in IWM extension, based on their experience with IWM, willingness to pass on their experience and learning, and capacity to pass these messages on in a way that other growers would find relevant. In particular, this involved identifying suitable vegetable growers to work with on case studies of effective IWM strategies, and again the VegNET team was particularly helpful in facilitating industry links.

3(b). Engagement of industry stakeholders appropriately in delivering project RD&E outcomes

Delivery of RD&E outcomes arising from the project involved the various activities and materials produced during this project, including extension materials and media items. Delivery of research and development outcomes involved packaging these into extension materials as well as field activities and webinars, with key results and messages passed on to industry in a relevant and usable format. Relevance of extension materials and activities benefited greatly from input of vegetable industry stakeholders across production, research and development, and extension.

Industry stakeholder engagement in field day delivery included: ensuring that topic and presentation format would provide attendees with relevant and useful information that they were then relatively likely to trial or adopt; and working together on field day logistics and planning. Partners included the Tasmanian Institute of Agriculture, vegetablesWA, and Greater Sydney Local Land Services.

When developing multimedia case studies of effective approaches to IWM, the team worked closely with vegetable growers (The Loose Leaf Lettuce Company and Ivankovich Farms in WA, and Schreurs & Sons in Vic), private and government agronomists (David Grays and Greater Sydney Local Land Services) and extension professionals (Greater Sydney Local Land Services, vegetablesWA and RM Consulting Group). The focus was on ensuring the case studies accurately reflected grower practice, and that the outcomes were relevant to the industry.

The project team sought to ensure that the topics, content and presentation style of written extension materials were likewise relevant to vegetable growers and their advisors, by engaging with various industry stakeholders. Feedback on draft Vegetable Industry Weed Manual 'tables of contents' as well as drafted material was sought from vegetable growers, extension professionals and agronomists across Australia, as well as from Hort Innovation and AUSVEG.

Delivery of published extension materials was carried out through project networks (e.g. social media), but further disseminated through regional grower groups and Industry Development Officers in each state and the Northern Territory. Availability of extension materials as well as the key messages they provided were promoted in industry newsletters and magazines (e.g. Appendix 5.11, Appendix 5.14). These established pathways were invaluable in maximising the reach of project outputs and messages.

3(c). Use of relevant methodologies for data collection and experimentation

In each case, the methodology for the various data collection activities as well as field and pot experiments carried out during the project was developed as a result of reviews of relevant literature, ensuring that the research approach was grounded in science and most likely to produce reliable and relevant data.

- Understanding the ecology and management of priority weeds of vegetable farms (Task 1, for more details see Appendix 1.1).
- Collecting baseline data on the weed seed bank of Australian vegetable production, including field data collection and weed seed enumeration (Task 2, for more details on methodology see Appendices 2.1 to 2.3).
- Field trial establishment, management and data collection for the cover crop trials (Task 3, for more details on methodology see Appendix 3.2).
- Cover crop and weed competition pot trial – method for pot trial establishment and management, and data collection and analysis (Task 3, for more details on methodology see Appendix 3.3).
- Hand weeding implement evaluation – selection of implements, field trial method and data collection and analysis (Task 3, for more details on methodology see Appendix 3.4).
- Economics of weeds and their management – method for case study data collection, analysis and interpretation (for literature review and more details on methodology see Appendix 4.1).

More information is available in the chapter 'Methodology', under Tasks 1 to 4.

4. Demonstrated effectiveness of weed management techniques

The various weed management techniques reviewed, evaluated or developed further during the course of the project offer demonstrable improvements to the efficiency and cost-effectiveness of IWM on Australian vegetable farms. The scale of the improvements available will depend on individual characteristics of vegetable farms, including farm size, crop/s grown, soil type, weed/s present and their prevalence, and grower experience and resources. Not all of the weed management techniques covered by the project will be relevant to all vegetable farms.

Cover crop suppression of weeds. The four field trials carried out during the project provided quantitative evidence of the relative capacity of different winter and summer cover crop varieties in suppressing weed germination, growth and seed production (Appendix 3.2). This activity provides vegetable growers with an evidence-based foundation for selecting and growing a cover crop during the fallow to manage weed populations, in addition to their other known benefits for soils and crop diseases.

Evaluation of hand weeding implements. Hand weeding is a mainstay of selective weed management once vegetable crops are growing, although it can be very expensive and must therefore be used judiciously. The hand weeding implement evaluation (Appendix 3.4) showed that a light-weight chipping hoe was the most effective and ergonomically efficient tool for hand weeding within growing vegetable crops, and that waiting until weeds are more mature before completing hand weeding will come at a significant cost to vegetable growers. In support of this finding, case studies and economic evaluation has suggested that diligent hand weeding to minimise weed seed set will cost more initially, but can eventually reap economic rewards. Vegetable growers will need to continue to rely on hand weeding, so these advances in our understanding of hand weeding efficiency and cost-effectiveness are useful in allowing growers to target this activity more strategically, and to derive greater efficiency from hand weeding.

Economics of innovative weed management practices. The assessment of innovative weed management practices (Appendix 4.1) found an improvement in whole farm operating profit of implementing a new weed control practices in 11 of the case study farms assessed, while in the remaining five cases whole farm operating profit was reduced. However, it was not possible to assign a dollar value to some of the benefits of the practices; for example, benefits for soil health, soil structure and disease management as a result of cover cropping. In. each of the case studies however, detailed information is available on how some of the weed control practices that were the focus of this project can not only reduce the weed burden, but also improve profitability of the farm. Profitability is a major motivator in farmer decisions to adopt new practices, and it is important to demonstrate that the weed control practices explored elsewhere in this project can improve farm profit while also reducing the weed burden.

Supplementary weed management practices. Some of the other weed management options available to Australian vegetable growers were not explored through field or pot trials in this project. However, the potential benefits of their use, as well as some limitations and drawbacks, were identified through literature review (Appendix 3.1). Adjustments to crop rotation, irrigation management, and crop orientation appear to have potential to contribute to successful IWM on vegetable farms, though their direct impacts on the weed burden are likely to be difficult to quantify. Thermal weed control options such as flame and steam weeding and soil solarisation have been available to the industry for some time, though their use appears to be mostly limited to organic production. Economic analysis of steam and

flame weeding conducted for this project did show, however, their potential to improve whole farm operating profit (Appendix 4.1). Robotic weeding technology is nearing commercial availability in Australia, and signs are promising that it will make a significant impact on IWM, reducing the weed burden and weed seed bank while increasing farm profitability – particularly as the technology becomes more affordable.

Recommendations

Here we present the research, development and extension (RD&E) priorities emerging from this project. These were identified by the researchers through an initial review of relevant literature which was periodically updated, discussions with industry stakeholders throughout Australia during the life of the project, and analysis of the results emerging from each of the research and outreach activities.

The following columns are included within the tables listed for each task.

- *Recommendation:* the priority issue to be addressed.
- *Importance to Industry:* to what extent the issue is desirable to farmers and other industry stakeholders.
- *Feasibility:* how practical it is to carry out the RD&E activity, and how likely it is to be adopted.

Task 1: IWM in high priority weeds

Following identification of priority weeds for the Australian vegetable industry in earlier research, this project has conducted a variety of field and glasshouse activities to determine approaches to improve management of selected priority weeds. This work, as well as reviews of relevant literature, has resulted in production of a series of weed management guides for priority species, now available to the industry.

It is important that industry extension and outreach networks continue to be utilised to make vegetable growers and their advisors available of these priority weed management guides, to help ensure that the current most important weeds of vegetable production are managed as effectively as possible.

Over time, other weed species are may become more significant for the vegetable industry, as they spread more widely or become increasingly difficult to manage. Ongoing monitoring of weed species present and their impact will allow the vegetable industry to be more responsive to emerging weed threats.

During this project, some of the vegetable growers we spoke to believed that particular herbicides were becoming less effective in managing certain weed species. However, herbicide resistance testing amongst weeds on vegetable farms was not a research focus for this project. Populations of certain priority species which were a focus of this project have already been reported as resistant to particular herbicides in other industries (addressed in Appendix 5.1).

This project has addressed the issue of herbicide resistance by promoting the message in the Vegetable Industry Weed Manual and other materials that effective IWM using a range of chemical and non-chemical weed management techniques together, rather than relying too heavily on a limited range of herbicides, can help to manage herbicide-resistant weed populations, and reduce the risk of other weeds developing resistance. This principle applies to all weed species and is a critical justification for implementing IWM.

Nonetheless, the industry may consider formal herbicide resistance surveying where herbicide resistance is suspected, to identify the extent of the issue for vegetable producers. This is particularly important given that many vegetable growers rely on a relatively limited range of registered products.

With respect to the issues of emerging priority weeds and herbicide resistance, the vegetable industry can continue to benefit from work being undertaken in broadacre cropping systems in Australia.

Table 3. Task 1 research, development and extension recommendations, ranked.

Recommendation	Importance to Industry	Feasibility
Ongoing extension of IWM principles and materials related to high priority weed species.	High	High
Continue to monitor high priority weeds, emerging problematic weeds, and adapt management practices as necessary.	High	Medium
Herbicide resistance surveys and identify follow-up strategies.	High	High

Task 2: Seed bank management

This project has shown, through a range of research and extension activities, that effective management of the soil weed seed bank can take time to deliver observable results, but has quantifiable benefits in reducing the weed burden within vegetable crops, and therefore financial benefits to vegetable producers.

We therefore encourage adoption of strategies currently available to vegetable growers that will assist in soil weed seed bank management. Examples may include: avoiding weedy fallows in favour of sprayed fallows or growing competitive cover crops; preparing weed-free crop beds before crop sowing or planting through stale or false seed beds; managing weeds in refuge sites such as crop verges, headlands and around farm infrastructure before they produce seed; and controlling weeds within growing crops before they produce seed, for example through diligent hand weeding or inter-row tillage. Ongoing diligence is critical.

These principles are already used effectively on some vegetable farms to deliver a minimal weed burden, and are explained in detail in the Vegetable Industry Weed Manual and case studies produced as part of this project. These materials can be promoted to the industry via relevant extension and outreach networks, to ensure vegetable growers are aware of this important principle that underpins IWM, and that effective adoption is maximised.

Emerging technologies at the time of writing, particularly field robotics, precision agriculture technologies and microwave weed management, also have considerable potential to further enhance soil weed seed bank management. These and other similar technologies that may become available in the future are worthy of continued attention by the industry. They appear poised to facilitate weed seed destruction before planting (microwave) and efficient management of weeds within growing crops (field robotics) to minimise weed seed production.

Table 4. Task 2 research, development and extension recommendations, ranked.

Recommendation	Importance to Industry	Feasibility
Ongoing extension of soil weed seed bank management principles.	High	High

Task 3: Supplementary weed management practices

With increasing difficulty in accessing labour throughout the horticulture industry, developing efficient (and potentially more automated/mechanised) weed control approaches is likely to become increasingly important to vegetable growers.

There are a range of weed management tactics which are currently available to vegetable growers, however their weed management benefits in Australian vegetable production have not yet been quantified under the diverse conditions prevalent across Australia. This includes stale and false seed beds, which is already considered to have important benefits (e.g. Appendix 1.15), as well as field management approaches that may only be relevant in certain vegetable production contexts, such as drop irrigation or crop row orientation. These approaches may be explored through field trials to quantify their benefits, vs business as usual weed management. The goal would be to determine the extent to which these approaches reduce the soil weed seed bank, and the weed burden within the crop.

The benefits of thermal weeding (flame and steam) vs business as usual weed management may also be quantified via field research, however work is most likely to be required for these technologies to continue to improve their efficiency and effectiveness, while reducing the cost of purchase and operation. However, adoption of these approaches is likely to remain low, except

Additionally, the potential weed management benefits of novel and emerging crop management approaches may be explored through field trials (in comparison with business as usual weed management). In some cases, such evaluation could be completed in the near future for approaches already in use, such as reduce tillage or strip till. In other cases, technologies such as field robotics/drones and microwave weed management will need to wait for these systems to become commercially available and more price-competitive.

As part of this project we explored the potential for cover crops to suppress weed populations during the fallow, as well as the efficiency and effectiveness of different hand weeding implements used within growing vegetable crops. The principles arising from this field activity are presented in the Vegetable Industry Weed Manual (Appendix 5.1) as well as other materials (e.g. Appendix 1.14), and warrant ongoing extension to vegetable growers to ensure that uptake of these approaches, where they are relevant to specific growers, is maximised.

Table 5. Task 3 research, development and extension recommendations, ranked.

Recommendation	Importance to Industry	Feasibility
Field research to optimise the weed management benefits of established approaches.	Medium	High
Field research to establish the weed management benefits and farming systems implications of emerging technologies.	Medium	Medium
Ongoing extension: cover cropping for weed suppression and weed seed bank management.	Medium	High
Ongoing extension: the principles and benefits of effective hand weeding.	Low	High

Task 4: Economics of weeds and their management

In this project, we adopted a case study approach to develop detailed information on the costs weeds impose on individual vegetable production enterprises, as well as the comparative costs and benefits of introducing innovative weed management practices at the farm-level (Appendix 4.1). This information should continue to prove useful to the industry in reinforcing the messages that weeds impose a significant cost, and that their effective management can deliver significant improvements in enterprise profitability. The comparative evaluation of innovations will allow vegetable growers considering these practices to weigh up the economic impacts that may be relevant to their farm.

As they become more widely utilised by vegetable growers, case study evaluation of weed management technologies such as selective management of weeds within crops using field robotics, targeted herbicide application using drones, and management of fallow weeds and the weed seed bank using microwave energy, will be very useful information for growers considering adoption of these technologies but unsure of their costs and their quantifiable benefits.

Because of the large variety of production systems, regional circumstances, and types of weeds problematic across the industry as a whole, the case study data cannot be used to deliver an industry-wide estimate of the economic impact of weeds, similar to the earlier work produced by McLeod (2018) and Sinden et al. (2004). An overall national estimate of the economic impacts of weed in vegetable production will provide valuable benchmark figures for key stakeholders such as Hort Innovation, AUSVEG and research providers. Such figures can be used to communicate with the public and decision-makers about the context and extent of weed management costs to the industry, and the possible need for further investment in this area. Similar economic impact benchmarks for areas such as pest and disease management may also be warranted.

Table 6. Task 4 research, development and extension recommendations, ranked.

Recommendation	Importance to Industry	Feasibility
Complete a national study of economic impact of weeds in vegetable production.	Medium	High
Case study analyses of the economics of emerging weed management technologies.	Low	Low

Task 5: Industry communication and extension

Vegetable growers are busy, and require clear and easily assimilated extension materials. Maximising the adoption of new practices among vegetable growers will mean delivering a clear message regarding how best to implement the new approach, as well as its likely benefits to the individual grower. These were the principles underpinning development of the extension materials delivered for this project – that they should be clear, concise and relevant.

In order to maximise the impact of these materials, they should be extended to the vegetable industry (growers and their advisors) through all relevant avenues beyond the life of this project. This will include, but not be limited to, email newsletters, industry magazines, social media, and in person via agronomists and industry development officers. We have worked with these forms of communication to extend IWM messages through the life of this project, and suggest that Hort Innovation continue this activity where possible to ensure the IWM message reaches its target audience. Promotion may also take place as part of broader messages regarding issues such as integrated pest management, management of soil health and quality, and management of soil-borne crop diseases.

Field days and demonstration sites were a critical opportunity for the project team to engage with industry during this project to ground-truth our research activity, obtain research data, and to deliver messages arising from the research. Our team attended and hosted several field days, particularly around the issue of cover cropping, and found these to be an ideal forum for discussing weed management with vegetable growers, agronomists, researchers, and extension officers. Industry stakeholders appear to benefit most by observing new approaches in person, and discussing these with their colleagues.

The industry may consider establishing field demonstration sites to showcase the benefits of a variety of supplementary weed management practices highlighted during this project:

Stale or false seed beds for weed management, vs business as usual options such as bed formation and pre-emergent herbicide application immediately before crop establishment.

Emergent technologies such as field robotics, drones, microwave and other thermal approaches, vs business as usual.

Existing extension teams at the time of writing may be well placed to lead these activities, including State/Territory extension staff or members of the VegNET team.

The VegNET Industry Development Officers were a critical source of advice, information, industry linkage, and assistance with logistics and communication with growers over the course of this project. Advice was also received on messages and content of our extension materials. Our team worked regularly with the VegNET team on these issues, and without their support the research and extension activities would have been more difficult to achieve. We also observed the benefits they provide to vegetable growers in allowing access to new information, ideas and demonstration activities. For their ongoing benefits to both research and extension, and to vegetable growers and their advisors, we therefore recommend the industry consider continuing the VegNET project beyond its current term, and to continue to promote synergies between Hort Innovation projects.

Table 7. Task 5 research, development and extension recommendations, ranked.

Recommendation	Importance to Industry	Feasibility
Ongoing extension/dissemination of Vegetable Industry Weed Manual and other resources produced by this project.	High	High
Field sites/days to showcase different weed management techniques.	High	Medium
Maintain industry extension capacity to continue effective dissemination of IWM principles.	High	Medium

Refereed scientific publications

Coleman, M., Fyfe, C., Tiwari Pokhrel, S., Marshall, G., Sindel, B., Kristiansen, P., 2018. Exploring and extending integrated weed management opportunities in the Australian vegetable industry. In: Johnson, S., Weston, L., Wu, H., Auld, B. (Eds.), 21st Australasian Weeds Conference Proceedings. Weed Society of New South Wales, Sydney, pp. 49-53 (Appendix 5.3).

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Tiwari, S., Kristiansen, P., Coleman, M., Vo, B., Fyfe, C., 2019. Weed seed banks of Australian vegetable fields. In: Hignell, K., Wu, H., Walsh, M (Eds.), Proceedings of the 20th NSW Biennial Weeds Conference. Weed Society of New South Wales, Newcastle, pp. 53-61 (Appendix 5.5).

Tiwari, S., Coleman, M., Sindel, B., Vo, B., Fyfe, C., Kristiansen, P., 2020. Weeds in the soil seed banks of vegetable fields: diversity, abundance and management. Paper submitted to *Weed Research* (Appendix 2.3).

Tiwari, S., Sindel, B.M., Coleman, M.J., Kristiansen, P., 2020. Plant species and emergence timing influence cover crop–weed interactions: evaluating competition between cereal rye and Nemat cover crops and common weeds fat hen and annual ryegrass. Paper submitted to *Renewable Agriculture & Food Systems* (Appendix 3.3).

Tiwari, S., Sindel, B.M., Smart, N., Coleman, M.J., Fyfe, C., Lawlor, C., Vo, B., Kristiansen, P., 2020. Hand weeding tools in vegetable production systems: an agronomic, ergonomic and economic evaluation. Paper submitted to the *International Journal of Agricultural Sustainability* (Appendix 3.4).

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Intellectual property, commercialisation and confidentiality

No project IP, project outputs, commercialisation or confidentiality issues to report.

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Appendices

Task 1: IWM in high priority weeds

The overall goal of this Task was to develop improved management strategies for high priority weeds in vegetable production, including understanding germination and early growth, timing, and optimising herbicide effectiveness. Relevant appendices included with the Final Report are as follows.

Appendix 1.1: Review of Literature – High priority weeds and their management.

Appendix 1.2: Review of Literature – Integrated Weed Management.

Appendix 1.3: Amaranth (*Amaranthus* spp.) – Weed management guide for Australian vegetable production.

Appendix 1.4: Blackberry nightshade (*Solanum nigrum*) – Weed management guide for Australian vegetable production.

Appendix 1.5: Chickweed (*Stellaria media*) – Weed management guide for Australian vegetable production.

Appendix 1.6: Common sowthistle (*Sonchus oleraceus*) – Weed management guide for Australian vegetable production.

Appendix 1.7: Dwarf nettle (*Urtica urens*) – Weed management guide for Australian vegetable production.

Appendix 1.8: Fat hen (*Chenopodium album*) – Weed management guide for Australian vegetable production.

Appendix 1.9: Marshmallow (*Malva parviflora*) – Weed management guide for Australian vegetable production.

Appendix 1.10: Nutgrass (*Cyperus rotundus*) – Weed management guide for Australian vegetable production.

Appendix 1.11: Pigweed (*Portulaca oleracea*) – Weed management guide for Australian vegetable production.

Appendix 1.12: Potato weed (*Galinsoga parviflora*) – Weed management guide for Australian vegetable production.

Appendix 1.13: Wild radish (*Raphanus raphanistrum*) – Weed management guide for Australian vegetable production.

Appendix 1.14: Effective Integrated Weed Management – Case Study. Diligent hand weeding ultimately pays off. The Loose Leaf Lettuce Company, Gingin, Western Australia.

Appendix 1.15: Effective Integrated Weed Management – Case Study. Managing weed seed banks through stale seed beds and inter-row tillage. Schreurs & Sons, Clyde, Victoria.

Appendix 1.16: Nutgrass (*Cyperus rotundus*). Management considerations using plastic mulch.

Task 2: Seed bank management

The overall goal of this Task was to quantify the role of the weed seed banks on vegetable farms, link weed life cycles to farming practices and incorporate this information into weed management strategies for vegetable growers. Relevant appendices included with the Final Report are as follows.

Appendix 2.1: Review of Literature – Assessing the weed seed bank.

Appendix 2.2: Weed seed bank assessment in vegetable production system.

Appendix 2.3: Weeds in the soil seed banks of vegetable fields: diversity, abundance and management.

Task 3: Supplementary weed control methods

The overall goal of this Task was to evaluate the effectiveness of a range of supplementary weed control methods, particularly as they relate to high priority weeds. Relevant appendices included with the Final Report are as follows.

Appendix 3.1: Review of Literature – Supplementary cultural methods for weed control in vegetable production.

Appendix 3.2: Weed management in vegetable production systems using cover crops.

Appendix 3.3: Plant species and emergence timing influence cover crop–weed interactions: evaluating competition between cereal rye and Nemat cover crops and common weeds fat hen and annual ryegrass.

Appendix 3.4: Hand weeding tools in vegetable production systems: an agronomic, ergonomic and economic evaluation.

Appendix 3.5: Resource competition and allelopathy of cover crops against weeds.

Appendix 3.6: Effect of organic herbicides on selected weeds and crops.

Appendix 3.7: Effect of different coloured plastic mulches on purple nutsedge (*Cyperus rotundus* L.) with and without crop.

Appendix 3.8: Optimizing mechanical control of pigweed (*Portulaca oleracea* L.).

Task 4: Economics of weeds and their management

The overall goal of this Task was to conduct robust economic analyses of the on-farm costs and benefits of weed management using farm-level data. Relevant appendices included with the Final Report are as follows.

Appendix 4.1: Economics of weeds and their management.

Task 5: Industry communication and extension

The overall goal of this Task was to develop a comprehensive integrated weed management (IWM) manual for vegetable producers based on products used in other agricultural sectors; and develop enhanced extension resources for weed management in vegetable production (including multi-lingual resources). Relevant appendices included with the Final Report are as follows.

Appendix 5.1: Integrated weed management for the Australian vegetable industry.

Appendix 5.2: Integrated weed management for the Australian vegetable industry – the principles. Translations in Khmer, Simplified Chinese and Vietnamese.

Appendix 5.3: Exploring and extending integrated weed management opportunities in the Australian vegetable industry.

Appendix 5.4: Abundance and distribution of weeds in seed banks of vegetable fields of Australia.

Appendix 5.5: Weed seed banks of Australian vegetable fields.

Appendix 5.6: Developing a strategic approach to managing weeds.

Appendix 5.7: On-farm trial. Weed management effectiveness through winter cover cropping.

Appendix 5.8: Managing weeds using cover crops – Forthside Trial Update.

Appendix 5.9: Managing weeds through winter cover cropping: results from year 1 of Myalup trial.

Appendix 5.10: Winter cover crop effects on weeds: results from Tas and WA trials.

Appendix 5.11: Managing important weed species on Australian vegetable farms.

Appendix 5.12: R&D investment Spotlight on ‘A strategic approach to weed management for the Australian vegetable industry (VG15070)’.

Appendix 5.13: Assessing the economic impact of weeds in Australian vegetable production.

Appendix 5.14: Diligent hand weeding ultimately pays off.

Appendix 5.15: What do weeds cost Australian vegetable growers?